ENVIRONMENTAL IMPACTS OF RENEWABLE ENERGY

ENERGY AND THE ENVIRONMENT

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As humans we tend to forget that Mother Nature does not need us to flourish and survive; instead, we need Earth to survive, period.

To a person with a saw, everything looks like lumber.

Contents

Preface

It is generally known and widely accepted that the use of all energy sources has some impact on our environment. Fossil fuels—oil, coal, and natural gas—do substantially more harm than renewable energy sources by almost any measure: air and water pollution, public health, wildlife and their habitat, water use, land use, and global climate change. In contrast to fossil fuels, renewable energy—wind, solar, geothermal, hydroelectric, biomass for electricity, and hydrokinetic—provide substantial benefits for our climate, our health, and our economy:

- Little or no global warming emissions
- Improved public health and environmental quality
- A vast and inexhaustible energy supply
- Creation of jobs and other economic benefits
- Stable energy prices
- A more reliable and resilient energy system

However, it is important to understand that renewable energy sources also have environmental impacts. The exact type and intensity of environmental impacts vary depending on the specific technology used, the geographic location, and a number of other factors:

- Air quality
- Cultural resources
- Ecological resources
- Water resources
- Land use
- Soil and geologic resources
- Paleontological resources
- Transportation
- Visual resources
- Socioeconomics
- Environmental justice
- Safety and health

Since 9/11, the intentional destruction of renewable energy sources (e.g., wind farms, solar farms, hydrokinetic systems, hydrodams, biomass feedstock and production sites, geothermal facilities, fuel cell manufacturing sites) and the accompanying damage to the environment as a result of terrorist activities is a very real possibility. All energy sources are considered critical infrastructure (and thus likely terrorist targets) by the U.S. Department of Homeland Security. For this reason, potential terrorist acts against renewable energy sources are addressed in this text, because the effects of such actions impact the environment in which we live.

Although carbon capture and sequestration (CCS) (or carbon capture and storage) is not a renewable energy source, it is also discussed in this book. The process of capturing waste carbon dioxide from large point sources such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere has been gaining the attention of regulators, environmentalists, and others. Many view carbon capture and sequestration as a panacea in preventing global climate change. In this book, we do not argue for or against the benefits of this point of view. Instead, beneficial or not, the point is made that the carbon capture and sequestration process has environmental impacts, and these are described in detail within this text. The important point woven into the warp and woof of this text is that, by understanding the current and potential environmental issues associated with each renewable energy source, we can take steps to effectively avoid, mitigate, or minimize these impacts as renewable energy sources become a larger portion of our electric power supply.

Environmental Impacts of Renewable Energy is designed to reach a wide range of diverse student and general reader backgrounds. The text focuses on the various forms of renewable energy derived from natural processes that replenish constantly: sun, wind, water (tides and waves), geothermal, biomass, hydroelectricity, biofuels, and hydrogen fuel cells. Along with exploring the derivation and production of the energy we need for future use—to literally sustain our future—the book also points out that it is critical to our very survival to avoid or to limit renewable-energy-generated pollution of the atmosphere, of surface water and groundwater, and of soil (the three environmental media). Because the environmental impacts of renewable energy can produce real-world problems, it logically follows that we can solve these problems by understanding the consequences of construction, operation, and maintenance of renewable energy facilities using real-world methods; that's what this book is all about.

To the Reader

In 1976, energy policy analyst Amory B. Lovins coined the term *soft energy path* to describe an alternative future where energy efficiency and appropriate renewable energy sources steadily replace a centralized energy system based on fossil and nuclear fuels. In 2009, Joshua Green, a writer for *Businessweek*, pointed out that in various publications Lovins further argued that the United States had arrived at an important crossroads and could take one of two paths. The first, supported by U.S. policy, promised a future of steadily increasing reliance on dirty fossil fuels and nuclear fission and had serious environmental risks. The alternative, which Lovins called the "soft path," favored "benign" sources of renewable energy such as wind power, solar power, biofuels, geothermal energy, and wave and tidal power, along with a heightened commitment to energy conservation and energy efficiency.

As a lifelong student, researcher, lecturer, and ardent advocate of the development and use of renewable or alternate energy sources (eventually excluding all fossil fuel use to the extent possible), I agree with Lovins in many respects, but I take issue with those who state that renewable energy sources are "benign." In my view, the definition of the term benign means something that is harmless, innocent, innocuous, or inoffensive. Thus, the labeling of renewable energy sources as benign implies that the use of renewable energy sources is totally safe. The truth is the use of renewable energy sources is not totally safe.

Again, I am an advocate for the use of renewable energy. Simply, I think using renewable energy sources instead of fossil fuels is a good thing. However, with any good thing there usually comes a bad thing. Nothing made by and used by humans is absolutely harmless to the environment … nothing … absolutely nothing. Only Mother Nature, with her ultimate plan, affects nature as we know it in beneficial ways. Even when she kills millions of us with her designed orchestrations (Earth- and life-altering events) that require changes to life as we know it, we must realize that these are simply planned and timed mechanizations. Remember, Mother Nature's plan is the ultimate plan. Who are we to argue otherwise?

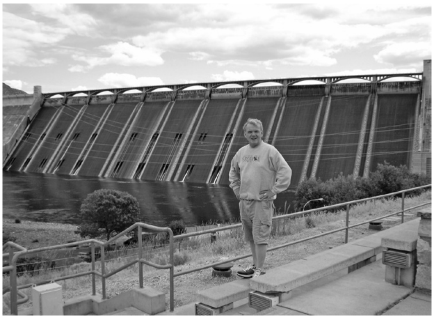
Anyway, because I do not agree with the idea that the so-called soft path is the "benign" path, I also cannot say that the impacts of renewable energy sources are necessarily bad, baneful, damaging, dangerous, deleterious, detrimental, evil, or harmful to the environment. The question is: What can I say in this book and elsewhere about renewable energy? I can say that I am biased toward the use of renewable energy, that I am for Lovins' soft path and against the hard path. But, I qualify this by also stating that renewable energy sources have impacts on the environment, both good and bad, and it is these bad impacts that this book is all about.

So, let's cut to the chase. My broad thesis is that renewable energy sources are not the panacea for solving our many pollution problems that they are popularly perceived to be. In reality, their adverse environmental impacts can be as strongly negative as the impacts of nonrenewable energy sources. Oh, before we begin the discussion, a final word … one of those bottom liners I tend to use. On the subject

of global climate change, the author is sure that things are changing but not entirely sure how. Much of the evidence is anecdotal, and there are not enough data to draw solid conclusions. When I speak of data, I am referring to some form of irrefutable evidence. What we have in the global climate change argument is not always a failure to communicate but instead a situation characterized as underdetermination. For example, consider this analogy: If all that we know is that exactly $10 was spent on prunes and apples, and that prunes cost $1 and apples $2, then we know enough to eliminate some possible purchase combinations (e.g., only 5 prunes could not have been purchased), but we would not have enough evidence to know which specific combination of prunes and apples was purchased.

Here's the real bottom line on global climate change. The historical record shows that Earth has a history of cyclical climate change over time. Is humankind the cause of the current changes in global climate? We simply do not know; the jury is still out. The causal factors remain to be determined.

Author



Frank R. Spellman, PhD, is a retired assistant professor of environmental health at Old Dominion University, Norfolk, Virginia, and the author of more than 90 books covering topics ranging from concentrated animal feeding operations (CAFOs) to all areas of environmental science and occupational health. Many of his texts are readily available online, and several have been adopted for classroom use at major universities throughout the United States, Canada, Europe, and Russia; two have been translated into Spanish for South American markets. Dr. Spellman has been cited in more than 450 publications. He serves as a professional expert witness for three law groups and as an incident/accident investigator for the U.S. Department of Justice and a northern Virginia law firm. In addition, he consults on homeland security vulnerability assessments for critical infrastructures, including water/wastewater facilities, and conducts audits for Occupational Safety and Health Administration and Environmental Protection Agency inspections throughout the country. Dr. Spellman receives frequent requests to co-author with well-recognized experts in various scientific fields; for example, he is a contributing author to the prestigious text *The Engineering Handbook*, 2nd ed. Dr. Spellman lectures on sewage treatment, water treatment, and homeland security, as well as on safety topics, throughout the country and teaches water/wastewater operator short courses at Virginia Tech in Blacksburg. He earned a BA in public administration, a BS in business management, an MBA, and both an MS and a PhD in environmental engineering.

1 Setting the Stage: The 411 on Energy Basics

> Sunlight pours energy on the Earth, and the energy gets converted from one form to another, in an endless cycle of life, death, and renewal. Some of the sunlight got stored underground, which has provided us with a tremendous "savings account" of energy on which we can draw. Our civilization has developed a vast thirst for this energy, as we've built billions and billions of machines large and small that all depend on fuel and electricity.
>
> **Hartmann (2004)**

> Oil creates the illusion of a completely changed life, life without work, life for free. … The concept of oil expresses perfectly the eternal human dream of wealth achieved through lucky accident. … In this sense, oil is a fairy tale and like every fairy tale a bit of a lie.
>
> **—Ryszard Kapuscinski (Polish journalist)**

> Massive changes in the existence of humanity are imminent. The oil shortage? Blame it all on the Greenies, it is their entire fault. There's something guttural, something personal, about the price of gas.
>
> **Steiner (2009)**

> Renewables can't save climate.
>
> **—*Virginian-Pilot (Norfolk, VA)*, September 24, 2013**

ENERGY

Defining energy can be accomplished by providing a technical definition or by a characterization in layman terms. Because the purpose of this book is to reach technical readers as well as a wide range of general readers, definitions provided herein and hereafter are best described as technical/nontechnical-based. Consider the definition of energy, for example; it can be defined in a number of ways. In the broad sense, energy means the capacity of something—a person, an animal or a physical system (machine)—to do work and produce change. In layman terms, energy is the amount of force or power that, when applied, can move an object from one position to another. It can also be used to describe someone doing energetic things, such as running, talking, and acting in a lively and vigorous way. It is used in science to describe how much potential a physical system has to change. It also is used in economics to describe the part of the market where energy itself is harnessed and sold to consumers. For our purposes in this text, we simply define energy in technical/nontechnical-based terms as something that can do work or the capacity of a system to do work.

There are two basic forms of energy: *kinetic energy* and *potential energy*. Kinetic energy is energy at work or in motion—that is, moving energy; for example, a car in motion or a rotating shaft has kinetic energy. In billiards, a player gives the cue ball kinetic energy when she strikes the ball with the cue. As the ball rolls, it exerts kinetic energy. When the ball comes into contact with another ball, it transmits its kinetic energy, allowing the next ball to be accelerated. Potential energy is stored energy, such as the energy stored in a coiled or stretched spring or an object stationed above a table. A roller coaster has the greatest potential energy when it is stopped at the top of a long drop. Another example of potential energy is when a can of carbonated soda remains unopened. The can is pressurized with gas that is not in motion but that has potential energy. When the can is opened, the gas is released and the potential energy is converted to kinetic energy.

According to the law of conservation of energy, energy cannot be made or destroyed but can be made to change forms. Moreover, when energy changes from one form to another, the amount of energy stays the same. Let's consider an example of the law of conservation of energy: The initial energy of something is measured. The energy then changes from potential (stored) energy to kinetic (moving) and back again. After that, the energy is measured again. The energy measured at the start is the same as that measured at the end; it will always be the same. One caveat to this explanation is that we now know that matter can be made into energy through processes such as nuclear fission and nuclear fusion. The law of conservation of energy has therefore been modified or amplified to become the law of conservation of matter and energy.

TYPES OF ENERGY

The many types of energy include the following:

- Kinetic (motion) energy
- Water energy
- Potential (at rest) energy
- Elastic energy
- Nuclear energy
- Chemical energy
- Sound energy
- Internal energy
- Heat/thermal energy
- Light (radiant) energy
- Electric energy

Energy sources can also be categorized as renewable or nonrenewable. When we use electricity in our home, the electrical power was probably generated by burning coal, by a nuclear reaction, or by a hydroelectric plant at a dam (EIA, 2009); therefore, coal, nuclear, and hydropower are called *energy sources*. When we fill up a gas tank, the source might be petroleum or ethanol made by growing and processing corn.

Energy sources are divided into two groups—*renewable* (an energy source that can be easily replenished) and *nonrenewable* (an energy source that we are using up and cannot recreate; petroleum, for example, was formed millions of years ago from the remains of ancient sea plants and animals). In the United States, most of our energy comes from nonrenewable energy sources. Coal, petroleum, natural gas, propane, and uranium are nonrenewable energy sources. They are used to make electricity, to heat our homes, to move our cars, and to manufacture all kinds of products. Renewable and nonrenewable energy sources can be used to produce secondary energy sources, including electricity and hydrogen. Renewable energy sources include the following:

- Solar
- Hydro
- Wind
- Geothermal
- Ocean thermal energy conversion
- Tidal energy
- Hydrogen burning
- Biomass burning

Renewable energy (energy sources that can be easily replenished) is the focus of this text. Unfortunately (depending on your point of view), nonrenewable energy sources on Earth are available in limited quantity and may vanish within the next 100 years. Moreover, keep in mind that nonrenewable sources are *not* environmental friendly and can have serious effects on our health. Notwithstanding the environmental and health impacts of using nonrenewable energy sources, it is important to point out both sides of the argument—that is, the benefits derived and non-benefits obtained by using these sources.

NONRENEWABLE ENERGY

Benefits

- Nonrenewable sources are easy to use.
- A small amount of nuclear energy will produce a large amount of power.
- Nonrenewable energy sources have little competition.
- Nonrenewable energy sources are relatively inexpensive when converting from one type of energy to another.

Non-Benefits

- Nonrenewable sources will expire some day.
- The speed at which such resources are being used can bring about serious environmental changes.
- Nonrenewable sources release toxic gases in the air when burned and can further exacerbate ongoing, cyclical climate change.
- Because nonrenewable sources are becoming scarcer, prices of these sources will begin to soar.

RENEWABLE ENERGY

Benefits

- Wind, sun, ocean, and geothermal energy are available in abundant quantities and are free to use.
- Renewable sources have low carbon emissions; therefore, they are considered to be environmentally friendly.
- Renewable energy helps stimulate the economy and create job opportunities.
- Renewable energy sources enable the country to become energy independent, not having to rely on foreign (often hostile) sources.

Non-Benefits

- Initial set-up costs of renewable energy sources are quite high.
- Solar energy is limited to daytime availability and cannot be obtained during the night or a rainy season.
- Geothermal energy can bring toxic chemicals from beneath the surface of the earth up to the top and can cause environmental damage.
- Hydroelectric dams are expensive to build and can affect natural flow and wildlife.
- Wind energy production requires high winds and must be sited properly to be effective. Also, wind turbines are tall structures that can affect bird populations.

ENERGY USE IN THE UNITED STATES

Use of energy in the United States is shared by four major sectors of the economy. Each end-use sector consumes electricity produced by the electric power sector (EIA, 2013):

- *Commercial*—18% (buildings such as offices, malls, stores, schools, hospitals, hotels, warehouses, restaurants, places of worship, and more)
- *Industrial*—32% (facilities and equipment used for manufacturing, agriculture, mining, and construction)
- *Residential*—21% (homes and apartments)
- *Transportation*—28% (vehicles that transport people or goods, such as cars, trucks, buses, motorcycles, trains, subways, aircraft, boats, barges, and even hot-air balloons)

Primary energy consumption in the United States was almost three times greater in 2012 than in 1949. In all but 18 of the years between 1949 and 2012, primary energy consumption increased over the previous year.

The year 2009 provided a sharp contrast to the historical trend, in part due to the economic recession. Real gross domestic product (GDP) fell 2% compared to 2008, and energy consumption declined by nearly 5%, the largest single year decline since 1949. Decreases occurred in all four of the major end-use sectors: commercial (3%), industrial (9%), residential (3%), and transportation (3%) (EIA, 2013).

MEASURING ENERGY

Energy can be measured. That is, the amount of energy a thing has can be given a number. As in other kinds of measurements, there are measurement units. The units of measurement for measuring energy are used to make the numbers understandable and meaningful. The SI unit for both energy and work is the joule (J). It is named after James Joule, who discovered that heat is a type of energy. In terms of SI units, 1 joule = 1 newton-meter, and 1 joule = 1 $kg \cdot m^2 \cdot s^{-2}$. The energy unit of measurement for electricity is the kilowatt-hour (kWh); 1 kWh is equivalent to 3,600,000 J (3600 kJ or 3.6 MJ). A common way to express energy is in the British thermal unit (Btu) (see Table 1.1). A Btu is the amount of heat energy it takes to raise the temperature of 1 pound of water by 1°F at sea level.

- 1000 joules = 1 Btu
- 1000 joules = 1 kilojoule = 1 Btu
- 1 therm = 100,000 Btu

Note that electricity is a secondary energy source. The energy sources we use to make electricity can be renewable or nonrenewable, but electricity itself is neither renewable nor nonrenewable. Many of the producers of renewable energy primarily produce electricity. Hydropower, for example, can be converted to mechanical power via a waterwheel connected to a gear train to power a grinding wheel to grind wheat or to a pump or other machine; however, today the primary purpose of hydropower is to generate electricity. Likewise, a windmill can also be connected to a gear train to power a pump or other machine, but today the primary purpose of wind turbines is to produce electricity. Solar power can be used to heat water to purify it and directly to produce steam which in turn powers a turbine to perform mechanical functions. Solar power can also be used to produce photovoltaic (PV) electrical energy. Even biomass liquid fuels can be used to power boilers that produce steam to power turbines connected to generators to produce electricity. In addition, waste off-gases or exhaust from various machines such as gas turbine engines can be used to heat boilers.

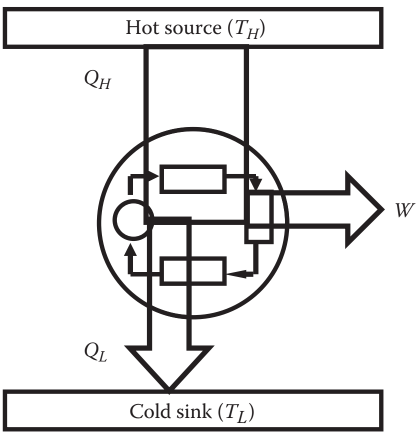
TABLE 1.1
Btu Conversion Factors

Energy Source	Physical Units and Btu (Weighted Averages)
Electricity	1 kilowatt-hour = 3412 Btu
Natural gas	1 cubic foot = 1028 Btu = 0.01 therms
Motor gasoline	1 gallon = 124,000 Btu
Diesel fuel	1 gallon = 139,000 Btu
Heating oil	1 gallon = 139,000 Btu
Propane	1 gallon = 91,333 Btu
Wood	1 cord = 20,000,000 Btu

The actual production of steam for powering turbines for energy conversion is accomplished by machines called *heat engines*. A few heat engine examples include an automobile engine that converts the chemical energy of gasoline into the mechanical energy of a piston and camshaft or the turbine in an electrical generating plant that converts heat into shaft work to run a generator which, in turn, produces electrical power. The heat engines of interest to us in this text are the Rankine cycle (or vapor cycle) and the Stirling cycle (or gas cycle) heat engines (Hinrichs and Kleinbach, 2006).

HEAT ENGINES

A heat engine is a device that converts thermal energy to mechanical output. The thermal energy input is called *heat*, and the mechanical output is called *work*. Typically, heat engines run on a specific thermodynamic cycle. Heat engines can be open to the atmospheric air (open cycle) or sealed and closed off to the outside (closed cycle). The driving agent of a heat engine is a temperature differential. That is, heat engines convert heat energy to mechanical work by exploiting the temperature gradient between a hot "source" and a cold "sink" (see Figure 1.1). Heat is transferred from the source, through the "working body" of the engine, to the sink, and in this process some of the heat is converted into work by exploiting the properties of a gas or liquid (the working substance). The lower the sink temperature or the higher the source temperature, the more work is available from the heat engine.



where

Q_H = Heat energy taken from the high-temperature system.
Q_L = Heat energy delivered to the low-temperature system.
W = Work.
T_H = Absolute temperature of heat source.
T_L = Absolute temperature of cold sink.

FIGURE 1.1 Heat engine diagram.

After doing work, the working substance can be either exhausted into the environment or sent back to the heat source to start the cycle over. If the working substance is returned to its initial state (gas or liquid), there has been no change in its total energy. Consequently, from the first law of thermodynamics, the total energy of a system can be increased by doing work on it or by adding heat, and the total work done by the system is just equal to the heat added (i.e., heat in minus heat out). The heat source may be direct solar radiation, geothermal steam, geothermal water, ocean water heated by the sun, combustion fuel, or nuclear energy. The two types of heat engines that are most commonly associated with renewable energy processes such as solar power and geothermal energy are the Rankine cycle and Stirling engines.

Rankine Cycle Heat Engine

Figure 1.2 illustrates the four processes as they occur in a closed-cycle Rankine cycle heat engine. The expansion can be accomplished through a cylinder with a piston, as in the locomotives one still sees in the old western movies or through a turbine. In the Rankine cycle heat engine, as described for turbine use, the working fluid changes state and is also called a vapor gas (i.e., hot air; not to be confused with fuel natural gas) cycle. Rankine cycle engines are all external combustion devices, such as external combustion gas turbine engines widely used in units for electrical generating stations.

As shown in the figure below, the first phase pumps the working fluid from low to high pressure; because the fluid is a liquid at this stage, the pump requires little input energy. In the second phase, the high-pressure liquid enters a boiler, where it is heated at constant pressure by an external heat source to become a dry saturated vapor. In the third phase, the dry saturated vapor expands through the turbine, thus generating power. In the process, both the temperature and pressure of the vapor are lowered, and it is possible that some condensation may occur. In the final phase, the wet vapor enters a condenser, where it is condensed at a constant pressure and temperature to become a saturated liquid. The pressure and temperature of the condenser are fixed by the temperature of the cooling coils as the fluid is undergoing a phase change.

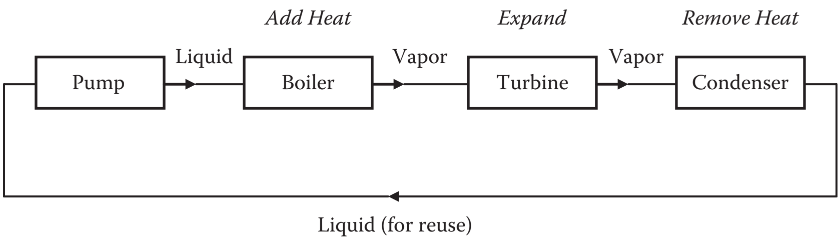


FIGURE 1.2 The four processes of the Rankine cycle.

Stirling Cycle Heat Engine

The Stirling cycle heat engine consists of isothermal compression, isometric heat addition, isothermal expansion, and isometric heat rejection. It operates by cyclical compression and expansion of air or other gas, the working fluid, at different temperature levels such that there is a net conversion of heat energy to mechanical work. Like a steam engine, the Stirling heat engine's heat flows in and out through the engine wall. The Stirling engine is noted for its high efficiency (results from heat regeneration), quiet operation, and the ease with which it can use almost any heat source. This compatibility with renewable energy sources has become increasingly significant as the price of conventional fuels rises and also in light of concerns such as climate change and peak oil. An example of this compatibility with renewable energy sources is evident when Stirling engines are placed at the focus of parabolic mirrors, where they can convert solar energy to electricity with an efficiency better than that of non-concentrated photovoltaic cells and as compared to concentrated photovoltaics.

THOUGHT-PROVOKING QUESTIONS

1.1 Is nuclear energy considered to be renewable energy?
1.2 What are the economic ramifications of running out of crude oil? Explain
1.3 Will the crude oil crisis come about gradually or suddenly? Explain
1.4 An economy based on renewable energy will help in our ongoing fight to reduce pollution. Explain.
1.5 Name 15 products produced by oil that we could get along without.

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2 Wind Power: Where Eagles Don't Dare

The wind goeth toward the south, and turneth about unto the north; it whirleth about continually, and the wind returneth again.

—Ecclesiastes 1:6

The Good, Bad, and Ugly of Wind Energy

Good: As long as Earth exists, the wind will always exist. The energy in the winds that blow across the United States each year could produce more than 16 billion GJ of electricity—more than one and one-half times the electricity consumed in the United States in 2000.

Bad: Turbines are expensive. Wind doesn't blow all the time, so they have to be part of a larger plan. Turbines make noise. Turbine blades kill birds.

Ugly: Some look upon giant wind turbine blades cutting through the air as grotesque scars on the landscape, as visible polluters.

The bottom line: Do not expect Don Quixote, mounted in armor on his old nag, Rocinate, with or without Sancho Panza, to lead the charge to build those windmills. Instead, expect—you can count on it, bet on it, and rely on it—that the charge will be made by the rest of us to satisfy our growing, inexorable need for renewable energy. What other choice do we have?

Recent Headlines on Wind Turbines

"Wind Turbines: A Different Breed of Noise?" (Seltenrich, 2014)

"Wind Turbine Health Effects: Are Wind Turbines Really Unhealthy for Humans?" (Casey, 2012a)

"How Noisy is a Wind Turbine?" (Casey, 2012b)

"U.S. to Allow Eagle Deaths—To Aid Wind Power" (Cappiello, 2013a)

"Eagle Deaths at Wind Farms Glossed Over" (Cappiello, 2013b)

INTRODUCTION*

Obviously, wind energy or power is all about wind. In simple terms, wind is the response of the atmosphere to uneven heating conditions. The atmosphere of Earth is constantly in motion. Anyone observing the constant cloud movement and weather changes around them is well aware of this phenomenon. Although its physical

* Adapted from Spellman, F.R. and Whiting, N.E., *Environmental Science and Technology*, Government Institutes Press, Lanham, MD, 2006.

DID YOU KNOW?

Wind speed is generally measured in meters per second (m/s), but Americans usually think in terms of miles per hour (mph). To convert m/s to mph, a good rule of thumb is to double the m/s value and add 10%.

manifestations are obvious, the importance of the dynamic state of our atmosphere is much less obvious. The constant motion of the atmosphere of Earth is both horizontal (*wind*) and vertical (*air currents*). This air movement is the result of thermal energy produced from heating of the surface of the Earth and the air molecules above. Because of differential heating of the surface of the planet, energy flows from the equator poleward.

The energy resources contained in the wind in the United States are well known and mapped in detail (Hanson, 2004). It is clear that air movement plays a critical role in transporting the energy of the lower atmosphere, bringing the warming influences of spring and summer and the cold chill of winter, and wind and air currents are fundamental to how nature functions. Still, though, the effects of air movements on our environment are often overlooked. All life on Earth has evolved or has been sustained with mechanisms dependent on air movement; for example, pollen is carried by the winds for plant reproduction, animals sniff the wind for essential information, and wind power was the motive force during the earliest stages of the Industrial Revolution. We can also see other effects of winds. Wind causes weathering (erosion) of the Earth's surface, wind influences ocean currents, and the wind carries air pollutants and contaminants such as radioactive particles that impact our environment.

In addition to the natural air movement processes described above, air movement has been harnessed by the wind industry and is playing a pivotal role in achieving a balanced energy mix in the United States. In 2012, wind energy was—for the first time ever—the number one source of new electricity generation capacity. More wind power capacity was installed in the United States than any other form of power generation (Siemens, 2014).

In practical terms, a wind turbine is defined as a device that converts kinetic energy from the wind into electrical power. In esthetic and thoughtful terms, a wind turbine is described as a clean, presentable structure that benefits the environment by generating a supply of clean and renewable electricity. When we look closer at wind turbines, we often find there are impacts associated with them, many of which are described in this chapter, but first we present the basics of air or wind movement and wind turbine operation in order to properly prepare the reader for the material that follows.

DID YOU KNOW?

Wind power consists of turning energy from the wind to other energy forms. There are different ways to harness it; for example, windmills produce mechanical energy to generate electricity.

WIND POWER BASICS

Air in Motion*

In all dynamic situations, forces are necessary to produce motion and changes in motion—winds and air currents. The air (made up of various gases) of the atmosphere is subject to two primary forces: gravity and pressure differences from temperature variations. *Gravity* (gravitational forces) holds the atmosphere close to the Earth's surface. Newton's law of universal gravitation states that every body in the universe attracts another body with a force equal to

$$F = G \frac{m_1 m_2}{r^2} \tag{2.1}$$

where F is the magnitude of the gravitational force between the two bodies, G is the gravitational constant ≈ 6.67×10^{-11} N (m²/kg²), m_1 and m_2 are the masses of the two bodies, and r is the distance between the two bodies.

The force of gravity decreases as an inverse square of the distance between the two bodies. Thermal conditions affect density, which in turn affects vertical air motion and planetary air circulation (and how air pollution is naturally removed from the atmosphere). Although forces acting in other directions can overrule gravitational force, gravity constantly acts vertically downward, on every gas molecule, which accounts for the greater density of air near the Earth.

Atmospheric air is a mixture of gases, so the gas laws and other physical principles govern its behavior. The pressure of a gas is directly proportional to its temperature. Pressure is force per unit area (pressure = force/area), so a temperature variation in air generally gives rise to a difference in pressure of force. This difference in pressure resulting from temperature differences in the atmosphere creates air movement—on both large and local scales. This pressure difference corresponds to an unbalanced force, and when a pressure difference occurs the air moves from a high- to a low-pressure region. In other words, horizontal air movements (called *advective winds*) result from temperature gradients, which give rise to density gradients and subsequently pressure gradients. The force associated with these pressure variations (*pressure gradient force*) is directed at right angles to (perpendicular to) lines of equal pressure (called *isobars*) and is directed from high to low pressure.

Localized air circulation gives rise to *thermal circulation* (a result of the relationship based on a law of physics whereby the pressure and volume of a gas are directly related to its temperature). A change in temperature causes a change in the pressure and volume of a gas. With a change in volume comes a change in density (density = mass/volume), so regions of the atmosphere with different temperatures may have different air pressures and densities. As a result, localized heating sets up air motion and gives rise to thermal circulation.

* Adapted from Spellman, F.R. and Bieber, R., *The Science of Renewable Energy*, CRC Press, Boca Raton, FL, 2011.

Once the air has been set into motion, secondary forces (velocity-dependent forces) act. These secondary forces are caused by Earth's rotation (Coriolis force) and contact with the rotating Earth (friction). The *Coriolis force*, named after its discoverer, French mathematician Gaspard Coriolis (1772–1843), is the effect of rotation on the atmosphere and on all objects on the Earth's surface. In the Northern Hemisphere, it causes moving objects and currents to be deflected to the right; in the Southern Hemisphere, it causes deflection to the left, because of the Earth's rotation. Air, in large-scale north or south movements, appears to be deflected from its expected path. That is, air moving poleward in the Northern Hemisphere appears to be deflected toward the east; air moving southward appears to be deflected toward the west.

Friction (drag) can also cause the deflection of air movements. This friction (resistance) is both internal and external. The friction of molecules generates internal friction, and external friction is caused by contact with terrestrial surfaces. The magnitude of the frictional force along a surface is dependent on the air's magnitude and speed, and the opposing frictional force is in the opposite direction of the air motion.

WIND ENERGY*

Wind energy is power produced by the movement of air. Since early recorded history, people have been harnessing the energy of the wind to, for example, mill grain and pump water. Wind energy propelled boats along the Nile River as early as 5000 BC. By 200 BC, simple windmills in China were pumping water, and windmills with woven reed sails were grinding grain in Persia and the Middle East.

The use of wind energy spread around the world, and by the 11th century people in the Middle East were using windmills extensively for food production; returning merchants and crusaders carried this idea back to Europe. The Dutch refined the windmill and adapted it for draining lakes and marshes in the Rhine River delta. When settlers took this technology to the New World in the later 19th century, they used windmills to pump water for farms and ranches and, later, to generate electricity for homes and industry. The first known wind turbine designed to produce electricity was built in 1888 by Charles F. Brush, in Cleveland, Ohio; it was a 12-kW unit that charged batteries in the cellar of a mansion. The first wind turbine used to generate electricity outside of the United States was built in Denmark in 1891 by Poul la Cour, who used electricity from his wind turbines to electrolyze water to make hydrogen for the gas lights at the local schoolhouse. By the 1930s and 1940s, hundreds of thousands of wind turbines were being used in rural areas of the United States that were not yet being served by the grid. The oil crisis in the 1970s created a renewed interest in wind energy, until the U.S. government stopped giving tax credits.

* Adapted from EERE, *History of Wind Energy*, Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, 2005 (http://www1.eere.energy.gov/windandhydro/wind_history.html).

TABLE 2.1
U.S. Energy Consumption by Source (2013)

Energy Source	Energy Consumption (quadrillion Btu)
Renewable total	9.291
Biomass (biofuels, waste, wood, and wood-derived)	4.607
Geothermal energy	0.221
Hydroelectric conventional	2.561
Solar thermal/PV energy	0.307
Wind energy	**1.595**

Source: EIA, *Monthly Energy Review*, Energy Information Administration, Washington, DC, 2014 (http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf).

Today, several hundred thousand windmills are in operation around the world, many of which are used for pumping water. The use of wind energy as a pollution-free means of generating electricity on a significant scale is attracting the most interest in the subject today. As a matter of fact, due to current and pending shortages and high costs of fossil fuels to generate electricity, as well as the green movement toward the use of cleaner fuels, wind energy is the world's fastest growing energy source and could power industry, businesses, and homes with clean, renewable electricity for many years to come. In the United States, wind-based electricity generating capacity has increased markedly since the 1970s. Today, though, it still represents only a small fraction of total electric capacity and consumption (see Table 2.1), despite the advent of $4/gal gasoline, increases in the cost of electricity, high heating and cooling costs, and worldwide political unrest or uncertainty in oil-supplying countries. Traveling the wind corridors of the United States (primarily Arizona, New Mexico, Texas, Missouri, and north through the Great Plains to the Pembina Escarpment and Turtle Mountains of North Dakota) gives some indication of the considerable activity and seemingly exponential increase in wind energy development and wind turbine installations; these machines are being installed to produce and provide electricity to the grid.

DID YOU KNOW?

We can classify wind energy as a form of solar energy. Winds are caused by uneven heating of the atmosphere by the sun, irregularities of the Earth's surface, and the rotation of the Earth. As a result, winds are strongly influenced and modified by local terrain, bodies of water, weather patterns, vegetative cover, and other factors. The wind flow, or motion of energy when harvested by wind turbines, can be used to generate electricity.

DID YOU KNOW?

Whenever wind energy is being considered as a possible source of renewable energy it is important to consider the amount of land area required, accessibility to generators, and aesthetics.

WIND POWER

The terms *wind energy* and *wind power* describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water), or a generator can convert this mechanical power into electricity (EERE, 2006a). We have been harnessing the energy of the wind for hundreds of years. From old Holland to farms in the United States, windmills have been used for pumping water or grinding grain; today, the modern equivalent of a windmill—a wind turbine—can use the energy of the wind to generate electricity. The blades of a wind turbine spin like aircraft propeller blades. Wind turns the blades, which in turn spin a shaft connected to a generator to produce electricity (Wind Energy EIS, 2009).

Wind Turbine Types

Whether referred to as *wind-driven generators*, *wind generators*, *wind turbines*, *wind-turbine generators*, or *wind energy conversion systems*, modern wind turbines fall into two basic groups: the horizontal-axis wind turbine (HAWT), like the traditional farm windmills used for water pumping, and the vertical-axis wind turbine (VAWT), like the eggbeater-style, Darrieus rotor model, named after its French inventor, the only vertical-axis machine with any commercial success. Wind hitting the vertical blades, called *aerofoils*, generates lift to create rotation. No yaw (rotation about vertical axis) control is needed to keep them facing into the wind. The heavy machinery in the nacelle (cowling) is located on the ground. Blades are closer to the ground where wind speeds are lower. Most large modern wind turbines are horizontal-axis turbines; therefore, this type is highlighted and described in detail in this text.

Horizontal-Axis Wind Turbines

Wind turbines are available in a variety of sizes and power ratings. Utility-scale turbines range in size from 100 kW to as large as several megawatts. Horizontal-axis wind turbines typically have two or three blades. Downwind horizontal-axis wind

DID YOU KNOW?

Groups of wind turbines are located in what is called a *wind farm* or a *wind park* (see Figure 2.1).

FIGURE 2.1 Wind turbines at the Tehachapi Pass Wind Farm in California. Wind development in the Tehachapi Pass began in the early 1980s, and this is one of the first large-scale wind farms installed in the United States.

turbines have a turbine with the blades behind (downwind from) the tower. No yaw control is needed because they naturally orient themselves in line with the wind; however, these downwind HAWTs experience a shadowing effect, in that when a blade swings behind the tower the wind it encounters is briefly reduced and the blade flexes. Upwind HAWTs usually have three blades in front (upwind) of the tower. These upwind wind turbines require a somewhat complex yaw control to keep them facing into the wind. They operate more smoothly and deliver more power and thus are the most commonly used modern wind turbines. The largest machine has blades that span more than the length of a football field, stands 20 building stories high, and produces enough electricity to power 1400 homes.

Inside the HAWT

Basically, a horizontal-axis wind turbine consists of three main parts: a turbine, a nacelle (the cover housing that houses all of the generating components in a wind turbine, including the generator, gearbox, drive train, and brake assembly), and a tower. Several other important parts are contained within the tower and nacelle, including anemometer, blades, brake, controller, bear box, generator, high-speed shaft, low-speed shaft, pitch, rotor, tower, wind direction, wind vane, yaw drive, and yaw motor (see Figure 2.2).

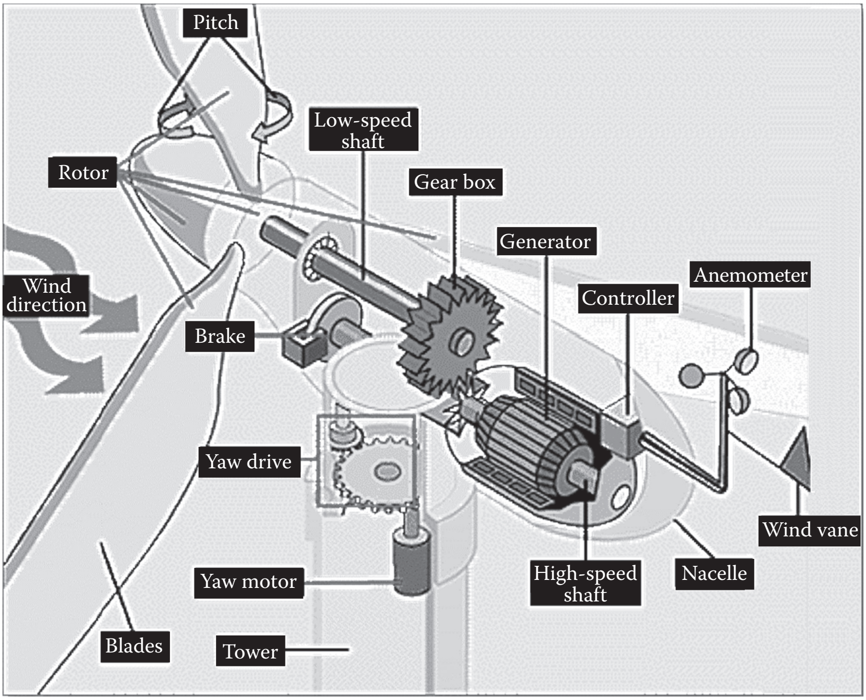

FIGURE 2.2 Horizontal-axis wind turbine components.

WIND TURBINE COMPONENTS

Anemometer—This device measures the wind speed and transmits wind speed data to the controller.

Blades—Wind blowing over the two or three blades causes the blades to lift and rotate; they capture the kinetic energy of the wind and help the turbine rotate.

Brake—A disc brake can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

Controller—The controller starts up the machine at wind speeds of about 8 to 16 mph and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.

Gear box—Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine, and engineers are exploring direct-drive generators that operate at lower rotational speeds and do not require gear boxes.

Generator—Usually an off-the-shelf induction generator that produces 60-hertz alternating-current electricity.

DID YOU KNOW?

During rotation of the nacelle, the cables inside the tower can twist, with the cables becoming more and more twisted if the turbine keeps turning in the same direction, which can happen if the wind keeps changing in the same direction. The wind turbine is therefore equipped with a cable twist counter, which notifies the controller that it is time to straighten the cables (Khaligh and Onar, 2010).

High-speed shaft—The shaft that drives the generator.
Low-speed shaft—A shaft that turns at about 30 to 60 rotations per minute.
Nacelle—Unit that sits atop the tower and contains the gearbox, generator, low- and high-speed shafts, controller, and brake.
Pitch—Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor turning in winds that are too high or too low to produce electricity.
Rotor—Comprised of the blades and the hub.
Tower—Made from tubular steel, concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.
Wind direction—An upwind turbine operates facing into the wind; other turbines are designed to run downwind, facing away from the wind.
Wind vane—Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.
Yaw drive—In upwind turbines, this is used to keep the entire nacelle and thus the rotor facing into the wind as the wind direction changes. Downwind turbines do not require a yaw drive, as the wind blows the rotor downwind.
Yaw motor—Powers the yaw drive.

WIND ENERGY SITE EVALUATION IMPACTS

Site evaluation phase activities, such as monitoring and testing, are temporary and are conducted at a smaller scale than those at the construction and operation phases. Potential impacts of these activities are presented below by type of affected resource. The impacts described are for typical site evaluation and exploration activities, such as ground clearing (removal of vegetative cover), vehicular and pedestrian traffic, borings for geotechnical surveys and guy wire installation, and positioning of equipment, such as meteorological towers. If excavation of road construction is necessary during this phase, potential impacts would be similar in character to those for the construction phase, but generally of smaller magnitude.

Air Quality

Impacts on air quality during monitoring and testing activities would be limited to temporary and local generation of vehicle emissions and fugitive dust. These impacts are unlikely to cause an exceedance of air quality standards or to impact climate change.

Cultural Resources

Surface disturbance is minimal during the site evaluation phase, and cultural resources buried below the surface are unlikely to be affected. Cultural material present on the surface could be disturbed by vehicular traffic, ground clearing, and pedestrian activity (including collection of artifacts). Monitoring and testing activities could affect areas of interest to Native Americans depending on the physical placement or level of visual intrusion. Surveys conducted during this phase to evaluate the presence or significance of cultural resources in the area would assist developers in designing the project to avoid or minimize impacts on these resources.

Ecological Resources

Impacts on vegetation, wildlife habitat, and aquatic habitat would be minimal during site monitoring and testing because of the limited nature of activities. The introduction and spread of invasive vegetation could occur as a result of vehicular traffic. Surveys conducted during this phase to evaluate the presence and/or significance of ecological resources in the area would assist developers in designing the project to avoid or minimize impacts on these resources.

Water Resources

There likely would have minimal impact on water resources, local water quality, water flows, and surface water/groundwater interactions. Very little water would likely be used during the site evaluation phase. Any water required could be trucked in from offsite.

Land Use

Monitoring and testing activities would likely result in temporary and localized impacts on land use. These activities could create a temporary disturbance to wildlife and cattle in the immediate vicinity of the monitoring/testing site while workers are present; however, monitoring equipment is unlikely to change land-use patterns over a longer period of time. Although a buffer area may be established around equipment to protect the public, wildlife, and the equipment, access to the area for continued recreational use would not be affected. There could be visual impacts, though, from the presence of equipment and access roads, potentially impacting the recreational experience. Monitoring and testing activities are unlikely to affect mining activities, military operations, or aviation.

Soils and Geologic Resources

Surface disturbance and use of geologic materials are minimal during the site evaluation phase, and soils and geologic resources are unlikely to be affected. These activities would also be unlikely to activate geological hazards or increase soil erosion. Borings for soil testing and geotechnical surveys provide useful site-specific data on these resources. Surface effects from pedestrian and vehicular traffic could occur in areas that contain special (e.g., cryptobiotic) soils.

Paleontological Resources

Surface disturbance is minimal during the site evaluation phase, and paleontological resources buried below the surface are unlikely to be affected. Fossil material present on the surface could be disturbed by vehicular traffic, ground clearing, and pedestrian activity (including collection of fossils). Surveys conducted during this phase to evaluate the presence and/or significance of paleontological resources in the area would assist developers in designing the project to avoid or minimize impacts on these resources.

Transportation

No impacts on transportation are anticipated during the site evaluation phase. Transportation activities would be temporary, intermittent, and limited to low volumes of heavy- and medium-duty pickup trucks and personal vehicles.

Visual Resources

Monitoring and testing activities would have temporary and minor visual effects caused by the presence of equipment.

Socioeconomics

Site evaluation and exploration activities are temporary and limited and would not result in socioeconomic impacts on employment, local services, or property values.

Environmental Justice

Site evaluation and exploration activities are limited and would not result in significant high and adverse impacts in any resource area; therefore, environmental justice impacts are not expected during his phase.

Hazardous Materials and Waste Management

Impacts from use, storage, and disposal of hazardous materials and waste would be minimal to nonexistent if appropriate management practices are followed.

Acoustics (Noise)

Activities associated with site monitoring and testing would generate low levels of temporary and intermittent noise; however, it is important to point out that wind turbine noise due to construction, operation, and maintenance activities is a major environmental issue and complaint. Because noise associated with wind turbines is a major environmental impact issue, an in-depth discussion about noise is provided below. Keep in mind that the noise generated and discussed here refers to that generated during all phases of wind turbine operation.

Noise is commonly defined as any unwanted sound. Based on the author's observation of the operation of wind farms in Washington, Oregon, California, Indiana, West Virginia, North Dakota, South Dakota, New Mexico, and Wyoming, turbine-generated noise can be characterized as ranging from the swooshing sound of rotating rotor blades to a deep, bass-like hum produced by a single operating wind turbine. Using a calibrated sound pressure level (SPL) decibel (dB) measuring device, the author determined that the wind turbine-generated noise monitored and measured varied depending on the size of the turbines, their location, and distance away from the turbine or wind farm. To better comprehend the material presented in this section, it is important to have a fundamental knowledge of noise, sound, and the properties involved. Thus, in the following section a basic introduction of noise and sound properties is presented.

Noise Basics

High noise levels are a hazard to anyone within hearing distance. High noise levels are a physical stress that may produce psychological effects by annoying, startling, or disrupting concentration, which can lead to accidents. High levels can also result in damage to hearing, resulting in hearing loss. When wind farms are taken into consideration, the noise produced has the potential to escalate into a severe nuisance for small, local populations. This impact alone can have detrimental effects on a wide range of related aspects including health and property values.

Noise and Hearing Loss Terminology

Many specialized terms are used to express concepts in noise, noise control, and hearing loss prevention. The individual or group concerned with wind turbine noise pollution and its potential impacts should be familiar with these terms. The National Institute for Occupational Safety and Health (NIOSH, 2005) definitions below were written in as nontechnical a fashion as possible:

Acoustic trauma—A single incident that produces an abrupt hearing loss. Welding sparks (to the eardrum), blows to the head, and blast noise are examples of events capable of providing acoustic trauma.

Action level—The sound level that, when reached or exceeded, necessitates implementation of activities to reduce the risk of noise-induce hearing loss. OSHA currently uses an 8-hour, time-weighted average of 85 dBA as the criterion for implementing an effective hearing conservation program.

Aerodynamic noise—Generated noise; noise of aerodynamic origin in a moving fluid arising from flow instabilities.

Attenuate—To reduce the amplitude of sound pressure (noise).

Attenuation, real ear attenuation at threshold (REAT)—A standardized procedure for conducting psychoacoustic tests on human subjects, it is designed to measure the sound protection features of hearing protective devices. Typically, these measures are obtained in a calibrated sound field and represent the difference between subjects' hearing thresholds when wearing a hearing protector vs. not wearing the protector.

Attenuation, real-world—Estimated sound protection provided by hearing protective devices as worn in "real-world" environments.

DID YOU KNOW?

In 1983, the Occupational Safety and Health Administration (OSHA) adopted a Hearing Conservation Amendment to 29 CFR 1910.95 requiring employers to implement *hearing conservation programs* in any work setting where employees are exposed to an 8-hour, time-weighted average of 85 dB and above (LaBar, 1989). Employers must monitor all employees whose noise exposure is equivalent to or greater than a noise exposure received in 8 hours where the noise level is constantly 85 dB. The exposure measurement must include all continuous, intermittent, and impulsive noise within an 80-dB to 130-dB range and must be taken during a typical work situation. This requirement is performance oriented because it allows employers to choose the monitoring method that best suits each individual situation (OSHA, 2002).

Audible range—The frequency range over which individuals with normal hearing acuity hear (approximately 20 to 20,000 Hz).

Audiogram—A chart, graph, or table resulting from an audiometric test showing an individual's hearing threshold levels as a function of frequency.

Audiologist—A professional specializing in the study and rehabilitation of hearing and who is certified by the American Speech–Language–Hearing Association or licensed by a state board of examiners.

Background noise—Noise coming from sources other than the particular noise sources being monitored.

Baseline audiogram—A valid audiogram against which subsequent audiograms are compared to determine if hearing thresholds have changed. The baseline audiogram is preceded by a quiet period so as to obtain the best estimate of the person's hearing at that time.

Continuous noise—Noise of a constant level as measured over at least one second using the "slow" setting on a sound level meter. Note that a noise that is intermittent (e.g., on for over a second and then off for a period) would be both variable and continuous.

Controls, administrative—Efforts, usually by management, to limit workers' noise exposure by modifying workers' schedules or location or by modifying the operating schedule of noisy machinery.

Controls, engineering—Any use of engineering methods to reduce or control the sound level of a noise source by modifying or replacing equipment, making any physical changes at the noise source or along the transmission path (with the exception of hearing protectors).

dB (decibel)—The unit used to express the intensity of sound. The decibel was named after Alexander Graham Bell. The decibel scale is a logarithmic scale in which 0 dB approximates the threshold of hearing in the mid-frequencies for young adults and in which the threshold of discomfort is between 85 and 95 dB SPL and the threshold for pain is between 120 and 140 dB SPL.

Dosimeter—When applied to noise, refers to an instrument that measures sound levels over a specified interval; stores the measures; calculates the sound as a function of sound level and sound duration; and describes the results in terms of, dose, time-weighted average, and (perhaps) other parameters such as peak level, equivalent sound level, or sound exposure level.

Double hearing protection—A combination of both ear-plug and ear-muff types of hearing protection devices is required for employees who have demonstrated temporary threshold shift during audiometric examination and for those who have been advised to wear double protection by a medical doctor in work areas that exceed 104 dBA.

Equal-energy rule—The relationship between sound level and sound duration based on a 3-dB exchange rate; that is, the sound energy resulting from doubling or halving a noise exposure's duration is equivalent to increasing or decreasing the sound level by 3 dB, respectively.

Exchange rate—The relationship between intensity and dose. OSHA uses a 5-dB exchange rate; thus, if the intensity of an exposure increases by 5 dB, the dose doubles. This is also referred to as the *doubling rate*. The U.S. Navy uses a 4-dB exchange rate; the U.S. Army and Air Force use a 3-dB exchange rate; and NIOSH recommends a 3-dB exchange rate. Note that the equal-energy rule is based on a 3-dB exchange rate.

Frequency—Rate at which pressure oscillations are produced; measured in hertz (Hz).

Hazardous noise—Any sound for which any combination of frequency, intensity, or duration is capable of causing permanent hearing loss in a specified population.

Hearing handicap—A specified amount of permanent hearing loss usually averaged across several frequencies that negatively impacts employment and/or social activities. Handicap is often related to an impaired ability to communicate. The degree of handicap will also be related to whether the hearing loss is in one or both ears, and whether the better ear has normal or impartial hearing.

Hearing loss—Often characterized by the area of the auditory system responsible for the loss; for example, when injury or a medical condition affects the outer ear or middle ear (i.e., from the pinna, ear canal, and ear drum to the cavity behind the ear drum, including the ossicles) the resulting hearing loss is referred to as a *conductive* loss. When an injury or medical condition affects the inner ear or the auditory nerve that connects the inner ear to the brain (i.e., the cochlea and the VIIIth cranial nerve) the resulting hearing loss is referred to as a *sensorineural* loss. Thus, when a welder's spark damages the ear drum that would be considered conductive hearing loss. Because noise can damage the tiny hair cells located in the cochlea, it causes a sensorineural hearing loss.

Hearing threshold level (HTL)—The hearing level, above a reference value, at which a specified sound or tone is heard by an ear in a specified fraction of the trials. Hearing threshold levels have been established so that 0 dB HTL reflects the best hearing of a group of persons.

Hertz (Hz)—The unit of measurement for audio frequencies. The frequency range for human hearing lies between 20 Hz and approximately 20,000 Hz. The sensitivity of the human ear drops off sharply below about 500 Hz and above 4000 Hz.

Impulsive noise—A term used to generally characterize impact or impulse noise, which is typified by a sound that rapidly rises to a sharp peak and then quickly fades. The sound may or may not have a "ringing" quality (such as a striking a hammer on a metal plate or a gunshot in a reverberant room). Impulsive noise may be repetitive, or it may be a single event (as with a sonic boom). *Note:* If impulses occurring in very rapid succession (such as with some jack hammers), the noise would not be described as impulsive.

Loudness—The subjective attribute of a sound by which it would be characterized along a continuum from "soft" to "loud." Although this is a subjective attribute, it depends primarily upon sound pressure level and, to a lesser extent, the frequency characteristics and duration of the sound.

Material hearing impairment—As defined by OSHA, an average hearing threshold level of 25 dB HTL at the frequencies of 1000, 2000, and 3000 Hz.

Mechanical noise—Noise generated as a result of moving parts or components such as gears, shafts, or reciprocating parts.

Medical pathology—A disorder or disease; with regard to noise, a condition or disease affecting the ear, which a physician specialist should treat.

Noise—Any unwanted sound.

Noise dose—The noise exposure expressed as a percentage of the allowable daily exposure. For OSHA, a 100% dose would equal an 8-hour exposure to a continuous 90-dBA noise. A 50% dose would equal an 8-hour exposure to an 85-dBA noise or a 4-hour exposure to a 90-dBA noise. If 85 dBA is the maximum permissible level, then an 8-hour exposure to a continuous 85-dBA noise would equal a 100% dose. If a 3-dB exchange rate is used in conjunction with an 85-dBA maximum permissible level, a 50% dose would equal a 2-hour exposure to 88 dBA or an 8-hour exposure to 82 dBA.

Noise dosimeter—An instrument that integrates a function of sound pressure over a period of time to directly indicate a noise dose.

Noise hazard area—Any area where noise levels are equal to or exceed 85 dBA. OSHA requires employers to designate work areas as a "noise hazard area," post warning signs, and warn employees when work practices exceed 90 dBA. Hearing protection must be worn whenever 90 dBA is reached or exceeded.

Noise hazard work practice—Performing or observing work where 90 dBA is equaled or exceeded. Some work practices, however, will be specified as a "rule of thumb." Whenever attempting to hold a normal conversation with someone who is 1 foot away and shouting must be employed to be heard, one can assume that a 90-dBA noise level or greater exists and hearing protection is required. Typical examples of work practices where hearing protection is required are jackhammering, heavy grinding, heavy equipment operations, and similar activities.

Noise-induced hearing loss—A sensorineural hearing loss that is attributed to noise and for which no other etiology can be determined.

Noise-level measurement—Total sound level within an area; includes workplace measurements indicating the combined sound levels of tool noise (from ventilation systems, cooling compressors, circulation pumps, etc.).

Noise reduction rating (NRR)—The NRR is a single-number rating method that attempts to describe a hearing protector based on how much the overall noise level is reduced by the hearing protector. When estimating A-weighted noise exposures, it is important to remember to first subtract 7 dB from the NRR and then subtract the remainder from the A-weighted noise level. The NRR theoretically provides an estimate of the protection that should be met or exceeded by 98% of the wearers of a given device. In practice, this does not prove to be the case, so a variety of methods for "de-rating" the NRR have been discussed.

Ototoxic—A term typically associated with the sensorineural hearing loss resulting from therapeutic administration of certain prescription drugs.

Ototraumatic—A broader term than ototoxic. As used in hearing loss prevention, refers to any agent (e.g., noise, drug, industrial chemical) that has the potential to cause permanent hearing loss subsequent to acute or prolonged exposure.

Presbycusis—The gradual increase in hearing loss that is attributable to the effects of aging and not related to medical causes or noise exposure.

Sensorineural hearing loss—Hearing loss resulting from damage to the inner ear (from any source).

Sociacusis—Hearing loss related to non-occupational noise exposure.

Sound intensity (I)—At a specific location, it is the average rate at which sound energy is transmitted through a unit area normal to the direction of sound propagation.

Sound level meter (SLM)—A device that measures sound and provides a readout of the resulting measurement. Some SLMs provide only A-weighted measurements, others provide A- and C-weighted measurements, and some can provide weighted, linear, and octave (or narrower) band measurements. Some SLMs are also capable of providing time-integrated measurements.

Sound power—The total sound energy radiated by a source per unit time. Sound power cannot be measured directly.

Sound pressure level (SPL)—A measure of the ratio of the pressure of a sound wave relative to a reference sound pressure. Sound pressure level in decibels is typically referenced to 20 mPa. When used alone (e.g., 90 dB APL), a given decibel level implies an unweighted sound pressure level.

Standard threshold shift (STS)—(1) OSHA uses the term to describe a change in hearing threshold relative to the baseline audiogram of an average of 10 dB or more at 2000, 3000, and 4000 Hz in either ear. It is used by OSHA to trigger additional audiometric testing and related follow-up. (2) NIOSH uses this term to describe a change of 15 dB or more at any frequency, 5000 through 6000 Hz, from baseline levels that is present on an immediate

retest in the same ear and at the same frequency. NIOSH recommends a confirmation audiogram within 30 days, with the confirmation audiogram being preceded by a quiet period of at least 14 hours.

Threshold shift—Audiometric monitoring programs will encounter two types of changes in hearing sensitivity (i.e., threshold shifts): permanent threshold shift (PTS) and temporary threshold shift (TTS). As the names imply, any change in hearing sensitivity that is persistent is considered a PTS. Persistence may be assumed if the change is observed on a 30-day follow-up exam. Exposure to loud noise may cause a temporary worsening in hearing sensitivity (i.e., a TTS) that may persist for 14 hours (or even longer in cases where the exposure duration exceeded 12 to 16 hours). Hearing health professionals need to recognize that not all threshold shifts represent decreased sensitivity, and not all temporary or permanent threshold shifts are due to noise exposure. When a permanent threshold shift can be attributable to noise exposure, it may be referred to as a *noise-induced permanent threshold shift* (NIPTS).

Velocity—The speed at which the regions of sound producing pressure changes move away from the sound source.

Wavelength (l)—The distance required for one complete pressure cycle to be completed (1 wavelength), measured in feet or meters.

Weighted measurements—Two weighting curves are commonly applied to measures of sound levels to account for the way the ear perceives the "loudness" of sounds.

A-weighting—A measurement scale that approximates the "loudness" of tones relative to a 40-db SPL, 1000-Hz reference tone. A-weighting has the added advantage of being correlated with annoyance measures and is most responsive to the mid-frequencies, 500 to 4000 Hz.

C-weighting—A measurement scale that approximates the "loudness" of tones relative to a 90-dB SPL, 1000-Hz reference tone. C-weighting has the added advantage of providing a relatively flat measurement scale that includes very low frequencies.

Noise Exposure

Noise literally surrounds us every day and is with us just about everywhere we go; however, the noise we are concerned with here is that produced by wind turbines. Excessive amounts of noise in the wind farm environment (and outside of it) cause many problems for people, including increased stress levels, interference with communication, disrupted concentration, and, most importantly, varying degrees of hearing loss. Exposure to high noise levels also adversely affects quality of life and increases accident rates.

DID YOU KNOW?

Windmills have been in use since 200 BCE and were first developed in Persia and China. Ancient mariners sailed to distant lands by making use of winds. Farmers used wind power to pump water and for grinding grains.

One of the major problems with attempting to protect an inhabitant's hearing acuity is the tendency of many people to ignore the dangers of noise. Because hearing loss, like cancer, is insidious (you do not always know that you have cancer and you do not always know that you have lost hearing), it's easy to ignore. It sort of sneaks up on you slowly and is not apparent (in many cases) until after the damage is done. Alarmingly, hearing loss from noise exposure has been well documented since the 18th century; yet, since the advent of the industrial revolution, the number of exposed people has greatly increased.

Determining Noise Levels

The unit of measurement for sound is the decibel. Decibels are the preferred unit for measuring sound; the name is derived from the word *bel*, a unit of measure in electrical communications engineering. The decibel is a dimensionless unit used to express the logarithm of the ratio of a measured quantity to a reference quantity. Determination of noise exposure is accomplished by conducting a noise-level survey of the site or area of concern. Sound measuring instruments are used to make this determination. These include noise dosimeters, sound level meters, and octave-band analyzers. The uses and limitations of each kind of instrument are discussed below.

Noise Dosimeter

The noise dosimeters used by OSHA meet the American National Standards Institute (ANSI) Standard S1.25-1978 (Specifications for Personal Noise Dosimeter), which sets performance and accuracy tolerances. For OSHA use, the dosimeter must have a 5-dB exchange rate, use a 90-dBA criterion level, be set at slow response, and use either an 80-dBA or a 90-dBA threshold gate, or a dosimeter can be used that has both capabilities, whichever is appropriate for evaluation.

Sound Level Meter

When conducting a noise-level survey, the operator should use an ANSI-approved sound level meter (SLM)—a device used most commonly to measure sound pressure. The SLM measures in decibels. One decibel is 1/10 of a bel and is the minimum difference in loudness that is usually perceptible. The sound level meter consists of a microphone, an amplifier, and an indicating meter, which responds to noise in the audible frequency range of about 20 to 20,000 Hz. Sound level meters usually contain weighting networks designated A, B, or C. Some meters have only one weighting network; others are equipped with all three. The A network approximates the equal loudness curves at low sound pressure levels, the B network is used for medium sound pressure levels, and the C network is used for high levels.

When conducting a routine sound level survey, using the A-weighted network (dBA) in the assessment of the overall noise hazard has become common practice. The A-weighted network is the preferred choice because it is thought to provide a rating of industrial noises that indicates the injurious effects such noise has on the human ear (i.e., gives a frequency response similar to that of the human ear at relatively low sound pressure levels). With an approved and freshly calibrated (always calibrate test equipment prior to use) sound level meter in hand, the user is ready to

begin the sound level survey. In doing so, the user is primarily interested in answering the following questions:

1. What is the noise level in each wind turbine and/or wind farm area?
2. What equipment or process is generating the highest/lowest level of noise?
3. Which local residents are exposed to the noise?
4. How long are nearby residents exposed to the noise?

When addressing these questions, the monitors record their findings as they move from location to location, following a logical step-by-step procedure. The first step involves using the sound level meter set in A-scale slow response mode to measure a wind farm grid area. When making such measurements, restrict the size of the area (grid) being measured to less than 1000 square feet. If the maximum sound level does not exceed 80 dBA, it can be assumed that all residents or visitors in this grid are in a relatively safe or satisfactory noise level.

The next step depends on the readings recorded when the entire work area was measured. For example, if the measurements indicate sound levels greater than 80 dBA, then another set of measurements must be taken in each grid. The purpose here, of course, is to determine two things: which wind turbine or group of turbines is making noise above acceptable levels (i.e., >80 dBA) and which residents and visitors are exposed to these levels.

If grid measurements indicate readings that exceed the 85-dBA level, another step must be performed. This step involves determining the length of time of exposure for residents and/or visitors (do not forget wind turbine service personnel). The easiest, most practical way to make this determination is to have these persons wear a noise dosimeter, which records the noise energy to which the person was exposed during an 8-hour period (or longer).

What happens next? It is necessary to determine if anyone is or can be exposed to noise levels that exceed the permissible noise exposure levels listed in Table 2.2. The key point to remember is that the findings must be based on a time-weighted average (TWA); for example, in Table 2.2, notice that a noise level of 95 dBA is allowed up to 4 hours per day. Note that this parameter assumes that the exposed person has good hearing acuity with no loss. If the exposed person has documented hearing loss, exposure to 95 dBA or higher, without proper hearing protection, may be unacceptable under any circumstances.

Octave-Band Noise Analyzers

Several Type 1 sound level meters have built-in octave-band analysis capability. These devices can be used to determine the feasibility of controls for individual noise sources for abatement purposes and to evaluate hearing protectors. Octave-band analyzers segment noise into its component parts. The octave-band filter sets provide filters with the following center frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16,000 Hz. The special signature of a given noise can be obtained by taking sound level meter readings at each of these settings (assuming that the noise is fairly constant over time). The results may indicate those octave bands that contain the majority of the total radiated sound power. Octave-band noise

TABLE 2.2
Permissible Noise Exposures per 29 CFR 1910.95

Duration per Day (hours)	Sound Level dBA Slow Response
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110
0.25 or less	115

Note: When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions $C_1/T_1 + C_2/T_2 + C_n/T_n$ exceeds unity, then the mixed exposure should be considered to exceed the limit value. C_n indicates the total time of exposure at a specified noise level, and T_n indicates the total time of exposure permitted at that level. Exposure to impulsive or impact noise should not exceed the 140-dB peak sound pressure level.

analyzers can assist users in determining the adequacy of various types of frequency-dependent noise controls. They also can be used to select hearing protectors because they can measure the amount of attenuation offered by the protectors in the octave bands responsible for most of the sound energy in a given situation.

Noise Units, Relationships, and Equations

A number of noise units, relationships, and equations that are involved with controlling noise hazards are discussed below.

Sound Power

Sound power of a source is the total sound energy radiated by the source per unit time. It is expressed in terms of the sound power level (L_w) in decibels referenced to 10^{-12} watts (w_0). The relationship to decibels is shown below:

$$L_w = 10 \log_{10} w/w_0 \tag{2.2}$$

where

L_w = Sound power level (decibels).
$\log_{10}$ = Logarithm to the base 10.
w = Sound power (watts).
w_0 = Reference power (10^{-12} watts).

DID YOU KNOW?

- Adding together two identical noise sources will increase the total sound-power level by 3 dB ($10 \log_2$).
- *Sound power* and *sound-power level* are often used to specify the noise of sound emitted from technical equipment such as fans, pumps, or other machines.
- Sound measured with sensors or microphones is *sound pressure*.
- SPL = sound production level.
- Decibel (dB) = unit of sound production level (logarithmic scale).
- dBA = A-weighted scale decibel (levels weighted according to sound frequency).
- L_{eq} = equivalent continuous sound level.
- SEL = sound equivalent level integrated per 1 second.
- Hertz (Hz) = cycles per second (measure of sound frequency).
- 1 kilohertz (kHz) = 1000 hertz.
- ROW = right of way (pertaining to highway noise)

Sound Pressure

Units used to describe sound pressures are

$$1 \text{ μbar} = 1 \text{ dyne/cm}^2 = 0.1 \text{ N/cm}^2 = 0.1 \text{ Pa} \tag{2.3}$$

Sound Pressure Level

$$\text{SPL (decibels)} = 10 \log(p^2/p_0) \tag{2.4}$$

where

p = Measured rms sound pressure (N/m^2, μbars).*
p_0 = Reference rms sound pressure (20 μPa, N/m^2, μbars).

Speed of Sound

$$c = f_1 \tag{2.5}$$

Wavelength

$$\lambda = c/f \tag{2.6}$$

Octave Band Frequencies

$$\text{Upper frequency band} = f_2 = 2f_1 \tag{2.7}$$

where

f_2 = Upper frequency band.
f_1 = Lower frequency band.

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* The root-mean-square (rms) value of a changing quantity, such as sound pressure, is the square root of the mean of the squares of the instantaneous values of the quantity.

$$\text{One-half octave band} = f_2 = \sqrt{2(f_1)} \tag{2.8}$$

where
f_2 = 1/2 octave band
f_1 = Lower frequency band

$$\text{One-third octave band} = f_2 = \sqrt[3]{2(f_1)} \tag{2.9}$$

where
f_2 = 1/3 octave band
f_1 = lower frequency band

Adding Noise Sources

When sound power is known:

$$L_w = 10\log \frac{w_1 + w_2}{w_0 + w_0} \tag{2.10}$$

where
L_w = Sound power (watts).
w_1 = Sound power of noise source 1 (watts).
w_2 = Sound power of noise source 2 (watts).
w_0 = Reference sound power (reference 10^{-12}) (watts).

Sound Pressure Additions

When sound pressure is known:

$$SPL \text{ (decibels)} = 10\log \frac{p^2}{p_0^2} \tag{2.11}$$

where
$p^2/p_0^2 = 10^{SPL/10}$.
p = Measured root-mean-square (rms) sound pressure (N/m², μbars).
p_0 = Reference rms sound pressure (20 μPa, N/m², μbars).

For three sources, the equation becomes

$$SPL = 10 \ \log \ \left(10^{SPL_1/10}\right) + \left(10^{SPL_2/10}\right) + \left(10^{SPL_3/10}\right) \tag{2.12}$$

When adding any number of sources, whether or not the sources are identical, the equation becomes

$$SPL = 10 \ \log \ \left(10^{SPL_1/10}\right) + \cdots + \left(10^{SPL_n/10}\right) \tag{2.13}$$

To determine the sound pressure level from multiple identical sources, use the following equation:

$$SPL_f = SPL_i + 10\log(n) \tag{2.14}$$

where
SPL_f = Total sound pressure level (dB).
SPL_i = Individual sound pressure level (dB).
n = Number of identical sources.

Noise Levels in a Free Field

$$SPL = L_w - 20\log(r) - 0.5 \tag{2.15}$$

where
SPL = Sound pressure (reference 0.00002 N/m^2).
L_w = Sound power (reference 10^{-12} watts).
r = Distance (feet).

Noise Levels with Directional Characteristics

$$SPL = L_w - 20\log(r) - 0.5 + \log(Q) \tag{2.16}$$

where
SPL = Sound pressure (reference 0.00002 N/m^2).
L_w = Sound power (reference 10^{-12} watts).
r = Distance (feet).
Q = Directivity factor.
= 2 for one reflecting plane.
= 4 for two reflecting planes.
= 8 for three reflecting planes.

Noise Level at a New Distance from the Noise Source

$$SPL = SPL_1 + 20\log\frac{d_1}{d_2} \tag{2.17}$$

where
SPL = Sound pressure level at new distance (d_2).
SPL_1 = Sound pressure level at d_1.
d_n = Distance from source.

Daily Noise Dose

The following formula combines the effects of different sound pressure levels and allowable exposure times:

$$\text{Daily noise dose} = \frac{C_1 + C_2 + C_3 + \cdots + C_n}{T_1 + T_2 + T_3 + \cdots T_n} \tag{2.18}$$

where
C_i = Number of hours exposed at given SPL_i.
T_i = Number of hours exposed at given SPL_i.

OSHA Permissible Noise Levels

$$T_{SPL} = 8/2^{(SPL-90)/5} \tag{2.19}$$

where
T_{SPL} = Time at given SPL (hours).
SPL = Sound pressure level (dBA).

Equivalent Eight-Hour TWA

$$TWA_{eq} = 16.61\log\left(\frac{D}{100}\right) + 90 \tag{2.20}$$

where
TWA_{eq} = Eight-hour equivalent TWA (dBA).
D = Noise dosimeter reading (%).

WIND ENERGY CONSTRUCTION IMPACTS

Typical activities during the wind energy facility construction phase include ground clearing (removal of vegetative cover), grading, excavation, blasting, trenching, vehicular and pedestrian traffic, and drilling. Activities conducted in locations other than the facility site include excavation/blasting for construction materials such as sands and gravels, as well as access road construction.

Air Quality

Emissions resulting from construction activities include vehicle emissions, diesel emissions from large construction equipment and generators; volatile organic compound (VOC) releases from storage and transfer of vehicle or equipment fuels; small amounts of carbon monoxide, nitrogen oxides, and particulates from blasting activities; and fugitive dust. Fugitive dust would be caused by

- Disturbing and moving soils (clearing, grading, excavation, trenching, backfilling, dumping, and truck and equipment traffic)
- Mixing concrete and associated storage piles
- Drilling and pile driving

DID YOU KNOW?

Wind energy is underutilized as of now and holds tremendous potential for the future. Although there has been a 25% increase in wind turbine use in the last 12 years, wind energy still provides only a small percentage of the energy of the world.

A construction permit is needed from the state or local air agency to control or mitigate these emissions; therefore, these emissions would not likely cause an exceedance of air quality standards or have an impact on climate change.

Cultural Resources

Direct impacts on cultural resources could occur from construction activities, and indirect impacts might be caused by soil erosion and increased accessibility to possible site locations. Potential impacts include the following:

- Complete destruction of the resource could occur if present in areas undergoing surface disturbance or excavation.
- Degradation or destruction of near-surface cultural resources on- and off-site could result from topographic or hydrological pattern changes or from soil movement (removal, erosion, sedimentation). (Note that the accumulation of sediment could protect some localities by increasing the amount of protective cover.)
- Unauthorized removal of artifacts or vandalism at the site could occur as a result of increase in human access to previously inaccessible areas, if significant cultural resources are present.
- Visual impacts could result from vegetation clearing, increases in dust, and the presence of large-scale equipment, machinery, and vehicles (if the resources have an associated landscape component that contributes to their significance, such as a sacred landscape or historic trail).

Ecological Resources

Ecological resources that could be affected include vegetation, fish, and wildlife, as well as their habitats. Adverse ecological effects during construction could be caused by the following:

- Erosion and runoff
- Fugitive dust
- Noise
- Introduction and spread of invasive vegetation
- Modification, fragmentation, and reduction of habitat
- Mortality of biota (i.e., death of plants and animals)
- Exposure to contaminants
- Interference with behavioral activities

Site clearing and grading, along with construction of access roads, towers, and support facilities, could reduce, fragment, or dramatically alter existing habitat in the disturbed portions of the project area. Ecological resources would be most affected during construction by the disturbance of habitat in areas near turbines, support facilities, and access roads. Wildlife in surrounding habitats might also be affected if the construction activity (and associated noise) disturbs normal behaviors, such as feeding and reproduction.

Water Resources

Water Use

Water would be used for dust control when clearing vegetation and grading and for road traffic; for making concrete for foundations of towers, substations, and other buildings; and for consumptive use by the construction crew. Water could be trucked in from offsite or obtained from local groundwater wells or nearby surface water bodies, depending on availability.

Water Quality

Water quality could be affected by

- Activities that cause soil erosion
- Weathering of newly exposed soils that could cause leaching and oxidation, thereby releasing chemicals into the water
- Discharge of waste or sanitary water
- Pesticide applications.

Flow Alteration

Surface and groundwater flow systems could be affected by withdrawals made for water use, wastewater and stormwater discharges, and the diversions of surface water flow for access road construction of stormwater control systems. Excavation activities and the extraction of geological materials could affect surface and groundwater flow. The interaction between surface water and groundwater could also be affected if the surface water and groundwater were hydrologically connected, potentially resulting in unwanted dewatering or recharging of water resources.

Land Use

Impacts on land use could occur during construction if there are conflicts with existing land use plans and community goals; conflicts with existing recreational, educational, religious, scientific, or other use areas: or conversion of the existing commercial and use for the area (e.g., mineral extraction). During construction, impacts on most land uses would be temporary, such as removal of livestock from grazing areas during blasting or heavy equipment operations, or temporary effects on the character of a recreation area due to construction noise, dust, and visual intrusions. Long-term land use impacts would occur if existing land uses are not compatible with wind energy development, such as remote recreational experiences; however, those uses could potentially be resumed if the land is reclaimed to predevelopment conditions.

When wind farm construction spreads, local opposition to the mass towers (some over 400 feet tall) impacts landowners' opinions, land values, and state regulations; however, this local opposition is relative in the sense that opinions are based on the receipt of or nonreceipt of monetary rewards for use of the land. That is, opposition is based on whether the wind farms constructed on personal

property accrue a monetary reward or usage fee for property owners for allowing the presence of turbines on their land. This view is typically different for residents who do not reap an economical benefit from the presence of wind turbines in their backyards.

Impacts on aviation could be possible if the project is located within 20,000 feet (6100 meters) or less of an existing public or military airport, or if the proposed construction involves objects that are greater than 200 feet (61 meters) in height. The Federal Aviation Administration (FAA) must be notified if either of these two conditions occurs, and the FAA would be responsible for determining if the project would adversely affect commercial, military, or personal air navigation safety. Similarly, impacts on military operations could occur if a project was located near a military facility if that facility conducts low-altitude military testing and training activities.

Soils and Geologic Resources

Sands, gravels, and quarry stone would be excavated for construction access roads; for concrete for buildings, substations, transformer pads, foundations, and other ancillary structures; and for improving ground surfaces for laydown areas and crane staging areas. Possible geological hazards such as landslides could be activated by excavation and blasting for raw materials, increasing slopes during site grading and construction of access roads, altering natural drainage patterns, and toe-cutting bases of slopes. Altering drainage patterns could also accelerate erosion and create slope instability. Surface disturbance, heavy equipment traffic, and changes to surface runoff patterns could cause soil erosion and impacts on special soils (e.g., cryptobiotic soils). Impacts of soil erosion could include soil nutrient loss and reduced water quality in nearby surface water bodies.

Paleontological Resources

Impacts on paleontological resources could occur directly from the construction activities or indirectly from soil erosion and increase accessibility to fossil locations. Potential impacts include the following:

- Complete destruction of the resource could occur if present in areas undergoing surface disturbance or excavation.
- Degradation or destruction of near-surface fossil resources on- and offsite could result from changes in topography, changes in hydrological patterns, and soil movement (removal, erosion, sedimentation). (Note that the accumulation of sediment could serve to protect some locations by increasing the amount of protective cover.)
- Unauthorized removal of fossil resources or vandalism to the site could occur as a result of increased human access to previously inaccessible areas if significant paleontological resources are present.

Transportation

Short-term increases in the use of local roadways would occur during the construction period. Heavy equipment likely would remain at the site. Shipments of materials are unlikely to affect primary or secondary road networks significantly, but this would depend on the location of the project site relative to material source. Oversized loads could cause temporary transportation disruptions and could require some modifications to roads or bridges (such as fortifying bridges to accommodate the size or weight). Shipment weight might also affect the design of access roads for grade determinations and turning clearance requirements.

Visual Resources

Although many of us consider wind turbines to be visually acceptable and in some cases even pleasing to look at, wind turbines disturb the visual area of other people by creating negative changes in the natural environment. The test of whether a wind turbine or wind farm is a visual pollutant is to ask this question: How many of us would seriously like one or more wind turbines a few hundred feet or meters from our homes? It is important to remember that wind turbines can be anywhere from a few meters to a hundred meters high. Having a wind turbine tower over one's home is the last thing many residents want. Having said this, the possible sources of visual impacts during construction include the following:

- Road development (e.g., new roads or expansion of existing roads) and parking areas could introduce strong visual contrasts in the landscape, depending on the route relative to surface contours and the width, length, and surface treatment of the roads.
- Conspicuous and frequent small-vehicle traffic for worker access and frequent large-equipment (e.g., trucks, graders, excavators, cranes) traffic for road construction, site preparation, and turbine installation could produce visible activity and dust in dry soils. Suspension and visibility of dust would be influenced by vehicle speeds and road surface materials.
- Site development could be intermittent, staged, or phased, giving the appearance that work starts and stops. Depending on the length of time required for development, the project site could appear to be under construction for an extended period. This could give rise to perceptions of lost benefit and productivity, like those alleged for the equipment. Timing and duration concerns may result.
- There would be a temporary presence of large cranes or other large machines to assemble towers, nacelles, and rotors. This equipment would also produce emissions while operational and could create visible exhaust plumes. Support facilities and fencing associated with the construction work would also be visible.
- Ground disturbance and vegetation removal could result in visual impacts that produce contrasts of color, form, texture, and line. Excavation for turbine foundations and ancillary structures, trenching to bury electrical

distribution systems, grading and surfacing roads, cleaning and leveling staging areas, and stockpiling soil and spoils (if not removed) would (1) damage or remove vegetation, (2) expose bare soil, and (3) suspend dust. Soil scars and exposed slope faces would result from excavation, leveling, and equipment movement. Invasive species could colonize disturbed and stockpiled soils and compacted areas.

SIDEBAR 2.1 Visual Conservation: BANANA vs. NIMBY, or Both

Renewable Energy Paradox

Ask an environmentalist if renewable energy is a good idea. It's a no-brainer, they'll say. Hell, yes. If you tell them that you will build a wind farm or a series of electrical power towers in their backyard, though, they will scream, "No way, Jose!"

Just as they are with fire or waterfall gazing, some drivers are also mesmerized whenever they drive Interstate 40 through Oklahoma and Texas or Interstate 15 through Tehachapi Pass, California, on clear days and witness a host of hundreds of whirling, swooshing, slashing wind turbines. Many of these folks do not need a road-to-Damascus change of view to accept these massive turbines. Moreover, they are not necessarily advocates for renewable energy; instead, they are simply captivated by the human-made machines as they stand tall against a backdrop of plains and deserts and hills and mountains and blue or cloud-filled nothingness.

This somewhat romantic view of wind farms is held by a few people here and there, but it is safe to say, without qualification, that many other people have a different view of whirling, swooshing wind turbines scattered helter-skelter across the U.S. landscape. Even though very few of these people dispute the environmental benefits of wind energy (or solar and other renewable energy producers), many feel that the construction of wind farms (anywhere) ruins or spoils the otherwise pristine landscape.

The possible or potential construction of wind farms (or solar or other renewable energy sources) often elicits the "not in my back yard" (NIMBY) phenomenon—even more so, in some cases, for the associated electric power transmission towers and lines. Generally, NIMBY opponents acknowledge the need for the wind turbines and transmission lines, while arguing that they just don't want them nearby to them. Most people understand the need for them, but hardly anyone wants to live within sight of them, usually because they look "ugly" or for personal safety concerns.

The opposition generated by the NIMBY phenomenon is one thing, but quite another is the opposition generated by the "build absolutely nothing anywhere near anything" (BANANA) phenomenon, which protests, unlike NIMBY, the overall necessity of any development. The opponents are often environmentalists, in which case the argument is generally we don't need new wind turbine farms and associated transmission lines and power stations. Simply, BANANA activists argue against any more of *whatever* is being planned. With regard to construction of new wind turbines and associated equipment, the BANANA argument is that instead we need to use power more wisely, not generate more.

Whether in reference to the NIMBY or the BANANA phenomenon, what we are talking about is complaints about visual pollution. Visual pollution is an aesthetic issue regarding the impacts of pollution impairing one's ability to enjoy a view or vista. Visual pollution disturbs coveted views by creating what are perceived as negative changes in the natural environment; that is, visual pollution intrudes on, ruins, spoils, and mars the natural landscape and can best be described as an eyesore. The most common negative changes or forms of visual pollution are buildings, automobiles, trash dumps, space debris, telephone and electric towers and wires, and electrical substations (see Figures SB2.1.1 and SB2.1.2).

FIGURE SB2.1.1 High-voltage power lines.

One thing is certain; you can't hide wind turbines from view. They can't be hidden nor can they be camouflaged like cell phone towers and satellite dishes (Komanoff, 2003; Pasqualetti, 2002; Righter, 2002; Saito, 2004). Because of their visibility (and for other reasons), siting and establishing wind-energy production farms and transmission infrastructure present unique challenges.

FIGURE SB2.1.2 Electrical substation.

FIGURE SB2.1.3 Power line right of way (ROW).

With regard to transmission siting, the remote location of much of the utility-scale wind power capacity requires the construction of new high-voltage transmission lines to transport electricity to population centers. Because transmission lines can cross private, public (state and federal), and tribal lands, the process of planning, permitting, and building new lines is highly visible and implicates many diverse interests—and it can be costly, time consuming, and controversial.

Another major consideration for the installation of transmission lines from remote locations (and any other location) is right of way (ROW). The right of way for a transmission corridor includes land set aside for the transmission line and associated facilities, land needed to facilitate maintenance, and land needed to avoid risk of fires and other accidents. It provides a safety margin between the high-voltage lines and surrounding structures and vegetation (see Figure SB2.1.3). Some vegetation clearing may be needed for safety or access reasons. A ROW generally consists of native vegetation or plants selected for favorable growth patterns (slow growth and low mature heights). However, in some cases, access roads constitute a portion of the ROW and provide more convenient access for repair and inspection vehicles. Vegetation clearing or recontouring of land may be required for access road construction. The width of a ROW varies depending on the voltage rating on the line, ranging from 50 feet to approximately 175 feet or more for 500-kV lines.

Before approval for new transmission is granted, the regulatory authority must determine that the project is necessary. Non-transmission alternatives must often be considered, including energy conservation, energy efficiency, distributed generation, and fully utilizing unused capacity on existing transmission lines. When new transmission lines are deemed necessary, developers and utilities must find the best routes to the greatest concentrations of renewable energy and build with the least possible impact on the environment. Transmission lines from tall transmission towers carry high-voltage energy (115 to 500 kV) over long distances to a substation. Both transmission and distribution lines (from substations) carry enough energy to harm or kill both people and birds. Kill birds? Yes, actually, contrary to popular belief, some birds are electrocuted by electrical power lines. Small birds do not usually get electrocuted because they fail to complete a circuit either by touching a grounded

wire or structure, or another energized wire, so the electricity stays in the line. Larger birds, however, such as the California condor, which has a wingspan of up to 9.5 feet, are more likely to touch a power line and ground wire, another energized wire, or a pole at the same time, giving electricity a path to the ground. In both situations, the birds are electrocuted and killed, a fuse is blown, power fails, and everyone is impacted.

Birds also fly into power lines. It is generally believed that birds collide with power lines because the lines are invisible to them or because they do not see the line before it is too late to avoid it. Birds' limited ability to judge distance makes power lines especially difficult to see, even as they are flying closer to them. Large birds are especially vulnerable because they are not always quick enough to change their direction before it is too late. Poor weather conditions, such as fog, rain or snow, as well as darkness, may make the lines even more difficult to see.

When birds collide with power lines they are either killed outright by the impact or injured by contact with electrical lines, resulting in crippling is likely fatal. Electrocutions can also start wildfires and cause power outages. An estimated 5 to 15% of all power outages can be attributed to bird collisions, with power lines (USFWS, 2005).

In addition to increasing wildlife mortality due to collisions and electrocutions, as well as by serving as perches for predators, transmission lines can fragment and interfere with wildlife habitats and corridors (WGA, 2009). Again, there are also concerns about the visual impacts of transmission lines. Moreover, many people feel that living or working near transmissions lines is hazardous to health. Burying transmission lines can help avoid many of the environmental and aesthetic issues, but burying lines may also have negative impacts on soil, vegetation, and other resources (Molburg et al., 2007), and underground lines are typically four times as expensive as overhead lines (Brown and Sedano, 2004). Also, although high-voltage direct-current (DC) lines can be buried, there is a limit on the maximum voltage and length of alternating-current (AC) lines that can be buried.

In all, constructing major new transmission infrastructure can require 7 to 10 years from planning to operation: 1 year for final engineering, 1 to 2 years for construction, and the rest of the time for planning and permitting. Substantial time and controversy are added to the process when environmental and related concerns are addressed at the end instead of at the beginning. The specific environmental impact concerns are addressed in the following sections.

Socioeconomics

Direct impacts would include the creation of new jobs for workers (approximately two workers per megawatt) at wind energy development projects and the associated income and taxes paid. Indirect impacts would occur as a result of the new economic development and would include new jobs at businesses that support the expanded workforce or provide project materials and the associated income taxes. Wind energy development activities could also potentially affect property value, either positively from increased employment effects or the image of clean energy or negatively from proximity to the wind farm and any associated or perceived environmental effect (noise, visual, etc.). Adverse impacts could occur if a large migrant workforce, culturally different from the local indigenous group, is brought in during construction. This influx of migrant workers could strain the existing community infrastructure and social services.

Environmental Justice

If significant impacts occurred in any resource areas, and the impact disproportionately affected minority or low-income populations, then there could be environmental justice concerns. Potential issues during construction are noise, dust, and visual impacts from the construction site and possible impacts associated with the construction of new access roads.

Hazardous Materials and Waste Management

Solid and industrial waste would be generated during construction activities. The solid waste would likely be nonhazardous and consist mostly of containers, packing material, and wastes from equipment assembly and construction crews. Industrial wastes would include minor amounts of paints, coatings, and spent solvents. Hazardous materials stored onsite for vehicle and equipment maintenance would include petroleum fluids (lubricating oils, hydraulic fluid, fuels), coolants, and battery electrolytes. Oils, transmission fluids, and dielectric fluids would be brought to the site to fill turbine components and other large electrical devices. Also, compressed gases would be used for welding, cutting, brazing, etc. These materials would be transported offsite for disposal, but impacts could result if the wastes are not properly handled and are released to the environment.

WIND ENERGY OPERATIONS IMPACTS

Typical activities during the wind energy facility operations phase include turbine operation, power generation, and associated maintenance activities that would require vehicular access and heavy equipment operation when large components are being replaced. Potential impacts from these activities are presented below, by the type of affected resource.

Air Quality

There are no direct air emissions from operating a wind turbine. Minor volatile organic compound (VOC) emissions are possible during routine maintenance activities of applying lubricants, cooling fluids, and greases. Minor amounts of carbon monoxide and nitrogen oxides would be produced during periodic operation of diesel emergency generators as part of preventative maintenance. Vehicular traffic would continue to produce small amounts of fugitive dust and tailpipe emissions during the operations phase. These emissions would not likely exceed air quality standards or have any impact on climate change.

Cultural Resources

Impacts during the operations phase would be limited to the unauthorized collection of artifacts and visual impacts. The threat of unauthorized collection would be present once access roads are constructed during the site evaluation or construction

phase, making remote lands accessible to the public. Visual impacts resulting from the presence of large wind turbines and associated facilities and transmission lines could affect some cultural resources, such as sacred landscapes or historic trails.

Ecological Resources

During operation, adverse ecological effects could occur from (1) disturbance of wildlife by turbine noise and human activity, (2) site maintenance (e.g., mowing), (3) exposure of biota to contaminants, and (4) mortality of birds and bats that collide with the turbines and meteorological towers. During the operation of a wind facility, plant and animal habitats could still be affected by habitat fragmentation due to the presence of turbines, support facilities, and access roads. In addition, the presence of an energy development project and its associated access roads may increase human use of surrounding areas, which could in turn impact ecological resources in the surrounding areas through

1. Introduction and spread of invasive vegetation
2. Fragmentation of habitat
3. Disturbance of biota
4. Increased potential for fire

As discussed in detail later, the presence of a wind energy project (and its associated infrastructure) could also interfere with migratory and other behaviors of some wildlife.

Water Resources

Impacts on water use and quality and flow systems during the operation phase would be limited to possible degradation of water quality resulting from vehicular traffic and pesticide application, if conducted improperly.

Land Use

Impacts on land use would be minimal, as many activities can continue to occur among the operating turbines, such as agriculture and grazing. It might be possible to collocate other forms of energy development, provided the necessary facilities could be installed without interfering with operation and maintenance of the wind farm. Collocation of other forms of energy development could include directionally drill oil and gas wells, underground mining, and geothermal or solar energy development. Recreation activities (e.g., off-highway vehicle use, hunting) are also possible, but activities centered on solitude and scenic beauty could be affected. Military operations and aviation could be affected by radar interference associated with the operating turbines, and low-altitude activities could be affected by the presence of turbines over 200 feet high.

Soils and Geologic Resources

Following construction, disturbed portions of the site would be revegetated and the soil and geologic conditions would stabilize. Impacts during the operations phase would be limited largely to soil erosion impacts cause by vehicular traffic for operators maintenance.

Paleontological Resources

Impacts during the operations phase would be limited to the unauthorized collection of fossils. This threat is present once the access roads are constituted in the site evaluation or construction phases, making remote land accessible to the public.

Transportation

No noticeable impacts on transportation are likely during operations. Low volumes of heavy- and medium-duty pickup trucks and personal vehicles are expected for routine maintenance and monitoring. Infrequent but routine shipments of component replacements during maintenance procedures are likely over the period of operation.

Visual Resources

Wind energy development projects would be highly visible in rural or natural landscapes, many of which have few other comparable structures. The artificial appearance of wind turbines may have visually incongruous industrial-type associations for some, particularly in a predominantly natural landscape; however, other viewers may find wind turbines visually pleasing and consider them a positive visual impact. Visual evidence of wind turbines cannot easily be avoided, reduced, or concealed, due to their size and exposed location; therefore, effective mitigation is often limited.

Additional issues of concern are shadow flicker (strobe-like effects from flickering shadows cast by the moving rotors), blade glint from the sun reflecting off moving blades, visual contrasts from support facilities, and light pollution from the lighting on facilities and towers (which are required safety features). Additional visual impacts from vehicular traffic would occur during maintenance and as towers, nacelles, and rotors are upgraded or replaced. When replacing turbines and other facility components, the opportunity and pressures to break uniformity of spacing between turbines and uniformity of size, shape, and color among facility components could increase visual contrast and visual clutter.

Infrequent outages, disassembly, and repair of equipment may occur, producing the appearance of idle or missing rotors, "headless" towers (when nacelles are removed), and lowered towers, as well as negative visual perceptions of lost benefits (e.g., loss of wind power) and "bone yards" (storage areas).

Socioeconomics

Direct impacts would include the creation of approximately one new job for every three megawatts of installed capacity for operations and maintenance workers at wind energy development projects, as well as the associated income and taxes paid. Indirect impacts would occur from new economic development, including new jobs at businesses that support the expanded workforce or that provide project materials and the associated income and taxes. Wind energy development activities could also potentially affect property values, either positively from increased employment effects or the image of clean energy or negatively from proximity to the wind farm and any associated or perceived environment effects (e.g., noise, visual).

Environmental Justice

Possible environmental justice impacts during operation include the alteration of scenic quality in areas of traditional or cultural significance to minority or low-income populations. Noise impacts and health and safety impacts are also possible sources of disproportionate effects.

Hazardous Materials and Waste Management

Industrial and sanitary wastes are generated during routine operations (e.g., lubricating oils, hydraulic fluids, coolants, solvents, cleaning agent, sanitary wastewaters). These wastes are typically put in containers, characterized and labeled, possibly stored briefly, and transported by a licensed hauler to an appropriate permitted off-site disposal facility as a standard practice. Impacts could result if these wastes were not properly handled and were released to the environment. Releases could also occur if individual turbine components or electrical equipment were to fail.

WIND ENERGY IMPACTS ON WILDLIFE

> He clasps the crag with crooked hands;
> Close to the sun in lonely lands,
> Ringed with the azure world, he stands.
> The wrinkled sea beneath him crawls;
> He watches from his mountain walls,
> And like a thunderbolt he falls.
>
> **—Alfred Lord Tennyson, *The Eagle***

Alfred Lord Tennyson, in his classic poem above, wants us to see the eagle as both a swift predator and a powerful bird who is nonetheless susceptible to defeat by other forces (most likely by humans). Human-made and installed wind turbines are responsible for bird deaths. This has been a less documented impact of wind turbines and has mainly been argued by wildlife groups. Noise standards, for example, for wind turbines developed by countries such as Sweden and New Zealand and some specific site-level standards implemented in the United States focus primarily on sleep disturbance and annoyance to humans (USFWS, 2014). Noise standards do not

generally exist for wildlife, except in a few instances where federally listed species may be impacted. Findings from recent research clearly indicate the need to better address noise–wildlife issues. As such, noise impacts on wildlife should clearly be included as a factor in wind turbine siting, construction, and operation.

A detailed description of eagle conservation guidance with regard to land-based wind energy is presented later. For now it is important to point out some of the key issues, which include (1) how wind facilities affect background noise levels; (2) how and what fragmentation, including acoustical fragmentation, occurs, especially to species sensitive to habitat fragmentation; (3) comparison of turbine noise levels at lower valley sites—where it may be quieter—to turbines placed on ridge lines above rolling terrain where significant topographic sound shadowing can occur with the potential to significantly elevate sound levels above ambient conditions; and (4) correction and accounting of a 15-dB underestimate from daytime wind turbine noise readings used to estimate nighttime turbine noise levels (Barber et al., 2010; Van den Berg, 2004). The sensitivities of various groups of wildlife can be summarized as follows:

- Birds (more uniform than mammals)—100 Hz to 8–10 kHz; sensitivity at 0.10 dB
- Mammals—<10 Hz to 150 kHz; sensitivity to –20 dB
- Reptiles (poorer than birds)—50 Hz to 2 kHz; sensitivity at 40 to 50 dB
- Amphibians—100 Hz to 2 kHz; sensitivity from 10 to 60 dB

Turbine blades at normal operating speeds can generate significant levels of noise. How much noise? Based on a propagation model of an industrial-scale, 1.5-MW wind turbine at 263-foot hub height, positioned approximately 1000 feet apart from neighboring turbines, the flowing decibel levels were determined for peak sound production. At a distance 300 feet from the blades, 45 to 50 dBA were detected; at 2000 feet, 40 dBA; and at 1 mile, 30 to 35 dBA (Kaliski, 2009). Declines in the densities of woodland and grassland bird species have been shown to occur at noise thresholds between 45 and 48 dB, respectively, whereas the most sensitive woodland and grassland species showed declines between 35 and 43 dB, respectively. Songbirds specifically appear to be sensitive to very low sound levels equivalent to those in a library reading room (~30 dBA) (Foreman and Alexander, 1998). Given this knowledge, it is possible that effects to sensitive species may be occurring at ≥1 mile from the center of a wind facility at periods of peak sound production.

Noise does not have to be loud to have negative effects. Very low-frequency sounds including infrasound (sound lower in frequency than 20 Hz) are also being investigated for their possible effects on both humans and wildlife. Wind turbine noise results in a high infrasound component (Salt and Hullar, 2010). Infrasound is inaudible to the human ear, but this unheard sound can cause human annoyance, sensitivity, disturbance, and disorientation (Anon., 2010). For birds, bats, and other wildlife, the effects may be more profound. Noise from traffic, wind, and operating turbine blades produces low-frequency sounds (<1 to 2 kHz) (Dooling, 2002; Lohr et al., 2003). Bird vocalizations are generally within the frequency range of 2 to 5 kHz (Dooling and Popper, 2007), and birds hear best between 1 and 5 kHz (Dooling, 2002). Although traffic noise generally falls below the frequency of bird communication and hearing,

several studies have documented that traffic noise can have significant negative impacts on bird behavior, communication, and ultimately on avian health and survival (Barber et al, 2010; Lengagne, 2008; Lohr et al., 2003). Whether these effects are attributable to infrasound effects or to a combination of other noise factors is not yet fully understood. The fact is that little is known about the combination effect of traffic noise and wind turbine noise. However, given that wind-generated noise, including blade turbine noise, produces a fairly persistent, low-frequency sound similar to that generated by traffic noise (Dooling, 2002; Lohr et al., 2003), it is plausible that wildlife effects from these two sounds could be similar. It is also plausible that wildlife effects from these two sounds combined could be detrimental to wildlife of all kinds. Based on experience, this book supports this view.

Some may feel that the combination of road noise and wind turbine noise causing wildlife effects is plainly a stretch. Although the author has studied, observed, measured, and monitored this phenomenon, the truth is little is known about the effects of noise related to road noise and wind turbines combined; moreover, at present, little to nothing on the subject is reported in the peer-reviewed literature.

Let's get back to why some people feel the statement that a combination of road noise and wind turbine noise has a wildlife effect is plainly a stretch. This point of view seems to be prevalent for those who do not travel the east–west U.S. interstates from East Coast areas to the Southwest or Pacific Northwest, or the north–south route through Indiana on I-65 and others. On many roads it is not uncommon to drive in any direction and see hundreds of tall wind turbines off in the distance far ahead and to the right and left of the highway. Although some of these wind turbines are very close to the shoulder of the roads, many wind turbine farms can only be seen off in the vast, far distance as one travels the highways. It is this perception of distance on some outlying, remote hillside or ridge in some unoccupied wilderness or high plains area that gives the unknowing viewer the misconception about noise from road traffic and wind turbines not having a combined effect. After all, if the wind turbines are off in some remote corner of nowhere, how can road noise add to normal wind turbine noise? Very easily, actually. Remember, service roads built to perform maintenance and preventive maintenance, such as inspection of components, servicing items on a regular basis (e.g., retorquing bolts), and replacing consumable items at or before a specified age (e.g., replacing filters, changing the oil in the gearbox), are utilized by light and heavy trucks and other vehicles on a routine basis, no matter the location. The larger the wind farm, the greater the access—the more traffic, the more noise. All access vehicles, including helicopters used to transport parts and personnel, produce noise, in some cases a lot of noise.

The counter argument, of course, is that wind turbines run on their own and require little or no operations and maintenance (O&M). If this were true (and it is not), then there would be very little traffic on the associated service roads and thus little noise added to wind turbine noise. Wind turbines, though, do not operate by themselves; they are normally operated remotely from a plant operations room by a human operator, but they can also be operated within the turbine nacelle. Their operation is also monitored by a Supervisory Control and Data Acquisition (SCADA) communication system designed to alert appropriate service personnel through computer warnings and automated telephone calls.

The major causes of wind turbine downtime have been operation and maintenance (O&M) work and faults. The occurrence of O&M work and faults has been variable. Some sites have downtown of no more than 43 hours per month, while others have had as much as 127 hours (NREL, 2000). O&M downtime includes all troubleshooting, inspections, adjustments, retrofits, and repairs performed on the turbines. Faults generally require no more than a reset and most can be performed remotely. Increased downtime for O&M work and fault reasons means more traffic to and from the turbine farm.

Fast-forwarding to wildlife effects resulting from wind turbine noise alone, it is important to point out that a bird's inability to detect turbine noise at a close range may also be problematic. The threshold for hearing in birds is higher than that for humans at all frequencies, and the overlap in the discernible frequencies between species indicates that birds do not filter out other species simply by being unable to detect theme (i.e., birds can hear songs of other species). In their environment, birds must be able to discriminate their own vocalizations and those of other species apart from any background noise (Dooling, 1982). Calls are important in the isolation of species, pair bond formation, precopulatory display, territorial defense, danger, advertisement of food sources, and flock cohesion (Knight, 1974).

For the average bird, within a signal frequency range of 1 to 4 kHz, noise must be 24 to 30 dB above the ambient noise level in order for a bird to detect it. Turbine blade and wind noise frequencies generally fall below the optimal hearing frequency of birds. Additionally, by the inverse square law, the sound pressure level decreases by 6 dB with every doubling of distance. Therefore, although the sound level of the blade may be significantly above the ambient wind noise level and detectable by birds at the source, as the distance from the source increases and the blade noise level decreases toward the ambient wind noise level, a bird may lose its ability to detect the blade and risk colliding with the moving blade.

Some researchers have attempted to blame avian collisions with turbine blades on birds' inability to divide their attention between surveying the ground for prey and monitoring the horizon and above for obstacles; that is, the birds are so busy searching the ground that they do not notice the turbines. This hypothesis derives from substituting our knowledge of human vision for that of avian vision. Humans are foveate animals; that is, we search the visual world with a small area of the retina known as the fovea, which is our area of sharpest vision, like someone searching a dark room with a narrow-beam searchlight. This results from our very low ratio (approximately 1:1) of photoreceptors to ganglion cells in the macular region of the retina. Outside the macular region, the ratio of receptors to ganglion cells increases progressively to 50:1 to 100:1, and our visual acuity drops sharply. Birds and many other animals, on the other hand, have universal macularity, which means that they have a low ratio of receptors to ganglion cells (4:1 to 8:1) out to the periphery of the retina. They maintain good acuity even in peripheral vision. In addition, raptors possess the specialization of two foveal regions: one for frontal vision and one for looking at the ground. Moreover, birds have various optical methods for keeping objects at different distances simultaneously in focus on the retina. Because of these considerations, failure to divide attention seems like an unlikely hypothesis.

Motion Smear

A bird approaching a moving blade under high wind conditions may be unable to see the blade due to motion smear—reduced visibility of the blades, especially at the tips—and may not hear the blade until it is very close—if it is able at all to hear it at all (Dooling, 2002). As an object moves across the retina with increasing speed, it becomes progressively blurred; this phenomenon is known as *motion smear*, *motion blur*, or *motion transparency* and is well known in human psychophysical research. It results because the human visual system is sluggish in its response to temporal stimulation; that is, the visual system in humans summates signals over periods of about 120 ms in daylight.

The phenomenon of motion smear is apparent at the tips of wind turbine rotor blades as the observer (bird, human, or camera) approaches the turbine. Motion smear is not apparent in the central regions of the rotors. Even though the central regions and the tips are rotating at the same number of revolutions per minute (RPM), the absolute velocity of the blades is much higher at the peripheral regions. The higher velocity of the bade tip has placed it in the temporal-summation zone, where the retina is sluggish in its ability to resolve temporarily separated stimuli. In contrast, the lower velocities of the more central portions are below the transition point between blur and non-blur, so the individual blades can be seen more or less clearly. Moreover, the absolute velocity of the blade in the visual world is not critical; rather, it is the absolute velocity of the image of the blade that sweeps across the retina that is the critical variable.

For reasons that will be explained later, as the observer approaches the turbine, the retinal image of the blades increases in velocity until the retina can no longer process the information. This results in motion smear or motion transparency—the blade becomes transparent to the view. A solution to avian collisions with wind turbines must take into account the causes of motion smear and consider whether blade patterns could minimize this effect.

Theory of Motion Smear

One of the characteristics of motion smear is that it eliminates the high spatial frequencies from visual patterns, which is why they appear to go out of focus and become virtually transparent. High spatial frequencies are those Fourier components of a visual object that are found at edges and corners and in the fine details. The print on this page, for example, is made up mainly of high spatial frequencies. If they are removed by optical blur or refractive error, the text becomes transparent and, in the worst case, virtually disappears. Motion smear causing bird collisions with seemingly slow-moving turbines seems paradoxical given the acute vision that most birds, especially raptors, possess; however, as the eye approaches the rotating blades, the retinal image of the blade increases in velocity until it is moving so fast that the retina cannot keep up with it. At this point the retinal image becomes a transparent blur that the bird probably interprets as a safe area to fly through, with disastrous consequences (NREL, 2000).

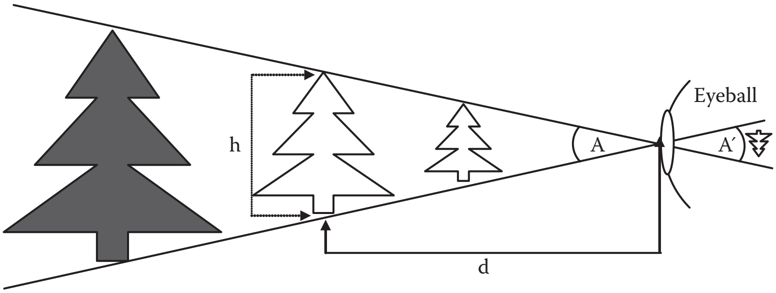

FIGURE 2.3 The law of the visual angle. Objects of different sizes and distances that subtend the same angle will cast the same size image on the retina. Angles A and A′ are the same.

Law of the Visual Angle

Figure 2.3 shows how objects of different sizes and different distances can form the same size image within the eye. The angle (A′) inside the eye is the same as the angle (A) from the eye to each of the objects. These angles, called *visual angles*, are the conventional units used to describe object size because they are directly related to retinal-image size, which is the only relevant variable for these purposes. Thus, a small object close to the eye can cast the same size retinal image as a large object seen from a much farther distance.

Another concern involves the effect of ambient noise on communication distance and an animal's ability to detect calls. For effects to birds, this can mean (1) behavioral and/or physiological effects, (2) damage to hearing from acoustic overexposure, and (3) masking of communication signals and other biologically relevant sounds (Dooling and Popper, 2007). Based on the 49 bird species whose behavioral audibility curves or physiological recordings have been determined, Dooling and Popper (2007) developed a conceptual model for estimating the masking effects of noise on birds. Based on the distance between birds and the spectrum level, bird communication was predicted to be "at risk" (~755-ft distance where noise was 20 dB), "difficult" (~755-ft distance where noise was 25 dB), and "impossible" (~755-ft distance where noise was 30 dB). Although clearly there is variation among species and there is no single noise level where one size fits all, this masking effect of turbine blades is of concern and should be considered as part of the cumulative impacts analysis of a wind facility on wildlife. It must be recognized that noise in the frequency region of avian vocalizations will be most effective in masking these vocalizations (Dooling, 2007).

Barber et al. (2010) assessed the threats of chronic noise exposure, focusing on grouse communication calls, urban bird calls, and other songbird communications. They determined that although some birds were able to shift their vocalizations to reduce the masking effects of noise, when shifts did not occur or were insignificant masking could prove detrimental to the health and survival of wildlife. Although much is still unknown in the real world about the masking effects of noise

on wildlife, the results of a physical model analyzing the impacts of transportation noise on listening area (i.e., the active space of vocalization in which animals search for sounds) of animals resulted in some significant findings. With a noise increase of just 3 dB—a noise level indentified as "just perceptible to humans"—this increase corresponded to a 50% loss of listening area for wildlife (Barber et al., 2010). Other data suggest that noise increases of 3 to 10 dB correspond to 30 to 90% reductions in alerting distances (i.e., the maximum distance at which a signal can be heard by an animal, particularly important for detecting threats) for wildlife, respectively (Barber et al., 2010). Impacts of noise could thus be putting species at risk by impairing signaling and listening capabilities necessary for successful communication and survival.

Swaddle and Page (2007) tested the effects of environmental noise on pair preference selection of zebra finches. They noted a significant decrease in females' preference for their pair-bonded males under high environmental noise conditions. Bayne et al. (2008) found that areas near noiseless energy facilities had total passerine (i.e., birds of the order Passeriformes which includes more than half of all bird species) density 1.5 times greater than areas near noise-producing energy facilities. Specifically, white-throated sparrows, yellow-rumped warblers, and red-eyed vireos were less dense in noisy areas. Habib et al. (2007) found a significant reduction in ovenbird pairing success at compressor sites (averaging 77% success) compared to noiseless well pads (92%). Quinn et al. (2006) found that noise increases perceived predation risk in chaffinches, leading to increased vigilance and reduced food intake rates, a behavior that could over time result in reduced fitness. Francis et al. (2009) showed that noise alone reduced nesting species richness and led to a different composition of avian communities. Although they found that noise disturbance ranged from positive to negative, response were predominately negative.

Schaub et al. (2008) investigated the influence of background noise on the foraging efficiency and foraging success of the greater mouse-eared bat, a model selected because it represents an especially vulnerable group of gleaning bats (predators of herbivorous insects) that rely on their capacity to listen for prey rustling sounds to locate food. Their study clearly found that traffic noise, and other sources of intense, broadband noise, deterred bats from foraging in areas where these noises were present, presumably because these sounds masked relevant sounds or echoes the bats use to locate food.

Although there are few studies specifically focused on the noise effects of wind energy facilities on birds, bats, and other wildlife, scientific evidence regarding the effects of other noise sources (e.g., transportation) is widely documented. The results show, as documented in the various examples above, that varying sources and levels of noise can affect both the sending and receiving of important acoustic signaling and sounds. This can also cause behavioral modifications in certain species of birds and bats such as decreased foraging and mating success and overall avoidance of noisy areas. The inaudible frequencies of sound may also have negative impacts on wildlife.

To this point we have focused on wildlife effects of wind turbines and wind turbine farms on birds. Little is known about the effects of noise related to wind turbines on invertebrates, fish, reptiles and amphibians, and various mammals. As

stated earlier, some correlation or association has been made between road noise and wind turbine noise in producing wildlife effects. Additional extrapolation in making the connection between road-generated and wind-turbine-generated noise is avoided here because not only is the jury still out but the fact is the jury has yet to be formed.

Given the mounting evidence regarding the negative impacts of noise (specifically, the low-frequency levels of noise such as those created by wind turbines) on birds, bats, and other wildlife, it is important to take precautionary measures to ensure that noise impacts at wind facilities are thoroughly investigated prior to development. Noise impacts on wildlife must be considered during the landscape site evaluation and constructions processes. In an attempt to meet this need, the U.S. Fish and Wildlife Service (USFWS, 2013) developed the Eagle Conservation Plan Guidance (ECPG). Few would argue against the point that, of all of America's wildlife, eagles hold perhaps the most revered place in our national history and culture. The United States has long established special protections for its bald and golden eagle populations. Now, as the nation seeks to increase its production of domestic energy, wind energy developers and wildlife agencies have recognized a need for specific guidance to help make wind energy facilities compatible with eagle conservation and the laws and regulations that protect eagles. The ECPG provides specific in-depth guidance for conserving bald and golden eagles in the course of siting, construction, and operating wind energy facilities. As research specific to noise effects from wind turbines further evolves, these findings should be added to ECPG guidelines and utilized to develop technologies and measures to further minimize noise impacts on wildlife (USFWS, 2013).

WIND ENERGY IMPACTS ON HUMAN HEALTH

Anyone looking at an operational wind turbine or a massive wind farm would have a particular perception about the view. For any number of reasons, the observer's perception might be positive or it might be negative—it's all in the eyes of the beholder (literally, the perception is subjective). But, the eyes are simply the windows to receive neuron-transmitted signals to our brain cells and thus to our thought process. One thought that such observers might have is that a wind turbine could not affect their health, but they would be wrong. What is health, exactly? For our purposes in this text, let's use the World Health Organization's definition of health: "Health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity."

Although from a practical and well-documented viewpoint, the operation of a wind turbine or wind turbine farm does not directly impact human health, it is also true that factors such as stress and loss of sleep contribute to health problems for some residents living close to these installations. Stress can be generated by frustrated residents having to put up with noise pollution and the adverse visual impact and loss of land value; also, loss of sleep can be experienced by people living close to wind turbines as a result of noise pollution.

Observers have complained about turbine noise annoyance and unpleasant sounds that include rhythmic modulation of low-frequency noise (which may be more annoying than steady noise) and increasing sound pressure levels, resulting

in increased levels of annoyance. Interestingly, such annoyance was reported more frequently when turbines were visible and when the observer reported a negative impact on surrounding landscape.

It has been widely reported that wind turbines are creating sounds and vibrations that can be sensed by people up to 10 miles away. Magee (2014, p. 227) noted that, "Nina Pierpont, MD, PhD, is reporting that people who live within 2 kilometers of wind turbines are reporting sickness that can be traced to the presence of these. Low frequency noise and infrasound (sound that is less than 20 Hz) appear to be the problem." The problem that Pierpont and others have reported is commonly called *wind turbine syndrome*, which is the disruption or abnormal stimulation of the inner ear's vestibular system caused by turbine infrasound and low-frequency noise. Symptoms of wind turbine syndrome include the following:

- Sleep problems
- Headaches
- Dizziness
- Exhaustion, anxiety, anger, irritability, and depression
- Problems with concentration and learning
- Tinnitus (ringing in the ears)

Along with the turbine noise annoyance generated by mechanical and aerodynamic factors—the feeling of resentment displeasure, discomfort, dissatisfaction, or offense that occurs when noise interferes with someone's thoughts, feeling, or daily activities (Concha-Barrientos et al., 2005)—there have been complaints about rhythmic light flicker causing intermittent shadows known as *shadow flicker* or *flickering shadows*. Schworm and Filipov (2013) reported that a woman from Kingston, Massachusetts, stated that the problem with shadow flicker begins in the late afternoon. Stripes of shadow whip across her living room, kitchen, and bedroom, a pulse of flashing light and dark that can continue more than an hour and makes Reilly think she is losing her mind. "You can't stay in your room. You get a headache," the woman said. "You can't live your life."

Another increasing complaint being heard concerning wind turbine noise generation is related to high levels of low-frequency noise over years of exposure. This problem is called *vibroacoustic disease* (VAD). The clinical progression is insidious, and lesions are found in many systems throughout the body. This disease or syndrome is commonly classified as mild, moderate, or severe as described below:

- *Mild* (1–4 years)—Slight mood swings, indigestion, heartburn, mouth/throat infections, bronchitis
- *Moderate* (4–10 years)—Chest pain, definite mood swings, back pain, fatigue, skin infections (fungal, viral, and parasitic), inflammation of the stomach lining, pain and blood in the urine, conjunctivitis, allergies
- *Severe* (>10 years)—Psychiatric disturbances, hemorrhages (nasal, digestive, conjunctiva mucosa), varicose veins, hemorrhoids, duodenal ulcers, spastic colitis, decrease in visual activity, headaches, severe joint pain, intense muscular pain, neurological disturbances

DID YOU KNOW?

Wind turbines are as tall as 20-story buildings and their three blades can be 60 meters long.

POWER TRANSMISSION LINES*

In the preceding paragraphs we have set the stage for the more detailed discussion that follows regarding the environmental impact of power transmission lines. Basically, energy transmission involves three stages of implementation: site evaluation, project construction, and transmission operation.

ENERGY TRANSMISSION SITE EVALUATION IMPACTS

Energy site evaluation phase activities are generally temporary and conducted at a smaller magnitude than those during the construction and operation phases. Potential impacts from these activities are presented by the type of affected resource and are described for typical site evaluation activities, such as limited ground clearing, vehicular and pedestrian traffic, borings for geotechnical surveys, and positioning of equipment. If excavation or access road construction is necessary at this stage, impacts on resources would be similar in character, but lesser in magnitude, to those for the construction phase. Route and access road selection that avoids major environmental impacts is ideal; therefore, additional activities that could occur during this phase are field surveys for recording significant resources present in the potential project area (e.g., threatened species and endangered species, wetlands, archaeological sites). These surveys are typical of the short and limited disturbance that occurs during the site evaluation phase. The following impacts may result from site evaluation activities.

Air Quality

Impacts on air quality during surveying and testing activities would be limited to temporary and local generation of vehicle and boring equipment emissions and fugitive dust and would not likely cause an exceedance of air quality standards nor have any impact on climate change.

Cultural Resources

The amount of surface and subsurface disturbance is minimal during the site evaluation phase. Cultural resources buried below the surface are unlikely to be affected, but material present on the surface could be disturbed by vehicular traffic, ground clearing, and pedestrian activity (including collection of artifacts). Surveying and testing activities could affect areas of interest to Native Americans depending on the

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* Adapted from Tribal Energy and Environmental Information Clearinghouse website, http://teeic.indianaffairs.gov/.

placement of equipment or level of visual intrusion. Surveys conducted during this phase to evaluate the presence or significance of cultural resources in the area would assist developers in routing and designing the project to avoid or minimize impacts on these resources.

Ecological Resources

Impacts on ecological resources (vegetation, wildlife, aquatic, biota, special status species, and their habitats) would be minimal and localized during surveying and testing because of the limited nature of the activities. The introduction or spread of some nonnative invasive vegetation could occur as a result of vehicular traffic, but this would be relatively limited in extent. Surveys conducted during this phase to evaluate the presence or significance of ecological resources in the area would assist developers in routing and designing the project to avoid or minimize impacts on these resources (e.g., wetlands, migratory birds, threatened and endangered species).

Water Resources

Minimal impact on water resources, local water quality, water flows, and surface water/groundwater interaction is anticipated. Very little water would likely be used or generated during the site evaluation phase. Any water needed could be trucked in from offsite.

Land Use

Site evaluation activities would likely result in temporary and localized impacts on land use. These activities could create a temporary disturbance in the immediate vicinity of a surveying or monitoring site (e.g., disturb recreational activities or livestock grazing). Site evaluation activities are unlikely to affect mining activities, military operations, or aviation.

Soils and Geologic Resources

The amount of surface disturbance and the use of geologic materials are minimal during the site evaluation phase, and soils and geologic resources are unlikely to be affected. Surveying and testing activities would be unlikely to activate geological hazards or increase soil erosion. Borings for soil testing and geotechnical surveys provide useful site-specific data on these resources. Surface effects from pedestrian and vehicular traffic could occur in areas that contain special (e.g., cryptobiotic) soils.

Paleontological Resources

The amount of subsurface disturbance is minimal during the site evaluation phase, and paleontological resources buried below the surface are unlikely to be affected. Fossil material present on the surface could be disturbed by vehicular traffic, ground clearing, and pedestrian activity (including collection of fossils). Surveys conducted

during this phase to evaluate the presence or significance of paleontological resources in the area would assist developers in routing and designing the project to avoid or minimize impacts on these resources.

Transportation

No impacts on transportation are anticipated during the site evaluation phase. Transportation activities would be temporary and intermittent and limited to low volumes of heavy- and medium-duty construction vehicles (e.g., pickup trucks) and personal vehicles.

Visual Resources

Surveying and testing activities would have temporary and minor visual effects caused by the presence of workers, vehicles, and equipment.

Socioeconomics

The activities during the site evaluation phase are temporary and limited and would not result in socioeconomic impacts on employment, local services, or property values.

Environmental Justice

Site evaluation phase activities are limited and would not result in significant adverse impacts in any resource area; therefore, environmental justice is not expected to be an issue during this phase.

ENERGY TRANSMISSION CONSTRUCTION IMPACTS

Typical activities during the construction phase of an energy transmission project include ground clearing and removal of vegetative cover, grading, excavation, blasting, trenching, drilling, vehicular and pedestrian traffic, and project component construction and installation. Activities conducted in locations other than within the project right of way (ROW) include excavation/blasting for construction materials (such as sands and gravels), access road and staging area construction, and construction of other ancillary facilities such as compressor stations or pump stations.

Air Quality

Emissions generated during the construction phase include vehicle emissions; diesel emissions from large construction equipment and generators; VOC emissions from storage and transfer of fuels for construction equipment; small amounts of carbon monoxide, nitrogen oxides, and particulates from blasting activities; and fugitive dust from many sources such as disturbing and moving soils (clearing, grading, excavating, trenching, backfilling, dumping, and truck and equipment traffic), mixing concrete, storage of unvegetated soil piles, and drilling and pile driving. Air quality impacts could also occur if cleared vegetation is burned.

Cultural Resources

Potential impacts on cultural resources include the following:

- Complete destruction of the resource could occur if present in areas undergoing surface disturbance or excavation.
- Degradation or destruction of near-surface cultural resources on- and off-site could result from changing the topography, changing the hydrological patterns, and soil movement (removal, erosion, sedimentation).
- Unauthorized removal of artifacts or vandalism could occur as a result of human access to previously inaccessible areas.
- Visual impacts could result from large areas of exposed surface, increases in dust, and the presence of large-scale equipment, machinery, and vehicles (if the resources have an associated landscape component that contributes to their significance, such as a sacred landscape or historic trail). Note that the accumulation of sediment mentioned above could serve to protect some buried resources by increasing the amount of protective cover.

Ecological Resources

Adverse impacts on ecological resources could occur during construction due to the following:

- Erosion and runoff
- Fugitive dust
- Noise
- Introduction and spread of invasive nonnative vegetation
- Modification, fragmentation, and reduction of habitat
- Mortality of biota
- Exposure to contaminants
- Interference with behavioral activities

Site clearing and grading, coupled with construction of access roads, towers, and support facilities, could reduce, fragment, or dramatically alter existing habitats in the disturbed portions of the project area. Wildlife in surrounding habitats might also be affected if construction activities (and associated noise) disturb normal behaviors, such as feeding and reproduction.

Water Resources

Water would be required for dust control, making concrete, and consumptive use by the construction crew. Depending on availability, it may be trucked in from offsite or obtained from local groundwater wells or nearby surface water bodies. Water quality can be affected by the following:

- Activities that cause soil erosion
- Weathering of newly exposed soils causing leaching and oxidation that can release chemicals into the water

- Discharges of waste or sanitary water
- Herbicide applications
- Contaminant spills, especially oil

Applying sand and gravel for road construction, layout areas, foundations, etc., can alter the drainage near where the material is used. The size of the area affected can range from a few hundred square feet (for a support tower foundation) to a few hundred acres (for an access road). Surface and groundwater flow systems could be affected by withdrawals made for water use, wastewater and stormwater discharges, and the diversion of surface water flow for access road construction or stormwater control systems. Excavation activities and the extraction of geological materials may affect surface and groundwater flow. The interaction between surface water and groundwater may also be affected if the two are hydrologically connected, potentially resulting in unwanted dewatering or recharging.

Land Use

Impacts on land use could occur during construction if there are conflicts with existing land use plans and community goals; conflicts with existing recreation, education, religious, scientific, or other use areas; or conversion or cessation of the existing commercial land use of the area (e.g., mineral extraction). During construction, most land use impacts would be temporary, such as removal of livestock from grazing areas during periods of blasting or heavy equipment operations; curtailing hunting near work crews; or temporary effects on the character of a recreation area because of construction noise, dust, and visual intrusions. Long-term land use impacts would occur if existing land uses are not compatible with an energy transmission project, such as remote recreational experiences. Within forested areas, ROW clearing could result in the long-term loss of timber production.

Impacts on aviation could be possible if the project is located within 20,000 feet (6100 meters) or less of an existing public or military airport or if proposed construction involve objects greater than 200 feet (61 meters) in height. The Federal Aviation Administration (FAA) must be notified if either of these two conditions occurs and would be responsible for determining if the project would adversely affect commercial, military, or personal air navigation safety. Similarly, impacts on military operations may occur if the project is located near a military facility and that facility conducts military testing and training activities that occur at low altitudes.

Soils and Geologic Resources

Surface disturbance, heavy equipment traffic, and changes to surface runoff patterns can cause soil erosion. Impacts of soil erosion include soil nutrient loss and reduced water quality in nearby surface water bodies. Impacts on special soils (e.g., cryptobiotic soils) could also occur. Sands, gravels, and quarry stone would be excavated for use in the construction of access roads; for use in making concrete for foundations and ancillary structures; for improving the ground surface for laydown areas and crane staging areas; and, as necessary, for use as backfill in pipeline

trenches. Mining operations would disturb the ground surface, and runoff would erode fine-grained soils, increasing the sediment load farther down in streams and rivers. Mining on steep slopes or on unstable terrain without appropriate engineering measures increases the landslide potential in the mining areas. Possible geological hazards (earthquakes, landslides, avalanches, forest fires, geomagnetic storms, ice jams, mudflows, rock falls, flash floods, volcanic eruptions, geyser deposits, ground settlement, sand dune migration, thermals springs, etc.) can be activated by excavation and blasting for raw material, increasing slopes during site grading and construction of access roads, altering natural drainage patterns, and toe-cutting bases of slopes. Altering drainage patterns accelerates erosion and creates slope instability.

Paleontological Resources

Potential impacts on paleontological resources during construction include (1) complete destruction of the resource if present in areas undergoing surface disturbance or excavation; (2) degradation or destruction of near-surface fossil resources on- and offsite resulting from changing the topography, changing the hydrological patterns, and soil movement (removal, erosion, sedimentation); and (3) unauthorized removal of fossil resources or vandalism to the locality as a result of human access to previous inaccessible areas. The accumulation of sediment mentioned above could serve to protect some localities by increasing the amount of protective cover.

Transportation

Short-term increases in the use of local roadways would occur during the construction period. Heavy equipment would need to be continuously moved as construction progresses along the linear project. Shipments of materials are not expected to significantly affect primary or secondary road networks but would depend on the ever-changing location of the construction site area relative to material source. Overweight and oversized loads could cause temporary disruptions and could require some modification to roads or bridges (such as fortifying bridges to accommodate the size or weight). The weight of shipments is also a parameter in the design of access roads for grade determinants and turning clearance requirements.

Visual Resources

Potential sources of visual impacts during construction include visual constraints in the landscape due to access roads and staging areas, conspicuous and frequent small-vehicle traffic for worker access, and frequent large-equipment (trucks, graders, excavators, cranes, and, possibly helicopters) traffic for project and access road construction. Project component installation would produce visible activity and dust in dry soils. Project construction may be progressive, persisting over a significant period of time. Ground disturbance (e.g., trenching and grading) would result in visual impacts that produce contrasts of color, form, texture, and line. Soil scars and exposed slope faces could result from excavation, leveling, and equipment movement.

Socioeconomics

Direct impacts would include the creation of new jobs for construction workers and the associated income and taxes generated by the project. As an example, the number of construction workers required for a 150-mile (241-kilometer) length of pipeline is only about 230 annual direct workers (fewer than 175 for an equivalent length of a transmission line or a petroleum pipeline). Indirect impacts are those impacts that would occur as a result of the new economic development and would include things such as new jobs at businesses that support the expanded workforce or that provide project materials and the associated income and taxes. Construction of an energy transmission project may affect the value of residential properties located adjacent to the ROW (there are conflicting reports as to whether these would be adverse, beneficial, or neutral).

Environmental Justice

If significant impacts were to occur in any of the resource areas and were to disproportionately affect minority or low-income populations, there could be an environmental justice impact. Issues that could be of concern are noise, dust, visual impacts, and habitat destruction from construction activities and possible impacts associated with new access roads.

ENERGY TRANSMISSION OPERATIONS IMPACTS

Typical activities during the operation and maintenance phase include operation of compressor stations or pump stations, ROW inspections, ROW vegetation clearing, and maintenance and replacement of facility components. Environmental impacts that could occur during the operation and maintenance phase would mostly occur from long-term habitat change with the ROW, maintenance activities (e.g., ROW vegetation clearing, facility component maintenance or replacement), noise (e.g., compressor station, corona discharge), the presence of workers, and potential spills (e.g., oil spills).

Air Quality

Vehicular traffic and machinery would continue to produce small amounts of fugitive dust and exhaust emissions during the operation and maintenance phase. These emissions would not likely cause an exceedance of air quality standards nor have any impact on climate change. Trace amounts of ozone would be produced by corona effects from transmission lines (e.g., less than 1.0 part per billion, which is considerably less than air quality standards). Routine venting of pipelines and breakout tanks (for liquid petroleum products and crude oil) would also cause localized air quality impacts.

Cultural Resources

Impacts during the operations and maintenance phase could include damage to cultural resources during vegetation management and other maintenance activities, unauthorized collection of artifacts, and visual impacts. This threat is present when

the access roads have been constructed and the ROW has been established, making remote areas more accessible to the public. Visual impacts resulting from the presence of the aboveground portion of a pipeline, transmission lines, and associated facilities could impact cultural resources that have an associated landscape component that contributes to their significance, such as a sacred landscape or historic trails.

Ecological Resources

During operations and maintenance, adverse impacts on ecological resources could occur from the following:

- Disturbance of wildlife from noise and human activity
- ROW maintenance (e.g., vegetation removal)
- Exposure or biota to contaminants
- Mortality of biota caused by collisions with transmission lines or aboveground pipeline components

Ecological resources may continue to be affected by the reduction in habitat quality associated with habitat fragmentation due to the presence of the ROW, support facilities, and access roads. In addition, the presence of an energy transmission project and its associated access roads may increase human use of surrounding areas, which in turn could impact ecological resources in the surrounding areas through

- Introduction and spread of invasive nonnative vegetation
- Fragmentation of habitat
- Disturbance of biota
- Collisions with or electrocution of birds
- Increased potential for fire

Water Resources

Impacts on water resources during the operation and maintenance phase would be limited to possible minor degradation of water quality resulting from vehicular traffic and machinery operation during maintenance (e.g., erosion and sedimentation) or herbicide contamination during vegetation management (e.g., from accentual sills). However, a large oil pipeline spill could potentially cause extensive degradation of surface waters or shallow groundwater.

Land Use

Land use impacts would be minimal, as many activities could continue with the ROW (e.g., agriculture and grazing). Other industrial and energy projects would likely be excluded within the ROW. In addition, construction of facilities (such as houses and other structures) would be precluded within the ROW, and roads would only be allowed to cross ROWs, not run along their length. Recreation activities (e.g.,

off-highway vehicle use, hunting) are also possible, although restrictions may exist for the use of guns, especially for aboveground pipelines or transmission lines. The ROW and access roads may make some areas more accessible for recreation activities. Activities centered on solitude and scenic beauty would potentially be affected. Military operations and aviation could be affected by the presence of transmission lines; for example, transmission lines could affect military training and testing operations that may occur at low altitudes (e.g., military training routes).

Soils and Geologic Resources

Following construction, disturbed portions of the site would be revegetated and the soil and geologic conditions would stabilize. Impacts during the operation phase would be limited largely to soil erosion impacts caused by vehicular traffic and machinery operation during maintenance activities. Any excavations required for pipeline maintenance would cause impacts similar to those from construction, but to a lesser spatial and temporal extent. Herbicides would likely be used for ROW maintenance. The accidental spills of herbicides or pipeline product would likely cause soil contamination. Except in the case of a large oil spill, soil contamination would be localized and limited in extent and magnitude.

Paleontological Resources

Impacts during the operations phase would be limited to unauthorized collection of fossils. This threat is present once the access roads are constructed and the ROW is established, making remote areas more accessible to the public.

Transportation

No noticeable impacts on transportation are likely during the operation and maintenance phase. Low volumes of heavy- and medium-duty pickup trucks, personal vehicles, and other machinery are expected to be used during this phase. Infrequent, but routine, shipments of component replacements during maintenance procedures are likely over the period of operation.

Visual Resources

The above portions of energy transmission projects would be highly visible in rural or natural landscapes, many of which have few other comparable structures. The artificial appearance of a transmission line or pipeline may have visually incongruous industrial-type associations for some, particularly in a predominately natural landscape. Visual evidence of these projects cannot be completely avoided, reduced, or concealed. Additional visual impacts would occur during maintenance from vehicular traffic, aircraft, and workers. Maintenance, replacement, or upgrades of project components would repeat the initial visual impacts of the construction phase, although at a more localized scale.

Socioeconomics

Direct impacts would include the creation of new jobs for operation and maintenance workers and the associated income and taxes paid. Indirect impacts are those impacts that would occur as result of the new economic development and would include things such as new jobs at businesses that support the expanded workforce or that provide project materials and the associated income and taxes. The number of project personnel required during the operation and maintenance phase would be about an order of magnitude less than during construction; therefore, socioeconomic impacts related directly to jobs would be minimal. Potential impacts on the value of residential properties located adjacent to an energy transmission project would continue during this phase.

Environmental Justice

Possible environmental justice impacts during operation include the alteration of scenic quality in areas of traditional or cultural significance to minority or low-income populations. Habitat modification, noise impacts, and health and safety impacts are also possible sources of environmental justice impacts.

WIND TURBINE OPERATIONS AND MAINTENANCE PERSONNEL SAFETY CONCERNS

Wind Energy Fatalities/Incidents

Wind energy workers are exposed to hazards that can result in fatalities and serious injuries. Many incidents involving falls, severe burns from electrical shocks and arc flashes/fires, and crushing injuries have been reported to OSHA. Some examples are given below:

- On August 29, 2009, at 8:30 a.m., a 33-year-old male lineman was shocked as he grasped a trailer ramp attached to a low-boy trailer containing an excavator. The excavator was being operated in anticipation of being offloaded from the trailer. The trailer was parked on a rural aggregate road adjacent to an access road for a wind turbine generator. The excavator operator rotated the upper works of the machine prior to moving the machine from the trailer. During the rotation the boom contacted a 7200-volt primary rural power line. The power line was approximately 12 feet from the road, and the trailer was parked approximately 2 feet from the road edge. The injured worker had entry wounds in his hands and exit wounds in his feet. He was transported by ambulance to a local hospital, where he was treated and admitted for observation. He was discharged approximately 24 hours later and returned to work the following day.
- On May 10, 2009, a worker was in the bottom power cabinet of a wind turbine to check the electrical connections. He came into contact with a bus bar, and an arc flash erupted, causing him injury. The victim was being taken to a hospital by a technician when they were met by an ambulance

on the way. After arriving at the hospital, the victim was later transferred by medi-vac to another hospital in Oklahoma City where he was treated for injuries. On June 12, the company was notified by a representative of the hospital that the victim had died.

- On November 11, 2005, a man and two coworkers were removing and replacing a broken bolt in the nacelle assembly of a wind turbine tower that was approximately 200 feet above the ground. They were heating the bolt with an oxygen–acetylene torch when a fire stated. The man retreated to the rear of the nacelle, away from the ladder access area. Although his two coworkers were able to descend the tower, the man fell approximately 200 feet to the ground, struck an electrical transformer box, and was killed.
- At approximately 11:40 a.m. on June 17, 1992, a worker attempted to descend an 80-foot ladder that accessed a wind turbine generator. The worker slipped and fell from the ladder and was killed. The victim was wearing his company-furnished safety belt, but the safety lanyards were not attached. Both lanyards were later discovered attached to their tie-off connection at the top of the turbine generator.
- A site foreman was replacing a 480-volt circuit breaker serving a wind turbine. He turned a rotary switch to what he thought was the open position in order to isolate the circuit breaker; however, the worker did not test the circuit to ensure that it was de-energized. The worker had placed the rotary switch in a closed position, and the circuit breaker remained energized by back feed from a transformer. Using two plastic-handled screwdrivers, he shorted two contacts on the breaker to discharge static voltage buildup. This caused a fault and the resultant electric arc caused deep flash burns to the worker's face and arms and ignited his shirt. The worker was hospitalized in a burn unit for 4 days.

Case Study 2.1. Wind Turbine Fatality*

The Oregon Department of Consumer and Business Services, Occupational Safety and Health Division (Oregon OSHA), fined Siemens Power Generation, Inc., a total of $10,500 for safety violations related to an August 25, 2007, wind turbine collapse that killed one worker and injured another.

"The investigation found no structural problems with the tower," said Michael Wood, Oregon OSHA administrator. "This tragedy was the result of a system that allowed the operator to restart the turbine after service while the blades were locked in a hazardous position. Siemens has made changes to the tower's engineering controls to ensure it does not happen again."

The event took place at the Klondike III Wind Farm near Wasco, where three wind technicians were performing maintenance on a wind turbine tower. After applying a service brake to stop the blades from moving, one of the workers entered the hub

* Adapted from Department of Consumer Business & Services, Oregon OSHA Releases Findings in Wind Turbine Collapse [news release], Oregon Occupational Safety and Health Administration, Salem, OR, February 26, 2008.

of the turbine. He then positioned all three blades to the maximum wind-resistance position and closed all three energy isolation devices on the blades. The devices are designed to control the mechanism that directs the blade pitch so workers do not get injured while they are working in the hub. Before leaving the confined space, the worker did not return the energy isolation devices to the operational position.

As a result, when he released the service brake, wind energy on the out-of-position blades created an "overspeed" condition, causing one of the blades to strike the tower and the tower to collapse, the Oregon OSHA investigation found. Chadd Mitchell, who was working at the top of the tower, died in the collapse. William Trossen, who was on his way down a ladder in that tower when it collapsed, was injured. The third worker was outside the tower and unharmed.

During the investigation, Oregon OSHA found several violations of safety rules:

- Workers were not properly instructed and supervised in the safe operation of machinery, tool, equipment, process, or practice they were authorized to use or apply. The technicians working on the turbine each had less than two months' experience, and there was no supervisor onsite. The workers were unaware of the potential for catastrophic failure of the turbine that could occur as a result of not restoring energy isolation devices to the operational position.
- The Company's procedures for controlling potentially hazardous energy during service or maintenance activities did not fully comply with Oregon OSHA regulations. Oregon OSHA requirements include developing, documenting, and using detailed procedures and applying lockout or tagout devices to secure hazardous energy in a "safe" or "off" position during service or maintenance. Several energy isolation devices in the towers, such as valves and lock pins, were not designed to hold a lockout device, and energy controls procedures in place at the time of the accident did not include the application and removal of tagout devices.
- Employees who were required to enter the hub (a permit-required confined space) or act as attendants to employees entering the hub had not been trained in emergency rescue procedures from the hub.

Wind Turbine Hazards and Applicable OHSA Standards and Controls

As shown in Case Study 2.1, wind energy employers need to protect their workers from workplace hazards. Workers should be engaged in workplace safety and health, and they need to understand how to protect themselves from these hazards. Even though the wind energy industry is a growing industry, the hazards are not unique, and OSHA has many standards that cover various worker on-the-job activities and exposures. The hazards (along with controls) that workers in wind energy may face are provided in this section.

Working around, with, or on wind turbines and associated equipment presents many hazards to the installers, operators, and maintenance personnel. The hazards along with applicable OSHA standards and controls include the following:

- Falls
- Confined space entry
- Fire
- Lockout/tagout
- Medical and first aid
- Crane, derrick, and hoist safety
- Electrical safety
- Machine guarding
- Respiratory protection

Each of these hazards and controls is briefly discussed below. (Note that many of the hazards discussed below apply, in one way or another, to other renewable energy sources.)

Falls*

Workers who erect and maintain wind turbines can be exposed to fall hazards. Wind turbines vary in height, but can be over 100 feet tall (some are over 400 feet tall). Exposure to high winds may make work at high elevations even more hazardous. OSHA has different fall protection requirements for construction (installation of towers) and general industry (maintenance). During installation, workers may need to access individual turbine sections to weld or fit individual sections together, run electrical or other lines, and install or test equipment—often at heights greater than 100 feet. Construction workers on wind farms when exposed to fall distances of 6 feet or more must be protected from falls by guardrail systems, safety net systems, or a personal fall arrest system.

Confined Space Entry†

Wind energy employers need to look at the spaces that workers enter to determine if they meet OSHA's definition of a confined space. By definition, a confined space:

- Is large enough for an employee to enter fully and perform assigned work
- Is not designed for continuous occupancy by the employee
- Has a limited or restricted means of entry or exit

Some confined spaces have recognized hazards, such as low oxygen environments, which can pose a risk for asphyxiation, or accumulation of hazardous gases. These confined spaces are called *permit-required confined spaces* (PRCSs) and require additional safety precautions. Wind energy employers need to look at the hazards of any confined spaces to determine whether those spaces are permit-required confined spaces. By definition, a PRCS has one or more of these characteristics:

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* Adapted from OSHA's *Green Job Hazards: Wind Energy—Falls*, http://www.osha.gov/dep/greenjobs/windenergy_falls.html; Spellman, F.R., *Safe Work Practices for Green Energy Jobs*, DEStech Publishers, Lancaster, PA, 2013.

† Adapted from OSHA's *Green Job Hazards: Wind Energy—Confined Spaces*, http://www.osha.gov/dep/greenjobs/windenergy_confined.html.

- Contains or has the potential to contain a hazardous atmosphere
- Contains a material with the potential to engulf someone who enters the space
- Has an internal configuration that might cause an entrant to be trapped or asphyxiated by inwardly converging walls or by a floor that slopes downward and tapers to a smaller cross section
- Contains any other recognized serious safety or health hazards

If workers are expected to enter permit-required confined spaces, the employer must develop a written permit space program and make it available to workers or their representatives. The permit space program must detail the steps to be taken to make the space safe for entry.

The configuration of all nacelles will classify them as confined spaces, and during the maintenance activities inside the nacelles workers may be exposed to hazards from electrical motors, gears, etc. Those hazards may classify a nacelle as a PRCS. Technicians required to work in nacelles should make sure to perform air sampling (such as for low oxygen levels or other hazardous gases) prior to entering a nacelle. It is recommended that such technicians should always carry portable gas monitors in their toolkits and make sure that they are maintained properly.

Fires*

Wind turbines may have fire hazards because of the electrical parts and the combustible materials such as insulation or the material of construction used in the turbine housing (nacelle) or lubricants involved in its operation. Wind energy employees need to be trained about fire hazards at the worksite and about what to do in a fire emergency. This plan should outline the assignments of key personnel in the event of a fire and provide an evacuation plan for workers on the wind turbines. Where employers require workers to use portable fire extinguishers, workers must be trained in the general principle of fire extinguisher use and the hazards involved with incipient-stage fire fighting. Workers should be made aware that while fighting initial fires toxic gases can be generated and oxygen can be depleted inside nacelles, and they can be exposed to such gases or can be asphyxiated from lack of oxygen.

If the employer chooses to use a fixed extinguishing system inside nacelles, then the freezing point of the extinguishing medium, the safety of workers (exposure to toxic gases and depletion of oxygen), and emergency escape methods should be taken into consideration. In addition to the fire extinguishing mechanism (whether the use of fire extinguishers or a fire extinguishing system, or both), fire detection systems and emergency alarm systems should be installed inside nacelles to give an early warning to workers to escape. If such systems are installed, they must be maintained in operable condition; see 29 CFR 1910.160(c) and 1910.165(d). Workers should know exactly what to do and how to escape in a fire emergency. Wind turbines should be provided with quick-escape descent devices for workers to escape in the event of a fire or other emergency.

* Adapted from OSHA's *Green Job Hazards: Wind Energy—Fires*, http://www.osha.gov/dep/greenjobs/windenergy_fire.html.

Lockout/Tagout*

Lockout/tagout refers to specific practices and procedures to safeguard employees from the unexpected energization or startup of machinery and equipment or the release of hazardous energy during service or maintenance activities. Approximately 3 million workers service equipment and face the greatest risk of injury if lockout/tagout is not properly implemented. Compliance with the lockout/tagout standard prevents an estimated 120 fatalities and 50,000 injuries each year. Workers injured on the job from exposure to hazardous energy lose an average of 24 work days for recuperation. In a study conducted by the United Auto Workers, 20% of the fatalities (83 of 414) that occurred among their members between 1973 and 1995 could be attributed to inadequate hazardous energy control procedures, specifically lockout/tagout procedures. Wind turbines have lots of internal machinery and equipment, including blades that need to be maintained. Workers performing servicing or maintenance may be exposed to injuries from the unexpected energization, startup of the machinery or piece of equipment, or relapse of stored energy in the equipment. Wind farm employers must implement lockout/tagout procedures outlined in OSHA standards; see 29 CFR 1910.269(d) and 29 CFR 1910.147.

The following are some of the significant requirements of a lockout/tagout procedure required under a lockout/tagout program:

- Only authorized employees may lockout or tagout machines or equipment in order to perform servicing or maintenance.
- Lockout devices (locks) and tagout devices must not be used for any other purposes and must be used only for controlling energy.
- Lockout and tagout devices (locks and tags) must identify the name of the worker applying the device.
- All energy sources to equipment must be identified and isolated.
- After the energy is isolated from the machine or equipment, the isolating devices must be locked out or tagged out in the "safe" or "off" position only by the authorized employees.
- Following the application of the lockout or tagout devices to the energy isolating devices, the stored or residual energy must be safely discharged or relieved.
- Prior to beginning any work on the equipment, the authorized employee should verify that the equipment is isolated from the energy source—for example, by operating the on/off switch on the machine or piece of equipment.
- The lock and tag must remain on the machine until the work is completed.
- Only the authorized employee who placed the lock and tag can remove the lock or tag, unless the employer has a specific procedure as outlined in OSHA's lockout/tagout standard.

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* Adapted from OSHA's *Green Jobs Hazards: Wind Energy—Lockout/Tagout*, http:www.osha.gov/dep/greenjobs/windenergy_loto.html.

DID YOU KNOW?

Bloodborne pathogens are infectious microorganisms in human blood that can cause disease in humans. These pathogens include, but are not limited to, hepatitis B (HBV), hepatitis C (HCV), and human immunodeficiency virus (HIV). Needlesticks and other sharps-related injuries may expose workers to bloodborne pathogens. Workers in many occupations, including first-aid team members, housekeeping personnel in some industries, and nurses and other healthcare personnel, may be at risk of exposure to bloodborne pathogens.

Medical and First Aid*

Wind farms are normally located in remote locations, away from a hospital or other emergency treatment facilities. This is a major concern if a worker gets hurt—can that worker be treated quickly? Wind energy employers should determine the estimates of emergency medical service response times for all of their wind farm locations at all times of the day and night when they have workers on duty, and they should use that information when planning their first-aid program. Employers must ensure that medical personnel are available for advice and consultation and that someone who is trained is available to provide first aid. Trained first-aid providers must be available at all wind farms of any size, if there is no nearby clinic or a hospital. If a worker is expected to render first aid as part of his or her job duties, the worker is covered by the requirements of the Occupational Exposure to Bloodborne Pathogens Standard (29 CFR 1910.1030). This standard includes specific training requirements.

The OSHA Electric Power Generation, Transmission, and Distribution standard requires that workers be trained in cardiopulmonary resuscitation (CPR), because a worker who may be exposed to an electric shock may experience a sudden cardiac arrest. In such adverse situations, automated external defibrillators (AEDs) can also assist in preventing a potential death. AEDs should be provided at wind farms, and workers should be trained in how to use them. This training can be done when CPR training is provided to workers.

Crane, Derrick, Rigging, and Hoist Safety†

Cranes, derricks, rigging equipment, and hoists are used to move the large, heavy loads during wind turbine installation and maintenance. Fatalities and serious injuries can occur if cranes are not inspected and used properly. Many fatalities can occur when the crane boom, load line, or load contacts power lines and shorts electricity to ground. Other incidents happen when workers are struck by the load, are caught inside the swing radius, or fail to assemble or disassemble the crane properly. There are significant safety issues to be considered, both for operators of the diverse

* Adapted from OSHA's *Green Job Hazards: Wind Energy—Medical and First Aid*, http://www.osha.gov/dep/greenjobs/windenergy_medical.html.

† Adapted from OSHA's *Green Job Hazards: Wind Energy—Crane, Derrick and Hoist Safety*, http://www.osha.gov/dep /greenjobs/windenegy_crane.html.

lifting devices and for workers who work near them. See OSHA's General Industry standards (29 CFR 1910.179 and 29 CFR 1910.180) and the Construction standard (19 CFR 1926.1417).

Because wind turbines are installed in windy areas, the effects of wind speed need to be taken into consideration for lifting activities. Stability can be an issue when the boom is high and wind coming from the rear, front, or side of the crane can cause the load to sway away from the crane, increasing the radius and thus possibly decreasing the crane capacity. An employer needs to determine the wind speeds at which it is not safe to continue lifting operations. Load charts do not generally take wind speeds into consideration. If the load chart or the operating manual does not have information on wind speeds and derating (i.e., operating below design limits to prolong life and ensure safety) information, the crane manufacturer should be consulted. The procedures applicable to the operation of the equipment, including rated capacities (load charts), recommended operating speeds, special hazard warnings, instructions, and operator's manual, must be readily available in the cab at all times for use by the operator (29 CFR 1926.1417(c)). The maximum allowable wind speed and derating information must be posted conspicuously in the cab or on the load chart.

Extremely cold weather conditions can have an impact on crane and lifting operations. When temperatures drop below 10°F, appropriate consideration should be given to crane hydraulics and possible derating of the crane. Bad weather such as rain, snow, or fog can also have an adverse impact on lifting. Equipment and operations must be adjusted to address the effect of wind, ice, and snow on equipment stability and rate capacity (29 CFR 1926.1417(n)). During thunderstorms, a crane boom can become a lightning rod. If there is an indication of possible thunderstorms, lifting activities should be suspended, the boom should be lowered to a safe position, and workers should leave the area. If the crane is struck by lightning, it should be thoroughly inspected prior to putting it back into service. Heavy rain along with high speed winds can also affect crane operations. Water can get into components such as brakes or clutches and render them inoperable. When these conditions exist, operators should wait until the components are dried out.

Electrical Safety*

Workers in wind farms are potentially exposed to a variety of serious hazards, such as arc flashes (which include arc flash burn and blast hazards), electrical shock, falls, and thermal burn hazards, that can cause injury and death. Wind farm employers are covered by the Electric Power Generation, Transmission, and Distribution standards and therefore are required to implement the safe work practices and worker training requirements of OSHA's Electric Power Generation, Transmission and Distribution standard (29 CF 1910.269). Workers need to pay attention to overhead power lines at wind farms. A hazard arises from the use of tools and equipment that can contact power lines; workers must stay at least 10 feet away from them, because they carry extremely high voltage. Fatal electrocution is the main hazard, but burns and falls from elevators can occur at wind farms.

* Adapted from OSHA's *Green Job Hazards: Wind Energy—Electrical*, http://www.osha.gov/dep/greenjobs/windenergy_electical.html.

Machine Guarding*

The production of a wind turbine involves thousands of parts—gears, blades, and many other such parts. Manufacturing wind turbines, therefore, will involve machines of various configurations that may expose workers to hazards of moving parts of the machines if they are not safeguarded properly. Additionally, the moving parts associated with the turbine, if not guarded properly, may have the potential to cause severe workplace injuries, such as crushed fingers or hands, amputations, burns, or blindness. Employers must ensure that the workers are protected from the machine hazards, and workers should make sure that the rotating parts and points of operation machines are properly guarded prior to using them.

Respiratory Protection†

Manufacturing turbine blades involve operations such as buffing and resurfacing, which may expose workers to harmful gases, vapors, and dusts. Workers must be protected from the inhalation hazards through the use of ventilation. If the ventilation alone is not adequate, then workers may also need to use appropriate respirators. The use of respirators may give a false sense of security, and workers should understand the limitations of the respirators. For example, during heavy exertion the respirator seal is often compromised, which allows the chemical to enter the breathing zone (without being filtered) through the gaps between the respirator and the face. In such situations, a worker who is not adequately trained may think that he or she is being protected. It is therefore essential for workers to be provided training in the proper use of respirators. In addition, they must be trained on the proper storage and maintenance of respirators.

WIND POWER: THE BOTTOM LINE

Technology is much more advanced today in utilizing our wind resource, and the United States is home to one of the best wind resource areas in the world: the Midwest states of North and South Dakota, Nebraska, Kansas, Montana, Iowa, and Oklahoma (Archer and Jacobson, 2004). However, as with any other source of energy, nonrenewable or renewable, there are advantages and disadvantages associated with their use. On the positive side, it should be noted that wind energy is a free, renewable resource, so no matter how much is used today there will still be the same supply in the future. Wind energy is also a source of clean, non-polluting electricity. Wind turbines can be installed on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Moreover, farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land—the height and distance between turbines mean that land used for wind turbines can also be used for agriculture and grazing; only

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* Adapted from OSHA's *Green Job Hazards: Wind Energy—Machine Guarding*, http://www.osha.gov/dep/greenjobs/windenergy_machineguarding.html.

† Adapted from OSHA's *Green Job Hazards: Wind Energy—Respiratory Protection*, http://www.osha.gov/dep/greenhobs/windenergy_respiratory.html.

about 5% of the land in a wind farm is actually occupied by the turbines themselves. One huge advantage of wind energy is that it is a domestic source of energy; in the United States, the wind supply is abundant.

On the other side of the coin, wind energy does have a few negatives—wind projects face opposition. Wind power must compete with conventional generation sources on a cost basis. Even though the cost of wind power has decreased dramatically in the past 10 years, the technology requires a higher initial investment than for fossil-fueled generators. The challenge to using wind as a source of power is that the wind is intermittent and does not always blow when electricity is needed. Wind energy cannot be stored (unless batteries are being used), and not all winds can be harnessed to meet the timing of electricity demands. Another problem is that good sites are often located in remote locations, far from cities where the electricity is needed. Moreover, wind resource development may compete with other uses for the land, and those alternative uses may be more highly valued than electricity generation. Finally, with regard to the environment, wind power plants have relatively little impact on the environment compared to other conventional power plants, but there is some concern over the noise produced by the rotor blades (most experts agree that wind turbine noise is generally not a major concern beyond a half mile) and aesthetic (visual) impacts. Sometimes birds are killed by flying into the rotors. Most of these problems have been resolved or greatly reduced through technological development or by properly siting wind plants, but the NIMBY point of view is still alive and strong in the United States and has succeeded in killing many projects, even renewable, clean energy projects.

Wind energy jobs are the proverbial double-edged sword. The development of wind energy provides benefits related to moving us toward energy independence, creates new jobs, and improves environmental conditions. However, wind energy jobs expose workers to a number of safety hazards. Workers may be exposed to the same conventional hazards found in most workplaces—such as slips, trips, and falls, confined spaces, electrical, fire, and other similar hazards. Additionally, though, wind energy workers may be exposed to new hazards, many of which have yet to be identified.

THOUGHT-PROVOKING QUESTIONS

2.1 What factors must be taken into account when considering wind energy as an alternative renewable energy source? Explain.
2.2 In your opinion, is wind power a viable source of renewable energy?
2.3 When opponents of wind farms argue against them for aesthetic reasons, the counter argument has been offered that the wind farm has to proceed based on their ecological benefits alone, along the lines of "eat your spinach" mode of persuasion. Does this argument make sense? Explain.
2.4 If you were assigned to design wind turbine farms to be aesthetically pleasing, how would you do it?
2.5 How would you protect wildlife from wind turbine operation?
2.6 If a hillside was filled with oil rigs instead of wind turbines, would you then prefer the wind turbines instead?

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3 Solar Energy

The sun: the star that symbolizes and provides life, power, strength, force, clarity, and, yes, energy.

ICARUS REVISITED AT IVANPAH

In Greek mythology, Icarus attempted to escape from Crete by means of wings that his father constructed from feathers and wax. Icarus ignored instructions not to fly too close to the sun, and the melting wax caused him to fall into the sea where he drowned. At the Ivanpah Solar Electric Generating System in the Mojave Desert, near the California/Nevada border, amid miles of rock and scrub, in a windy stretch once roamed by tortoises and coyotes, is a vast array of 7- by 10-foot solar mirrors. From above, these mirrors create the image of an ethereal lake shimmering atop the desert floor. A modern Icarus-like horror is played out at this site whenever birds fly over and end up with scorched wings and bodies, or even worse for those who dive into this faux lake and are literally fried by the 1000°F degree heat flux radiated by the mirrors. Unfortunately, for many of these feathered victims there is no Phoenix complex. The victims are cooked alive without hope of regeneration.

ENERGY FROM THE SUN

The sun nourishes our planet. When we consider the sun and solar energy, we quickly realize that there is nothing new about renewable energy. The sun was the first energy source; it has been around for 4.5 billion years, as long as anything else we are familiar with. On Earth, without the sun, there would be nothing—absolutely nothing. The sun provided light and heat to the first humans. During daylight, the people searched for food. They hunted and gathered and probably stayed together for safety. When nightfall arrived and it was dark, we can only imagine that they huddled together for warmth and safety under the light of the stars and moon, waiting for the sun and its live-giving and life-sustaining light to return.

Solar energy (a term used interchangeably with solar power) uses various technologies to take advantage of the power of the sun to produce energy. Solar energy is one of the best renewable energy sources available because it is one the cleanest sources of energy. Direct solar radiation absorbed in solar collectors can provide space heating and hot water. Passive solar can be used to enhance the solar energy used in buildings for space heating and lighting requirements. Solar energy can also be used to produce electricity, and this is the type of green (renewable) energy that we focus on in this section. The two major categories of solar energy technologies are distinguished by the way they convert sunlight into electricity: photovoltaics (PV) and concentrating solar power (CSP). These two solar electric technologies present the greatest potential (USDOE, 2010).

CAUTION!

SOLAR PANELS: LIFT THEM SAFELY!

Never climb ladders while carrying solar panels.

Always use lifting equipment whenever possible, such as ladder hoists, swing hoists, or truck-mounted cranes/conveyors.

If lifting equipment is not used, manually lift panels to the roof using ropes, platforms, or other methods in accordance with best materials handling practices.

Photovoltaics

Photovoltaic (*photo*, light; *volt*, from electricity pioneer Alessandro Volta) technology makes use of the abundant energy in the sun by employing a semiconductor material—traditionally silicon but, increasingly, other materials as well—to convert sunlight directly into electricity. Photovoltaics is the direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the *photoelectric effect* (discovered and described by Becquerel in 1839) that causes them to absorb photons of light and release electrons. When these free electrons are captured, an electric current results (i.e., electricity is the flow of free electrons) that can be used as electricity. The first photovoltaic module (billed as a solar battery) was built by Bell Laboratories in 1954. In the 1960s, the space program began to make the first serious use of the technology to provide power aboard spacecraft. Space program use helped this technology make giant advancements in reliability and helped to lower costs associated with photovoltaics; however, it was the oil embargo of the 1970s (the so-called energy crisis) that focused attention on using photovoltaic technology for applications other than the space program. Photovoltaics can be used in a wide range of products, from small consumer items to large commercial solar electric systems.

Figure 3.1 illustrates the operation of a basic *photovoltaic cell*, also called a *solar cell*. Solar cells are made of silicon and other semiconductor materials such as germanium, gallium arsenide, and silicon carbide that are used in the microelectronics industry. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are jarred loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides,

DID YOU KNOW?

Solar energy is a completely free source of energy, and it is found in abundance. Although the sun is 90 million miles from the Earth, it takes less than 10 minutes for light to travel that far.

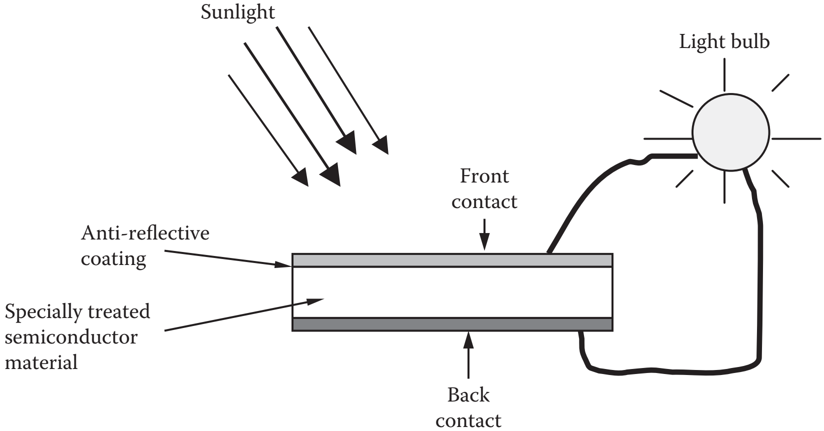

FIGURE 3.1 Operation of basic photovoltaic cell.

forming an electrical circuit, the electrons can be captured in the form of an electrical current (recall that electron flow is electricity). This electricity can then be used to power a load, such as a light, tool, or toaster, for example.

A *photovoltaic module* is comprised of a number of solar cells electrically connected to each other and mounted on a support panel or frame (see Figure 3.2). Modules are designed to supply electricity at a certain voltage (e.g., 12 volts). The current produced is directly dependent on how much light strikes the module. Multiple modules can be wired together to form an array. In general, the larger the area of

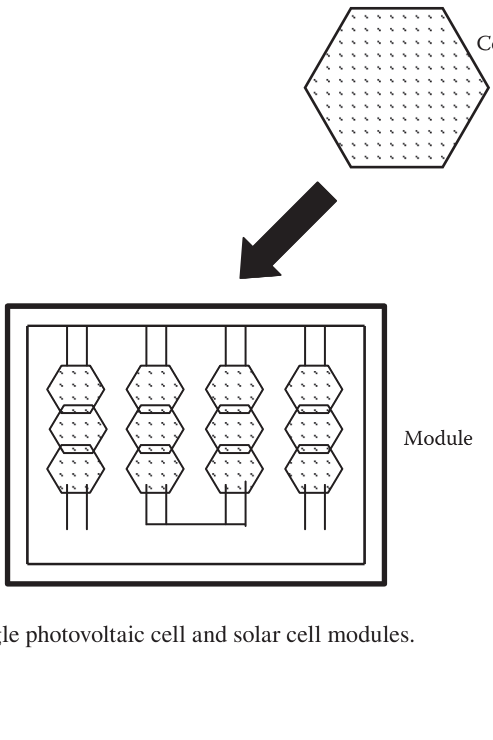

FIGURE 3.2 Single photovoltaic cell and solar cell modules.

DID YOU KNOW?

Solar energy can be used for making brackish or saline water potable. Without using electricity or chemicals, wastewater can be treated. Obtaining salt from seawater is also one of the oldest uses of solar energy.

a module or array, the greater amount of electricity will be produced. Photovoltaic modules and arrays produce direct-current (DC) electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination.

Concentrating Solar Power

Concentrating solar power (CSP) offers a utility-scale, firm, dispatchable renewable energy option that can help meet a nation's demand for electricity. CSP plants produce power by first using mirrors to focus sunlight to heat a working fluid. Ultimately, this high-temperature fluid is used to spin a turbine or to power an engine that drives a generator that produces electricity. Concentrating solar power systems can be classified by how they collect solar energy: linear concentrators, dish/engine systems, or power tower systems (NREL, 2012b).

- *Linear concentrators* collect the sun's energy using long rectangular, curved (U-shaped) mirrors. The mirrors are tilted toward the sun, focusing sunlight on tubes (or receivers) that run the length of the mirrors. The reflected sunlight heats a fluid flowing through the tubes. The hot fluid is then used to boil water in a conventional steam-turbine generator to produce electricity. The two major types of linear concentrator systems are parabolic trough systems, where receiver tubes are positioned along the focal line of each parabolic mirror, and linear Fresnel reflector systems, where one receiver tube is positioned above several mirrors to allow the mirrors greater mobility in tracking the sun.
- *Dish/engine systems* use a mirrored dish similar to a very large satellite dish. The dish-shaped surface directs and concentrates sunlight onto a thermal receiver, which absorbs and collects the heat and transfers it to the engine generator. The most common type of heat engine used today in dish/engine systems is the Stirling engine (conceived in 1816). This system uses the fluid heated by the receiver to move pistons and create mechanical power. The mechanical power is then used to run a generator or alternator to produce electricity.
- *Power tower systems* use a large field of flat, sun-tracking mirrors known as heliostats to focus and concentrate sunlight onto a receiver on the top of a tower. A heat-transfer fluid heated in the receiver is used to generate steam, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam as the heat transfer fluid. Other

> advanced designs are experimenting with molten nitrate salt because of its superior heat-transfer and energy-storage capabilities. The energy-storage capability, or thermal storage, allows the system to continue to dispatch electricity during cloudy weather or at night.

Smaller CSP systems can be located directly where the power is needed. For example a single, dish/engine system can produce 3 to 25 kilowatts of power and is well suited for such distributed applications. Larger, utility-scale CSP applications provide hundreds of megawatts of electricity for the power grid. Both linear concentrator and power tower systems can be easily integrated with thermal storage, helping to generate electricity during cloudy periods or at night. Alternatively, these systems can be combined with natural gas, and the resulting hybrid power plants can provide high-value, dispatchable power throughout the day.

ENVIRONMENTAL IMPACTS OF SOLAR ENERGY

All energy-generating technologies, including solar technologies, affect the environment in many ways. Solar energy has some obvious advantages in that the source is free; however, the initial investment in operating equipment is not. Solar energy is also environmentally friendly, requires almost no maintenance, and reduces our dependence on foreign energy supplies. Probably the greatest downside of solar energy use is that in areas without direct sunlight during certain times of the year solar panels cannot capture enough energy to provide heat for homes or offices. Geographically speaking, the higher latitudes do not receive as much direct sunlight as tropical areas. Because of the position of the sun in the sky, solar panels must be placed in sun-friendly locations such as the U.S. desert southwest and the Sahara region of northern Africa.

Land Use and Siting

Most of the land used for larger utility-scale solar facilities, depending on their location, can raise concerns about land degradation and habitat loss. This is the case even if abandoned industrial, fallow agricultural, or former mining sites are used. Total land area requirements vary depending on the technology, the topography of the site, and the intensity of the solar resource. Estimates for utility-scale PV systems range from 3.5 to 10 acres per megawatt, while estimates for CSP facilities are between 4 and 16.5 acres per megawatt (UCS, 2013). Unlike wind facilities, there is less opportunity for solar projects to share land with agricultural uses; however, land impacts

DID YOU KNOW?

Abandoned mine lands (AMLs) are those lands, waters, and surrounding watersheds where extraction, beneficiation, or processing of ores and minerals (excluding coal) has occurred. These lands also include areas where mining or processing activity is temporarily inactive.

for utility-scale solar systems can be minimized by siting them at lower-quality locations such as brownfields, existing transportation and transmission corridors, or abandoned mining land (AML) (Hand et al., 2012; USEPA, 2011).

Water Resources

Just as with the production of energy from all other sources, in one way or another solar energy production has a *water footprint*, defined as the total volume of freshwater used to produce energy and the services consumed by the production process. Water consumption for solar generation varies by technology and location. For our purposes in this text, water consumption is defined as the amount of water that is "evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (Kenny et al., 2009). Water consumption is distinct from water withdrawal. Water withdrawal is the total amount of "water removed from the ground or diverted from a surface-water source for use" (Kenny et al., 2009) but which may be returned to the sources. Both water withdrawal and consumption are important metrics, but consumption is a very useful metric for water-scarce regions, especially in the context of future resource development, because consumption effectively removes water from the system so it is not available for other uses (e.g., agriculture, drinking).

Table 3.1 shows estimated water-consumption ranges for solar deployment in 2030 and 2050 under a U.S. Department of Energy scenario. These values represent estimates of gross water consumption for deployed solar technologies only; that is, they do not consider the amount of water consumption avoided due to replacement of other electricity-generating technologies by solar. Table 3.2 gives water use estimates for solar, wind, fossil fuel, and nuclear generating technologies. Biomass and co-fired biomass power plants have cooling/generating water consumption similar to that of comparable coal plants, but water consumption related to growing biomass fuel is highly variable (Gerbens-Leenes et al., 2009; Macknick et al., 2011). As Table 3.2 shows, many solar configurations can reduce water consumption dramatically compared with conventional technologies that use evaporative cooling systems (i.e., cooling towers).

Solar cooling towers regulate temperature by dissipating heat from recirculating water used to cool process equipment. Heat is rejected from the tower primarily through evaporation; therefore, by design, cooling towers consume significant amounts of water (see Table 3.2). The Achilles heel of solar cooling towers is twofold: (1) equipment failure and (2) operator and/or management error. The thermal efficiency and longevity of the cooling tower and equipment used to cool depend on the proper operation and management of water recirculated through the tower. Water leaves a cooling tower system in any one of four ways (EERE, 2013):

1. *Evaporation*—This is the primary function of the tower and is the method that transfers heat from the cooling tower system to the environment. The quantity of evaporation is not a subject for water efficiency efforts (although improving the energy efficiency of the systems being cooled will reduce the evaporative load on the tower).

TABLE 3.1
U.S. Solar-Related Water Consumption for Solar Technology Deployment in 2030 and 2050 under USDOE (2012) Scenario

	Solar Generation in 2030 (TWh)	Solar-Related Water Consumption in 2030 (billion gal)	Solar Generation in 2050 (TWh)	Solar-Related Water Consumption in 2050 (billion gal)
Rooftop PV	164	0–0.8	318	0–1.6
Utility-scale PV	341	0–1.7	718	0–3.6
CSP[a]	137	14–75	412	42–227
Total	642	14–78	1448	42–232

Source: USDOE, *SunShot Vision Study*, U.S. Department of Energy, Washington, DC, 2012.

[a] The CSP water-use values shown here reflect a range of trough/tower water-use estimates. The low number reflects trough/tower technology with 90% use of dry cooling and 10% use of wet cooling, with per-megawatt-hour consumption at the low end of the trough/tower ranges. The high number reflects trough/tower technology with 50% use of wet cooling and 50% use of dry cooling, with per-megawatt-hour consumption at the high end of the trough/tower ranges. The USDOE scenario assumes 100% dry cooling as a conservative estimate of costs, but it is likely that the mix would consist of various technologies. Thus, the values given in this table are meant to illustrate a range of possible scenarios of CSP deployment. Dish/engine CSP technologies were used in these calculations because substantially more data are available for them, but, assuming dish/engine technologies meet the price and performance characteristics envisioned in the USDOE scenario, widespread deployment of these technologies could help reduce CSP-related water use.

2. *Drift*—A small quantity of water may be carried from the tower as mist or small droplets. Drift loss is small compared to evaporation, and blowdown and is controlled with baffles and drift eliminators.
3. *Blowdown or bleed-off*—When water evaporates from the tower, dissolved solids (such as calcium, magnesium, chloride, and silica) are left behind. As more water evaporates, the concentration of these dissolved solids increases. If the concentration gets too high, the solids can cause scale to form within the system or the dissolved solids can lead to corrosion problems. The concentration of dissolved solids is controlled by blowdown. Carefully monitoring and controlling the quantity of blowdown provides the most significant opportunity to conserve water in cooling tower operations.
4. *Basin leaks or overflows*—Properly operated towers should not have leaks or overflows. Float control equipment must be checked to ensure that the basin level is being maintained properly, and the system valves must be checked to make sure that there are no unaccounted for losses.

TABLE 3.2
Water Intensity of Electricity Generation by Fuel Source and Technology[a]

Generation Technology	Cooling System	Water Consumed for Cooling (gal/MWh)	Other Water Consumed in Generation (gal/MWh)	Water Consumed in Producing Fuel (gal/MWh)
CSP trough or tower (wet-cooled)[b]	Closed-loop cooling tower	710–960	40–60	0
CSP trough or tower (dry-cooled)[c]	Dry air cooling	0	30–80	0
CSP dish/engine[d]	Dry air cooling	0	4–6	0
PV[e]	None	0	0–5	0
Wind[f]	None	0	0	0
Pulverized coal[f,g]	Closed-loop cooling tower	360–590	60–120	5–74
Pulverized coal with CO_2 capture[f,h]	Closed-loop cooling tower	700–770	150–180	5–74
Integrated gasification combined cycle (IGCC)[f,i]	Closed-loop cooling tower	250–370	40–70	5–74
IGCC with CO_2 capture[f,j]	Closed-loop cooling tower	390–410	130–150	5–74
Natural gas combined cycle (CC)[f,k]	Closed-loop cooling tower	180–280	2	11
Nuclear[f,l]	Closed-loop cooling tower	580–850	30	45–150

Source: USDOE, SunShot Vision Study, U.S. Department of Energy, Washington, DC, 2012.

[a] The table does not account for water consumption in system manufacturing or construction of any of the technologies. Water consumption for fuel extraction is considered for fossil and nuclear. All wet-cooled Rankine power cycles are assumed to use closed-loop cooling towers with four cycles of concentration and blowdown water discharge to an onsite evaporation pond. Water consumption values for wet-cooled Rankine power cycles using once-through cooling systems are not shown because their large water withdrawal requirements make them infeasible for the Southwest. Dry cooling is possible with all Rankine cycles, although it is explicitly shown for CSP only.

[b] From Cohen et al. (1999) and Viebahn et al. (2008). Other water consumed for trough and tower technologies includes water for washing mirrors and steam-cycle blowdown and makeup. Mirror soiling rates/washing rates are site and developer specific. Towers will be at the lower end of the cooling-water range and troughs at the higher end due to thermal efficiency differences.

[c] From Brightsource Energy (2007) and Kelly (2006). Other water consumed for trough and tower technologies includes water for washing mirrors and steam-cycle blowdown and make-up. Mirror soiling rates/washing rates are site and developer specific. There is more uncertainty in other water consumed for dry-cooled trough/tower technologies than for wet-cooled technologies because fewer dry-cooled plants have been built.

[d] Dish/engine washing rates and other water use are not well documented and vary by site and developer. The estimate of 4 to 6 gal/MWh is based on Leitner (2002) and CEC (2010b), as well as on industry knowledge.

[e] Utility-scale PV washing rates and other water use are not well documented and vary by site and developer. The estimate of 0 to 5 gal/MWh is based on Aspen Environmental Group (2011) and on industry knowledge.

[f] From USDOE (2006).

[g] From NETL (2007, 2010). Cooling and other-generation values are for new subcritical and supercritical coal plants.

[h] From NETL (2010). Cooling and other-generation values are for new subcritical and supercritical coal plants.

[i] From NETL (2007, 2010).

[j] From NETL (2010).

[k] From EPRI (2002) and NETL (2007).

[l] From Gleick (1993) and Gerdes and Nichols (2009).

The sum of water that is lost from the tower must be replaced by make-up water:

$$\text{Make-up water} = \text{Evaporation} + \text{Blowdown} + \text{Drift}$$

A key parameter used to evaluate cooling tower operation is *cycles of concentration*. This is calculated as the ratio of the concentration of dissolved solids (or conductivity) in the blowdown water compared to the make-up water. Because dissolved solids enter the system in the make-up water and exit the system in the blowdown water, the cycles of concentration are also approximately equal to the ratio of volume of make-up to blowdown water. From a water efficiency standpoint, cycles of concentration should be maximized, which will minimize blowdown water quantity and reduce make-up water demand. However, this can only be done within the constraints of make-up water availability and cooling tower chemistry. Dissolved solids increase as cycles of concentration increase, which can cause scale and corrosion problems unless carefully controlled.

Other cooling types (e.g., once-through and pond systems) may have different water consumption and withdrawal rates, but these technologies are generally not feasible in arid regions due to their higher withdrawal rates. Photovoltaics consume little, if any, water during operation; some PV operators wash panels to maintain optimal performance, whereas others do not. Concentrating solar technologies, including concentrating photovoltaics (CPV) and CSP, require water for rinsing panels, mirrors, and reflectors to ensure maximum energy production. Manufacturing solar technologies also consumes water. For a trough-based CSP facility with 6 hours of two-tank indirect thermal energy storage (TES), Burkhardt et al. (2010) estimated that about 120 gal/MWh are consumed, mainly in the production of solar collector assemblies, nitrate salts, and heat-transfer fluid (HTF). While water-consumption values for PV manufacturing have not been established, Fthenakis and Kim (2010) provided some information about water withdrawals related to PV manufacturing (i.e., water used in the PV manufacturing process but not entirely consumed, with some of the water processed and returned to the immediate water environment). Water consumed to extract, process, and transport fuels can be significant for fossil fuel and nuclear technologies but is not required for solar and wind technologies (see Table 3.2).

The largest water consumption associated with solar-electricity production is for cooling CSP trough and tower plants. The amount of water a CSP system consumes for cooling depends on the technology, cooling system, location, climate, and water availability. Three types of CSP cooling systems can be deployed: wet (once-through or evaporative cooling using cooling towers), dry, or hybrid (combination wet/dry). *Wet cooling* (using cooling towers—evaporative water cooling) is the most common cooling method for new power plants and currently offers the highest performance at the lowest overall cost (Turchi et al., 2010), but it also consumes the largest amount of water. *Dry cooling* cuts operational water consumption by as much as 97% compared with wet cooling, but it increases capital costs and reduces efficiency on hot days (Turchi, 2010). In addition, dry-cooling technology is significantly less effective at temperatures above 100°F. The cost of electricity from a dry-cooled parabolic-trough plant in the Mojave Desert is about 7% higher than from a similar wet-cooled plant (Turchi, 2010; USDOE, 2009). Dish/engine CSP plants are dry cooled.

To overcome the cost and performance penalty associated with dry cooling, some developers are considering *hybrid systems* that employ dry cooling when temperatures are below 38°C (100°F) and wet cooling for hotter periods. Hybrid systems can consume 40 to 90% less water than a wet-cooled system while maintaining 97 to 99% of the performance (USDOE, 2009); however, hybrid systems currently have a higher life-cycle cost than wet-cooled systems (Turchi et al., 2010).

In addition to consuming water for cooling, trough and tower CSP systems consume a relatively small amount of water to produce steam for electricity generation. In a typical Rankine cycle steam turbine, water in a closed loop is heated to produce steam and spin a turbine, then cooled, re-condensed, and used again. A relatively small amount of water—compared with the water consumed in an evaporative cooling system—is drained to remove particulates and salts (the blowdown process) in the boiler and cooling systems. The amount of blowdown water depends on the quality of the source water; more is required when using degraded water sources. Dish/engine CSP plants with Stirling engines do not use a water–steam cycle; the movement of a gas is used to produce electricity in these systems.

The distribution of solar water consumption will not be uniform across the United States; it will be highest in the arid Southwest, where CSP development will be concentrated. Unless dry cooling is used, siting CSP in arid areas presents a potentially insurmountable deployment challenge because of water constraints in these areas (Carter and Campbell, 2009). The West accounted for half of all U.S. population growth from 1990 to 2000, creating additional demand for water (Anderson and Woosley, 2005). Water resources in arid regions may also decline with climate change, and the Southwest has experienced the most rapid warming in the United States (U.S. Global Change Research Program, 2009). Water consumption per unit of area for PV and CSP is less intensive than for a number of other activities. Thus, although water consumption is likely to be an issue of contention in the Southwest going forward, it is possible that solar developers will be able to obtain water rights from existing water-rights holders, sometimes resulting in less intensive water consumption.

Hazardous Waste

Like all other technologies, solar technologies require proper waste management and recycling. PV is associated with a few particular waste management and recycling issues, whereas CSP shares issues with other technologies that use common materials such as concrete, glass, and steel. Waste management and recycling issues for each technology are discussed below, with a focus on the issues surrounding PV. The PV cell manufacturing process includes a number of hazardous materials, such as

DID YOU KNOW?

Unlike wind turbine-produced electricity, solar power is noise pollution free. It has no moving parts and does not require any fuel other than sunlight to produce power.

compounds of cadmium (Cd), selenium (Se), and lead (Pb), and there are concerns about potential emissions at the end of a module's useful life. Managing the disposal and/or recycling of these materials to avoid groundwater contamination (via landfills) and air pollution (via incinerators) is an important environmental consideration. Another important consideration is that in creating millions of solar panels each year millions of pounds of polluted sludge and contaminated water are produced. To dispose of the material properly, the producers must transport it by truck or rail far from their own plants to waste facilities hundreds or, in some cases, thousands of miles away. The fossil fuels used to transport that waste are not typically considered in calculating solar's carbon footprint, giving scientists and consumers who use the measurement to gauge a product's impact on global climate change the impression that solar is cleaner than it is (Anon., 2013).

In addition to materials contained within the completed module, a number of chemicals may be used during PV manufacturing. For crystalline silicon modules, feedstock materials are made through a purification process, the byproducts of which typically include silicon tetrachloride ($SiCl_4$). To reduce costs and protect the environment, most of today's manufacturing plants use a closed-loop process that greatly minimizes waste products by converting, separating, and reusing trichlorosilane from the $SiCl_4$ byproduct. Silicon nitride (SiN_4) is used as an antireflective-coating material and is generally deposited via chemical vapor deposition. This process requires the safe handling and management of pyrophoric silane gas—a gas that can ignite spontaneously when exposed to air. Silane is also the major feedstock in thin-film amorphous silicon (a-Si) PV and is often used as a coupling agent to adhere fibers to polymer materials. The a-Si/thin-film tandem segment of the PV industry also uses nitrogen trifluoride (NF_3) for reactor cleaning, which has a global warming potential 17,000 times greater than CO_2. The controlled use and production of NF_3 have been proven for specific production and end-use systems (for example, in the liquid crystal display industry), and its use in the a-Si/microcrystalline silicon PV industry will not alter the environmental benefits of PV replacing fossil fuels if best practices are adopted globally (Fthenakis et al., 2010).

The greatest concern surrounding thin-film cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) PV is potential exposure to Cd, which the U.S. Environmental Protection Agency defines as a Class B1 carcinogen (i.e., probable human carcinogen). Typical CdTe PV material contains 5 g of Cd per m^2 of module, whereas typical CIGS material (which can contain cadmium sulfide) contains less than 1 g of Cd per m^2 of module (Fthenakis and Zweibel, 2003). Although Cd is not emitted during normal module operation, small emissions could occur during manufacturing or accidental fires. However, the life-cycle Cd emissions of CdTe and CIGS PV are orders of magnitude lower than Cd emissions from the operation of fossil fuel power plants (Fthenakis, 2004; Fthenakis et al., 2005, 2008).

Not all the news about PV production and subsequent PV waste is negative. Recycling can help resolve end-of-life (cradle-to-grave) PV module issues, and the PV industry is proactively engaged in building recycling infrastructure. The technical and economic feasibility of recycling the semiconductor materials, metals, and glass from manufacturing scrap and spent PV modules has been established (Fthenakis, 2000). Furthermore, recycling can provide a significant secondary source of materials that

may be used in the production of future PV technologies, such as tellurium, indium, and germanium (Fthenakis, 2009). First Solar® (Tempe, AZ), which manufactures thin-film CdTe PV, established the industry's first comprehensive pre-funded module collection and recycling program, which the company claims will result in recycling 90% of the weight of each recovered First Solar PV module. In Europe, the PV industry has established PV Cycle, a voluntary program to recycle PV modules (PV Cycle, 2014). The United States could adopt this type of industry-wide approach to manage the large-scale recycling and management of PV materials.

The major constituents of CSP plants include glass, steel, and concrete. In addition, some CSP plants will contain a significant quantity of nitrate salt and organic heat transfer oil. All of these materials are recyclable (USDOE, 2012).

ECOLOGICAL IMPACTS

All development creates ecological and other land-use impacts. The primary impacts of solar development relate to land used for utility-scale PV and CSP. Even with the most careful land selection, the projected utility-scale solar development may have significant local land-use impacts, especially on portions of the southern United States. Solar development should be consistent with national and local land-use priorities. With regard to direct ecological impacts of solar development, these include soil disturbance, habitat fragmentation, and noise. Indirect impacts include changes in surface water quality because of soil erosion at the construction site. The specific impacts of utility-scale solar development will depend on the project location, solar technology employed, size of the development, and proximity to existing roads and transmission lines.

The potential ecological impacts in the southwestern United States are particularly important because of the large scale of solar development envisioned for this area. The Southwest supports a wide variety of plant communities and habitats, including arid and semiarid desert-scrub and shrub land, grasslands, woodlands, and savannas. The wildlife in these areas includes diverse species of amphibians, reptiles, birds, and small and large mammals. Government agencies and conservation groups have identified a significant list of species that may be affected by solar development (USDOE, 2010c).

Altering plant communities with development can strain wildlife living in or near these communities, making it more difficult to find shelter, hunt, forage, and reproduce. Fenced-in power plants can add further strain by affecting terrestrial and avian migration patterns. Aquatic species also can be affected—as can terrestrial and avian species that rely on aquatic habitats—if the water requirements of solar development result in substantial diversion of local water sources. Large areas covered by solar collectors also may affect plants and animals by interfering with natural sunlight, rainfall, and drainage. Solar equipment may provide perches for birds of prey that could affect bird and prey populations.

The potential impacts of solar development are not limited to ecological impacts. Solar development could affect a variety of activities that take place on public and private land. For example, conflicts may arise if development impacts cultural sites, or interferes with U.S. Department of Defense (DOD) activities. In addition, loss

TABLE 3.3
Albedo of Some Surface Types

Surface	Albedo (% Reflected)
Water (low sun)	10–100
Water (high sun)	3–10
Grass	16–26
Glacier ice	20–40
Deciduous forest	15–20
Coniferous forest	5–15
Old snow	40–70
Fresh snow	75–95
Sea ice	30–40
Blacktopped tarmac	5–10
Desert	25–30
Crops	15–25

of forage base could result in reduced grazing, which would disrupt the longstanding economic and cultural characteristics of ranching operations. Potential direct impacts include conversion of land to provide support services and housing for people who move to the region to support the solar development, with associated increases in roads, traffic, and penetration into previously remote areas. The additional transmission infrastructure associated with solar development could create various impacts as well.

These are merely examples of the types of impacts that may be associated with solar development. For an exhaustive discussion, see USDOE (2010c) and other detailed environmental-impact studies. Less well-studied impacts are also important and must be evaluated as solar development progresses. For example, the local and global climate effects of changes in albedo due to widespread PV and CSP deployment are not well studied. *Albedo* is the ratio between the light reflected from a surface and the total light falling on it. Albedo is a surface phenomenon—basically a radiation reflector. Albedo always has a value less than or equal to 1. An object with a high albedo, near 1, is very bright, while a body with a low albedo, near 0, is dark. For example, freshly fallen snow typically has an albedo that is between 75% and 90%; that is, 75% to 95% of the solar radiation that is incident on snow is reflected. At the other extreme, the albedo of a rough, dark surface, such as a green forest, may be as low as 5%. The albedo values of some common surfaces are listed in Table 3.3. The portion of insolation not reflected is absorbed by the Earth's surface, warming it. This means that Earth's albedo plays an important role in the Earth's radiation balance and influences the mean annual temperature and the climate on both local and global scales. One study evaluated the net balance between the greenhouse gas emissions reduction resulting from PV replacing fossil-fuel-based power generation (with PV growing to meet 50% of world energy demand in 2100) and a decrease in desert albedo due to PV module covering, concluding that the PV albedo effect would have little impact on global warming (Nemet, 2009).

With regard to solar energy production and the possible impact on global warming (climate change), note that there are no global climate change emissions associated with generating electricity from solar energy. However, there are emissions associated with other stages of the solar life-cycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. Most estimates of life-cycle emissions for photovoltaic systems are between 0.07 and 0.18 pounds of carbon dioxide equivalent per kilowatt-hour.

SOLAR ENERGY JOB HAZARDS*

Fatalities and Incidents

Solar energy workers are exposed to hazards that can result in fatalities and serious injuries. Many incidents involving falls, electrocution, severe burns from electrical shocks, and arc flashes/fires have been reported to OSHA. Some examples are given below:

- *Solar panel installer dies when he falls off a roof.* A 30-year-old solar panel installer died after he fell 45 feet off the roof of a three-story apartment building. He was part of a three-man crew working to install solar panels on a sloped roof. The worker walked backward and stepped off the roof while checking the position of some brackets. No one was wearing personal fall protection equipment and no other fall protection system was in place.
- *Solar energy technician is electrocuted.* A 34-year-old solar energy technician died after being injured at work. He was bringing a metal brace to a rooftop work site. The technician was standing on a scaffold and lifting the brace when it reached the top of the scaffold. The other end of the brace swung into a nearby high-voltage power line. The technician was shocked by the electrical current and fell 35 feet to the ground. He died the next day of injuries from the electrocution and fall.
- *Deadly skylights! Solar energy and warehouse workers killed.* A 46-year-old electrical worker and a 56-year-old warehouse worker both died after falling through skylights while working on a roof. The electrician was carrying a solar panel and tripped on the ledge of the skylight and fell backward through the skylight. The warehouse worker was on the warehouse roof repairing a broken air conditioner. It is not known exactly how the warehouse worker fell through the skylight.

Workers in the solar energy industry are potentially exposed to many of the same hazards as those who work with or around wind turbines. In addition, solar energy workers can be exposed to a variety of serious hazards, such as arc flashes (which include arc flash burn and blast hazards), electric shock, and thermal burn hazards that can cause injury and death. Solar energy employers (connecting to grid) are covered by the Electric Power Generation, Transmission, and Distribution standard

* Adapted from OSHA's *Green Job Hazards: Solar Energy*, http://osha.gov/dep/greenjobs/solar.html.

(29 CFR 1910.269) and therefore may be required to implement the safe work practices and worker training requirements of the standard. Although solar energy is a growing industry, the hazards are not unique, and OSHA has many standards that cover them. The hazards and controls that workers in the solar energy industry may encounter are provided below.

Hazards and Controls

- Falls
- Lockout/tagout
- Crane and hoist safety
- Electrical
- Thermal stress
- Personal protective equipment (PPE)

Falls*

Workers who install and/or maintain solar panels often work on roofs, use ladders and scaffolding, are in proximity of ledges and sunroofs, and are exposed to fall hazards. As more solar panels are installed on the surface of a roof, the walking area that once was available may no longer be available to workers. This may force workers to squeeze by or walk very close to skylights and/or roof hatches. Employers must make sure that skylights are guarded or that workers near skylights use personal fall protection. OSHA has different fall protection requirements for construction (installation of solar panels) and general industry (maintenance). Construction workers involved in the installation of solar panels exposed to fall distances of 6 feet or more must be protected from falls by using one of the following methods.

Guardrail Systems

Many times the nature and location of the work will dictate the form that fall protection takes. An employer who chooses to use a guardrail system must comply with the following provisions:

- The top edge height of top rails, or equivalent guardrail system members, must be between 39 and 45 inches above the walking/working level, except when conditions warrant otherwise and all other criteria are met (e.g., when employees are using stilts, the top edge height of the top rail must be increased by an amount equal the height of the stilts).
- Midrails, screens, mesh, intermediate vertical members, or equivalent intermediate structures must be installed between the top edge and the walking/working surface when there is no wall or other structure at least 21 inches high.

* Adapted from OSHA's *Green Job Hazards: Solar Energy—Falls*, http://www.osha.gov/dep/greenjobs/solar_falls.html.

    - Midrails must be midway between the top edge of the guardrail system and the walking/working level.
    - Screens and mesh must extend from the top rail to the walking/working level and along the entire opening between rail supports.
    - Intermediate members (such as balasters) between posts must be no more than 19 inches apart.
    - Other structural members (such as additional midrails or architectural panels) must be installed to leave no openings wider than 19 inches.
- Guardrail systems must be capable of withstanding at least 200 pounds of force applied within 2 inches of the top edge, in any direction and at any point along the edge, and without causing the top edge of the guardrail to deflect downward to a height less than 39 inches above the walking/working level.
- Midrails, screens, mesh, and other intermediate members must be capable of withstanding at least 150 pounds of force applied in any direction at any point along the midrail or other member.
- Guardrail systems must not have rough or jagged surfaces that would cause punctures, lacerations, or snagged clothing.
- Top rails and midrails must not cause a projection hazard by overhanging the terminal posts.

Safety Net Systems

Employers who choose to use a safety net system must comply with the following provisions:

- Safety nets must be installed as close as practicable under the surface on which employees are working, but in no case more than 30 feet below.
- When nets are used on bridges, the potential fall area must be unobstructed.
- Safety nets must extend outward from the outermost projection of the work surface as follows:

Vertical Distance from Working Level to Horizontal Plane of Net	Minimum Required Horizontal Distance of Outer Edge of Net from Edge of Working Surface
Up to 5 feet	8 feet
5 to 10 feet	10 feet
More than 10 feet	13 feet

- Safety nets must be installed with sufficient clearance to prevent contact with the surface or structures under them when subjected to an impact force equal to the drop test described below.
- Safety nets and their installations must be capable of absorbing an impact force equal to the drop test described below.
- Safety nets and safety net installations must be drop-tested at the jobsite
    - After initial installation and before being used
    - Whenever relocated
    - After major repair
    - At 6-month intervals if left in one place

- The drop test consists of a 400-pound bag of sand, 28 to 32 inches in diameter, dropped into the net from the highest surface at which employees are exposed to fall hazards, but not from less than 42 inches about that level.
- When the employer can demonstrate that it is unreasonable to perform the drop-test described above, the employer or a designated competent person shall certify that the net and net installation have sufficient clearance and impact absorption by preparing a certification record prior to the net being used as a fall protection system. The certification must include
  - Identification of the net and net installation
  - Date that it was determined that the net and net installation were in compliance
  - Signature of the person making the determination and certification
- The most recent certification records for each net and net installation must be available at the jobsite for inspection.
- Safety nets must be inspected for wear, damage, and other deterioration at least once a week and after any occurrence that could affect the integrity of the system.
- Defective nets should not be used, and defective components must be removed from service.
- Objects that have fallen into the safety net, such as scrap pieces, equipment, and tools, must be removed as soon as possible from the net and at least before the next work shift.
- Maximum mesh size must not exceed 6 inches by 6 inches. All mesh crossings must be secured to prevent enlargement of the mesh opening, which must be no longer than 6 inches, measured center-to-center.
- Each safety net, or section thereof, must have border rope for webbing with a minimum breaking strength of 5000 pounds.
- Connections between safety net panels must be as strong as integral net components and must not be spaced more 6 inches apart.

Personal Fall Arrest System

A personal fall arrest system is one option for the protection that OSHA requires for workers on construction sites who are exposed to vertical drops of 6 feet or more. Employers who choose to use a personal fall arrest system must comply with the following provisions:

- Be sure that personal fall arrest systems will, when stopping a fall,
  - Limit maximum arresting force to 1800 pounds.
  - Be rigged such that an employee can neither free fall more than 6 feet nor contact any lower level.
  - Bring an employee to a complete stop and limit maximum deceleration distance to 3.5 feet.
  - Have sufficient strength to withstand twice the potential impact energy of a worker free falling a distance of 6 feet or the free fall distance permitted by the system, whichever is less.

- Remove systems and components from service immediately if they have been subjected to fall impact, until inspected by a competent person and deemed undamaged and suitable for use.
- Promptly rescue employees in the event of a fall or ensure that they are able to rescue themselves.
- Inspect systems before each use for wear, damage, and other deterioration, and remove defective components from service.
- Do not attach fall arrest system to guardrail systems or hoists.
- Rig fall arrest systems to allow movement of the worker only as far as the edge of the walking/working surface, when used at hoist areas.

Solar panels should be lifted safely to the rooftops. Workers should never be allowed to climb ladders while carrying solar panels. Lifting equipment, such as ladder hoists, swing hoists, or truck-mounted cranes/conveyors, should be used wherever possible. Maintenance work on solar panels is generally considered to fall under OSHA's general industry standards. Such workers when exposed to fall hazards of 4 feet or more must be protected by a standard railing. If such a railing is not possible, then the workers must be protected by a fall protection device such as a personal fall arrest system or a safety net.

Lockout/Tagout*

Lockout/tagout (LOTO) refers to specific practices and procedures designed to safeguard employees from the unexpected energization or startup of machinery and equipment or from the release of hazardous energy that could occur during service or maintenance activities. Approximately 3 million workers service equipment and face the greatest risk of injury if lockout/tagout is not properly implemented. Compliance with the lockout/tagout standard prevents an estimated 120 fatalities and 50,000 injuries each year. Workers injured on the job from exposure to hazardous energy lose an average of 24 work days for recuperation. In a study conducted by the United Auto Workers, 20% of the fatalities (83 of 414) that occurred among their members between 1973 and 1995 were attributed to inadequate hazardous energy control procedures, specifically lockout/tagout procedures. Solar energy equipment can generate electrical energy and may be connected to electrical circuits. Workers may be exposed to electrical hazards from solar panels and from electrical circuits. Employers should ensure that workers, while installing or servicing solar panels, cover the solar panel, and employers should protect workers from electrical circuits. Workers performing servicing or maintenance of solar panels may be exposed to injuries from the unexpected energization or release of stored energy in the equipment. Solar energy employers may be required to follow procedures outlined in the OSHA standards 29 CFR 1910.269(d) or 29 CFR1910.147.

* Adapted from OSHA's *Green Jobs Hazards: Solar Energy—Lockout/Tagout*, http:www.osha.gov/dep/greenjobs/solar_loto.html.

Crane and Hoist Safety*

Cranes are often used during the installation and maintenance of solar panels, but fatalities and serious injuries can occur if the cranes are not inspected and used properly. Many fatalities can occur when the crane boom, load line, or load contacts power lines and shorts electricity to ground. Other incidents happen when workers are struck by the load, are caught inside the swing radius, or fail to assemble or disassemble the crane properly. There are significant safety issues to be considered, both for the operators of the diverse "lifting" devices and for workers who work near them. See OSHA's general industry standards 29 CFR 1910.179 and 29 CFR 1910.180 and construction standard 19 CFR 1926.1417 for specific crane requirements.

Electrical Safety†

Solar energy workers are potentially exposed to a variety of serious electrical hazards, such as arc flashes (which include arc flash burn and blast hazards), electrical shock, falls, and thermal burn hazards that can cause injury and death. Workers may be exposed to electric shocks and burns when hooking up the solar panels to an electric circuit. Because solar panels generate electricity, employers in the solar energy sector may be covered by the Electric Power Generation, Transmission, and Distribution standard (29 CFR 1910.269) and, therefore, may be required to implement the safe work practices and worker training requirements of the standard. Typically, solar panel installations are covered by OSHA Subpart S standards in part 1910, if they are not connected to distribution systems (i.e., a system that is supplying power to a town or more buildings) or if they are only emergency or standby nature. If solar panels supply power to a distribution system, then the provisions contained in 29 CFR 1910.269 will apply. Workers must pay attention to overhead power lines and stay at least 10 feet away from them because they carry extremely high voltage. Fatal electrocution is the main hazard, but burns and falls from elevators can occur while installing solar panels. Another hazard is from using tools and equipment that can contact power lines.

Thermal Stress‡

Solar energy workers often work in very hot weather where hazards include dehydration, heat exhaustion, heat stroke, and death. Employers should monitor employees, and workers should be trained to identify and report early symptoms of any heat-related illness. Workers may also be exposed to extreme cold weather conditions and should be protected from such conditions.

* Adapted from OSHA's *Green Job Hazards: Solar Energy—Crane and Hoist Safety*, https://www.osha.gov/dep/greenjobs/solar_crane.html.

† Adapted from OSHA's *Green Job Hazards: Solar Energy—Electrical*, http://www.osha.gov/dep/greenjobs/solar_electrical.html.

‡ Adapted from OSHA's *Green Job Hazards Solar Energy—Heat/Cold Stress,* http://www.osha.gov/dep/greenjobs/solar_heat.html.

Personal Protective Equipment*

Using personal protective equipment (PPE) is often essential, but it is generally the last line of defense after engineering controls, work practices, and administrative controls. Solar energy employers must assess their workplace to determine if hazards are present that require the use of protective equipment. Solar energy workers can be exposed to many hazards that may require the use of safety glasses, hard hats, gloves, respirators, or other personal protective equipment, and workers must use them. Electrical protective equipment must be maintained in a safe and reliable condition. They must be periodically inspected or tested.

THOUGHT-PROVOKING QUESTIONS

3.1 The sun has been described in many ways. How would you describe the sun?
3.2 Is there a difference between solar energy and solar power? Explain.
3.3 Do you feel that solar energy can eventually replace nonrenewable energy sources?

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* Adapted from OSHA's *Green Job Hazards Solar Energy—Personal Protective Equipment*, http://www.osha.gov/dep/greenjobs/solar_ppe.html.

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4 Hydropower

> Bureaus build roads into new hinterlands, then buy more hinterlands to absorb the exodus accelerated by the roads. A gadget industry pads the bumps against nature-in-the-raw; woodcraft becomes the art of using gadgets. And now, to cap the pyramid of banalities, the trailer. To him who seeks in the woods and mountains only those things obtainable from travel or golf, the present situation is intolerable. But to him who seeks something more, recreation has become a self-destructive process of seeking but never quite finding, a major frustration of mechanized society.
>
> **—Leopold (1949)**

When we speak of water and its many manifestations, we are speaking of that endless quintessential cycle that predates all other cycles. Water is our most precious natural resource; we can't survive without it. There is no more water today than there was yesterday—that is, no more this year than there was 100 million years ago. The water present today is the same water used by all the animals that ever lived, by cave dwellers, Caesar, Cleopatra, Christ, da Vinci, John Snow, Teddy Roosevelt, and the rest of us—again, there is not one drop more or one drop less of water than there has always been. This life-giving cycle, a unique blend of thermal and mechanical aspects, is dependent on solar energy and gravity (see Figure 4.1) for its existence. Nothing on Earth is truly infinite in supply, but the energy available from water sources, in practical terms, comes closest to that ideal (Spellman, 2008).

THE RACHEL RIVER*

The Rachel River, a hypothetical river system in the northwestern United States, courses its way through an area that includes a Native American reservation. The river system outfalls to the Pacific Ocean, and the headwaters begin deep and high within the Cascade Range in the state of Washington. For untold centuries, this river system provided a natural spawning area for salmon. The salmon fry thrived in the river and eventually grew the characteristic dark blotches on their bodies and transformed from fry to parr. When the time came to make their way to the sea, their bodies larger and covered with silver pigment, the salmon, now called smolt, inexorably migrated to the ocean, where they thrived until time to return to the river and spawn, about 4 years later. In spawning season, the salmon instinctively headed toward the odor generated by the Rachel River (their homing signal) and up the river to their home waters, as their life-cycle instincts demanded.

* Adapted from Spellman, F.R. and Whiting, N.E., *Environmental Science and Technology*, 2nd ed., Government Institutes, Rockville, MD, 2006.

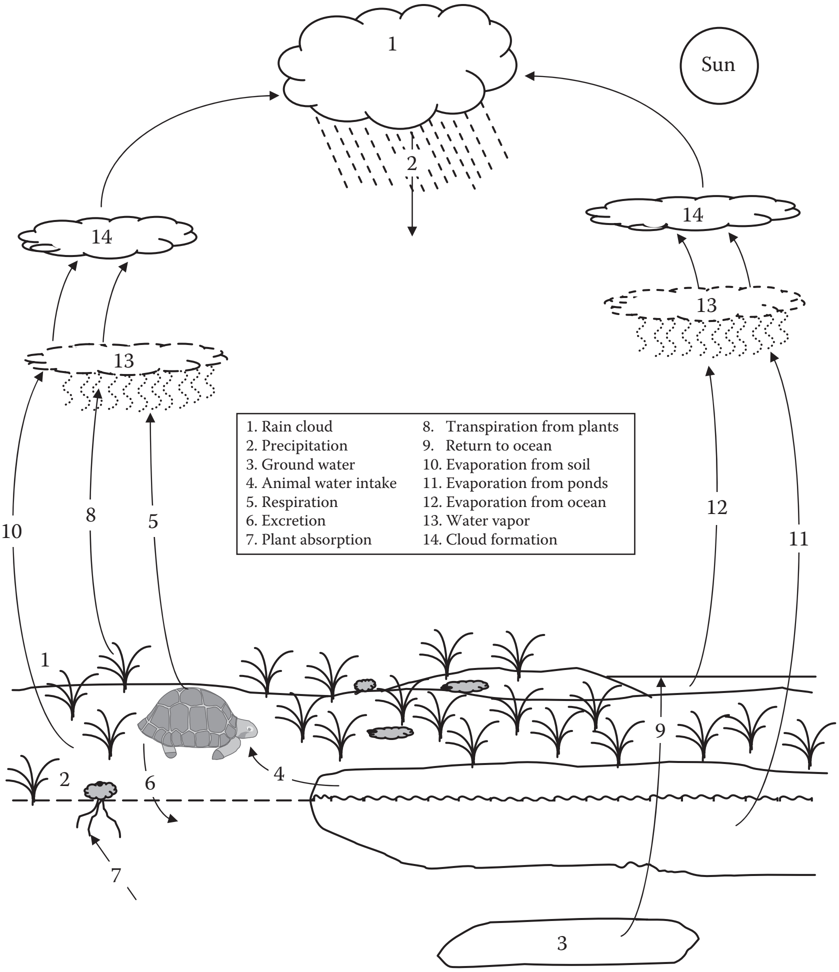

FIGURE 4.1 Water cycle. (Adapted from *Water Cycle*, AB35366, © Carolina Biological Supply Co., April 16, 1966.)

Before non-Native American settlers arrived in this pristine wilderness region, nature, humans, and salmon lived in harmony and provided for each other. Nature gave the salmon the perfect habitat; the salmon provided Native Americans with sustenance, and the Native Americans gave both their natural world and the salmon the respect they deserved.

After the settlers came to the Rachel River Valley, changes began to take place. The salmon still ran the river and humans still fed on the salmon, but the circumstances quickly changed. The settlers wanted more land, and Native Americans were forced to give way; they were either killed or forcibly moved to other places, such as reservations, while the settlers did all they could to erase Native American beliefs and cultural inheritance. The salmon still ran the streams.

After the settlers drove out the Native Americans, the salmon continued to run for a while, but more non-Native Americans continued to pour into the area. As the area became more crowded, the salmon still ran, but by now their home, their habitat, the Rachel River, had begun to show the effects of modern civilization. The prevailing philosophy was, "If we don't want it any more, we can just throw it away." The river provided a seemingly endless dump—out of the way, out of sight, out of mind. And they threw their trash, all the mountains of trash they could manufacture, into the river. The salmon still ran.

More time passed. More people moved in, and the more people that came into the area, the bigger their demands. In its natural course, sometimes the river flooded, creating problems for the settler populations. Also, everyone wanted power to maintain their modern lifestyles, and hydropower was constantly pouring down the Rachel River to the ocean. So the people built flood control systems and a dam to convert hydropower to hydroelectric power. (Funny … the Native Americans didn't have a problem with flood control. When the river rose, they broke camp and moved to higher ground. Hydroelectric power? If you don't build your life around things, you don't need electricity to make them work. With the sun, the moon, and the stars and healthy, vital land at hand, who would want hydroelectric power?)

The salmon still ran.

Building dams and flood control systems takes time, but humans, although impatient, have a way of conquering and using time (and anything else that gets in the way) to accomplish their goals, including construction projects. As the years passed, the construction moved closer to completion, and finally ended. The salmon still ran—but in reduced numbers and size. Soon local inhabitants couldn't catch the quantity and quality of salmon they had in the past. They began to ask, "Where are the salmon?"

But no one seemed to know. Obviously, the time had come to call in the scientists, the experts. The inhabitants' governing officials formed a committee, funded a study, and hired some scientists to tell them what was wrong. "The scientists will know the answer. They'll know what to do," they said, and that was partly true. Notice that they didn't try to ask the Native Americans. They also would have known what to do. The salmon had already told them.

The scientists came and studied the situation, conducted tests, tested their tests, and decided that the salmon population needed to grow. They determined that an increased population could be achieved by building a fish hatchery, which would take the eggs from spawning salmon, raise the eggs to fingerling-sized fish, release them into specially built basins, and later release them to restock the river. A lot of science goes into the operation of a fish hatchery. It can't operate successfully on its own (although Mother Nature never has a serious problem with it when left alone) but must be run by trained scientists and technicians following a proven protocol based on biological studies of salmon life cycles.

When the time was right, the salmon were released into the river—meanwhile, other scientists and engineers realized that some mechanism had to be installed in the dam to allow the salmon to swim downstream to the ocean, and the reverse, as well. In the lives of salmon (anadromous species that spend their adult lives at sea but return to freshwater to spawn), what goes downstream must go upstream. The

salmon would eventually need some way of getting back up past the dam and into their home water, their spawning grounds. So, the scientists and engineers devised and installed fish ladders in the dam so the salmon could climb the ladders, scale the dam, and return to their native waters to spawn and die.

After a few seasons, the salmon again ran strong in the Rachel River. The scientists had temporarily—and at a high financial expenditure—solved the problem. Nothing in life or in nature is static or permanent. All things change. They shift from static to dynamic, in natural cycles that defy human intervention, relatively quickly, without notice—like a dormant volcano, or the Pacific Rim tectonic plates.

After a few years, local Rachel River residents noticed an alarming trend. Studies over a 5-year period showed that no matter how many salmon were released into the river, fewer and fewer returned to spawn each season. So they called in the scientists again. And again they thought, "Don't worry. The scientists will know. They'll tell us what to do." The scientists came in, analyzed the problem, and came up with five conclusions:

1. The Rachel River is extremely polluted from both point and nonpoint sources.
2. The Rachel River Dam had radically reduced the number of returning salmon to the spawning grounds.
3. Foreign fishing fleets off the Pacific Coast were depleting the salmon.
4. Native Americans were removing salmon downstream, before they even got close to the fish ladder at Rachel River Dam.
5. A large percentage of water was being withdrawn each year from rivers for cooling machinery in local factories. Large rivers with rapid flow rates usually can dissipate heat rapidly and suffer little ecological damage unless their flow rates are sharply reduced by seasonal fluctuations. This was not the case, though, with the Rachel River. The large input of heated water from Rachel River area factories back into the slow-moving Rachel River was creating an adverse effect called *thermal pollution*. Thermal pollution and salmon do not mix. First and foremost, increased water temperatures lower the dissolved oxygen (DO) content by decreasing the solubility of oxygen in the river water. Warmer river water also causes aquatic organisms to increase their respiration rates and consume oxygen faster, increasing their susceptibility to disease, parasites, and toxic chemicals. Although salmon can survive in heated water—to a point—many other fish and organisms (the salmon's food supply) cannot. Heated discharge water from the factories also disrupts the spawning process and kills the young fry.

The scientists prepared their written findings and presented them to city officials, who read them and were initially pleased. "Ah!" they said. "Now we know why we have fewer salmon!" But what was the solution? The scientists looked at each other and shrugged. "That's not our job," they said. "Call in the environmental folks."

The salmon still ran, but not up the Rachel River to its headwaters.

Within days, the city officials hired an environmental engineering firm to study the salmon depletion problem. The environmentalists came up with the same causal conclusions as the scientists, but they also noted the political, economic, and

philosophical implications of the situation. The environmentalists explained that most of the pollution constantly pouring into the Rachel River would be eliminated when the city's new wastewater treatment plant came on line and that specific *point-source pollution* would be eliminated. They explained that the state agricultural department and their environmental staff were working with farmers along the lower river course to modify their farming practices and pesticide treatment regimes to help control the most destructive types of *nonpoint-source pollution*. The environmentalists explained that the Rachel River dam's current fish ladder was incorrectly configured but could be modified with minor retrofitting.

The environmentalists went on to explain that the overfishing by foreign fishing fleets off the Pacific Coast was a problem that the federal government was working to resolve with the governments involved. The environmentalists explained that the state of Washington and the federal government were also addressing a problem with the Native Americans fishing the downriver locations, before the salmon ever reached the dam. Both governmental entities were negotiating with the local tribes on this problem. Meanwhile, local tribes had litigation pending against the state and federal government to determine who actually owned fishing rights to the Rachel River and the salmon.

The final problem was thermal pollution from the factories, which was making the Rachel River unfavorable for spawning, decreasing salmon food supply, and killing off the young salmon fry. The environmentalists explained that to correct this problem, the outfalls from the factories would have to be changed and relocated. The environmentalists also recommended construction of a channel basin whereby the ready-to-release salmon fry could be released in a favorable environment, at ambient stream temperatures. This would give them a controlled one-way route to safe downstream locations where they could thrive until it was time to migrate to the sea.

After many debates and newspaper editorials, the city officials put the matter to a vote and voted to fund the projects needed to solve the salmon problem in the Rachel River. Some short-term projects are already showing positive signs of change, long-term projects are underway, and the Rachel River is on its way to recovery. In short, scientists are professionals who study to find *the* answer to a problem through scientific analysis and study. Their interest is in pure science. The environmentalists (also scientists) can arrive at the same causal conclusions as general scientists, but they are also able to factor in socioeconomic, political, and cultural influences, as well.

But, wait! It's not over yet. Concerns over disruption of the wild salmon gene pool by hatchery trout are drawing attention from environmentalists, conservationists, and wildlife biologists. Hatchery- or farm-raised stock of any kind is susceptible to problems caused by, among other things, a lack of free genetic mixing and the spread of disease, infection, and parasites, as well as reinforcement of negative characteristics. When escaped hatchery salmon breed with wild salmon, the genetic strain is changed and diseases can be transmitted. Many problems can arise.

Yes, many problems arise and solutions are constantly sought. When nature's natural processes are interrupted, changed, or manipulated in any way, humans need to adjust to the changes, but so does Mother Nature. The question is are the human-made changes to natural surroundings a good or bad thing? It depends. On what? It depends on your point of view.

For many, the Rachel River case study probably generates more questions than answers, because there are a number of vignettes within the account, many of which could give rise to separate case studies of their own. However, if we focus on the dam only and its implications, not only for the human inhabitants but also for the natural resources involved, environmental scientists would study the construction of such a human-made structure based on facts, science, and the pros and cons. For example, let's consider the pros and cons (USGS, 2014a).

Pros to hydroelectric power (as compared to other power-producing methods) include the following:

- Fuel is not burned, so there is minimal pollution.
- Water to run the power plant is provided free by nature.
- Hydropower plays a major role in reducing greenhouse gas emissions.
- Operations and ma intenance costs are relatively low.
- The technology is reliable and has been proven over time.
- It is renewable, because rainfall renews the water in the reservoir, so the fuel is almost always there.

Cons to hydroelectric power (as compared to other power-producing methods) include the following:

- Investment costs are high.
- Hydropower is dependent on precipitation.
- In some cases, there is an inundation of a wildlife habitat.
- In some cases, there is a loss or modification of fish habitat.
- Dams can cause fish entrainment or passage restriction (stranding).
- In some cases, there can be changes in reservoir and stream water quality.
- In some cases, local populations can be displaced.

HISTORICAL PERSPECTIVE

When we look at rushing waterfalls and rivers, we may not immediately think of electricity, but water-powered (hydroelectric) power plants are responsible for lighting many of our homes and neighborhoods. Hydropower is the harnessing of water

DID YOU KNOW?

During the 2008 presidential campaign, Barack Obama touted the prospect that investing in clean energy could produce 5 million jobs. The idea of creating jobs helped underpin the $90 billion clean-energy stimulus in 2009 and later efforts and remains a staple of administration rhetoric. The fact is that renewable energy has not been the job creator that its boosters envisioned. Although the amount of wind and solar power generated has more than doubled since President Obama took office, renewable energy jobs have not.

TABLE 4.1
History of Hydropower

Date	Hydropower Event
BCE	Hydropower was used by the Greeks more than 2000 years ago to turn water wheels for grinding wheat into flour.
Mid-1770s	French hydraulic and military engineer Bernard Forest de Belidor wrote a four-volume work describing vertical- and horizontal-axis machines.
1775	U.S. Army Corps of Engineers was founded, with establishment of a Chief Engineer for the Continental Army.
1880	Michigan's Grand Rapids Electric Light and Power Company, generating electricity by dynamo belted to a water turbine at the Wolverine Chair Factory, lit up 16 Brush-arc lamps.
1881	Niagara Falls city street lamps were powered by hydropower.
1882	World's first hydroelectric power plant began operation on the Fox River in Appleton, Wisconsin.
1886	About 45 water-powered electric plants were operating in the United States and Canada.
1887	First hydroelectric plant in the west was opened in San Bernardino, California.
1889	Two hundred electric plants in the United States used water power for some or all of their power generation.
1901	First Federal Water Power Act was passed.
1902	Bureau of Reclamation was established.
1907	Hydropower provided 15% of U.S. electrical generation.
1920	Hydropower provided 25% of U.S. electrical generation. The Federal Power Act established the Federal Power Commission with authority to issue licenses for hydro development on public lands.
1933	Tennessee Valley Authority was established.
1935	Federal Power Commission authority was extended to all hydroelectric projects built by utilities engaged in interstate commerce.
1937	Bonneville Dam, the first federal dam, began operation on the Columbia River in Oregon and Washington. The federal Bonneville Power Administration was established in the Pacific Northwest.
1940	Hydropower provided 40% of electrical generation. Conventional capacity had tripled in the United States since 1920.
1980	Conventional capacity had nearly tripled in the United States since 1900.
2003	About 10% of U.S. electricity came from hydropower. Capacity was about 80,000 MW of conventional capacity and 18,000 MW of pumped storage.

Source: EERE, *History of Hydropower*, Energy Efficiency & Renewable Energy, U.S. Department of Energy, Washington, DC, 2008 (http://www1.eere.energy.gov/windandhydro/hydro_history.html).

to perform work. The power of falling water has been used in industry for thousands of years (see Table 4.1). The Greeks used water wheels to grind wheat into flour more than 2000 years ago. In addition to grinding flour, the power of water has been used to saw wood and power textile mills and manufacturing plants.

TABLE 4.2
U.S. Energy Consumption by Energy Source (2008)

Energy Source	Energy Consumption (quadrillion Btu)
Total	99.438
Renewable	7.367
Biomass (total)	3.852
Biofuels	1.372
Waste	0.436
Wood and wood-derived fuels	2.044
Geothermal energy	0.360
Hydroelectric conventional	**2.512**
Solar thermal/PV energy	0.097
Wind energy	0.546

Source: EIA, *U.S. Energy Consumption by Energy Source*, Environmental Investigation Agency, Washington, D.C., 2007 (http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/table1.html).

The technology for using falling water to create hydroelectricity has existed for more than a century. The evolution of the modern hydropower turbine began in the mid-1700s when a French hydraulic and military engineer, Bernard Forest de Belidor, wrote a four-volume work describing the use of a vertical-axis vs. horizontal-axis machine. Water turbine development continued into the 1800s. A Brush-arc light dynamo driven by a water turbine provided theater and storefront lighting in Grand Rapids, Michigan, in 1880, and in 1881 a Brush dynamo connected to a turbine in a flour mill provided street lighting at Niagara Falls, New York. These two projects used direct-current (DC) technology.

Alternating current (AC) is used today. That breakthrough came when the electric generator was coupled to the turbine in 1882, which resulted in the world's first hydroelectric plant, located on the Fox River in Appleton, Wisconsin. The Appleton hydroelectric power plant is considered to be one of the major accomplishments of the Gilded Age (1878–1889) (Library of Congress, 2009). People across the United States soon enjoyed electricity in their homes, schools, and offices, where they were able to read by electric lamp instead of candlelight or kerosene. Today, we take electricity for granted and cannot imagine life without it.

Table 4.2 shows the energy consumption by energy source for 2008; in that year, hydropower power accounted for 2.512 quadrillion Btu. Ranging in size from small systems (100 kW to 30 MW) for a home or village to large projects (capacity greater than 30 MW) that produce electricity for utilities, hydropower plants are of three types: *impoundment*, *diversion*, and *pumped storage*. Some hydropower plants use dams, and some do not. Many dams were built for other purposes, and the hydropower function was added later. The United States has about 80,000 dams, of which only 2400 produce power. The other dams are for recreation, stock/farm ponds, flood control, water supply, and irrigation. The types of hydropower plants are described below.

Impoundment

The most common type of hydroelectric power plant is an impoundment facility. An impoundment facility, typically a large hydropower system, uses a dam to store river water in a reservoir. This type of facility works best in mountainous or hilly terrain where high dams can be built and deep reservoirs can be maintained. Potential energy available in a reservoir depends on the mass of water contained in it, as well as on overall depth of the water. Water released from the reservoir flows through a turbine and makes it spin, which in turn activates a generator that produces electricity. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level.

Diversion

A diversion (sometimes called *run-of-river*) facility channels all or a portion of the flow of a river from its natural course through a canal or penstock, and the current is used to drive a turbine. This approach may not require the use of a dam. This type of system is best suited for locations where a river drops considerably per unit of horizontal distance. The ideal location is near a natural waterfall or rapids. The chief advantage of a diversion system is the fact that, lacking a dam, it has far less impact on the environment than an impoundment facility (Gibilisco, 2007).

Pumped Storage

When demand for electricity is low, a pumped storage facility stores energy by pumping water from a lower reservoir to an upper reservoir. During periods of high electrical demand, the water is released back to the lower reservoir to generate electricity.

KEY DEFINITIONS

- *Dam facilities* have substantial water storage and a powerhouse at the base of the dam.
- *Run-of-the-river* typically features a small diversion dam that delivers water into a penstock, a pipe that delivers water to the powerhouse, which is located farther down the river.

DID YOU KNOW?

The potential energy in a specific slug or parcel of water is expressed in newton-meters (N·m). The newton is the standard unit of force, equivalent to 1 meter per second squared (1 m/s^2). This is the product of the mass of the slug in kilograms, the acceleration of gravity in meters per second squared (about 9.8 m/s^2), and the elevation of the parcel in meters (the vertical distance it falls as its energy is harnessed). The equivalent kinetic-energy unit is the joule (J), which is in effect equal to a watt-second (W·s).

- *Upstream reach* is the segment of the river above the diversion forebay or reservoir.
- *Bypass reach* is the segment of the river or stream between the diversion structure or dam and the powerhouse. Dam facilities do not have bypass reaches.
- *Downstream reach* is the segment of the river or stream below the powerhouse discharge.

HYDROPOWER BASIC CONCEPTS*

Air pressure (at sea level) = 14.7 pounds per square inch (psi)

The relationship shown above is important because our study of hydropower basics begins with air. A blanket of air many miles thick surrounds the Earth. The weight of this blanket on a given square inch of the Earth's surface will vary according to the thickness of the atmospheric blanket above that point. As shown above, at sea level the pressure exerted is 14.7 pounds per square inch (psi). On a mountaintop, air pressure decreases because the blanket is not as thick.

1 cubic foot (ft^3) of water = 62.4 lb

The relationship shown above is also important; note that both cubic feet and pounds are used to describe a volume of water. A defined relationship exists between these two methods of measurement. The specific weight of water is defined relative to a cubic foot. One cubic foot of water weighs 62.4 lb. This relationship is true only at a temperature of 4°C and at a pressure of 1 atmosphere, conditions referred to as *standard temperature and pressure* (STP). One atmosphere equals 14.7 psi at sea level, and 1 ft^3 of water contains 7.48 gal. The weight varies so little that, for practical purposes, this weight is used for temperatures ranging from 0 to 100°C. One cubic inch of water weighs 0.0362 lb. Water 1 ft deep will exert a pressure of 0.43 psi on the bottom area (12 in. × 0.0362 lb/$in.^3$). A column of water 2 ft high exerts 0.86 psi (2 ft × 0.43 psi/ft), one 10 ft high exerts 4.3 psi (10 ft × 0.43 psi/ft), and one 55 ft high exerts 23.65 psi (55 ft × 0.43 psi/ft). A column of water 2.31 ft high will exert 1.0 psi. To produce a pressure of 50 psi requires a 115.5-ft water column (50 psi × 2.31 ft/psi).

The two important points being made here are

1. 1 ft^3 of water = 62.4 lb (see Figure 4.2).
2. A column of water 2.31 ft high will exert 1.0 psi.

Another relationship is also important. As noted above, at standard temperature and pressure, 1 ft^3 of water contains 7.48 gal and weighs 62.4 lb. Thus, we can determine the weight of 1 gal of water:

$$\text{Weight of 1 gal water} = 62.4\ \text{lb/ft}^3 \div 7.48\ \text{gal/ft}^3 = 8.34\ \text{lb/gal}$$

* Adapted from Spellman, F.R., *The Science of Water*, CRC Press, Boca Raton, FL, 2008.

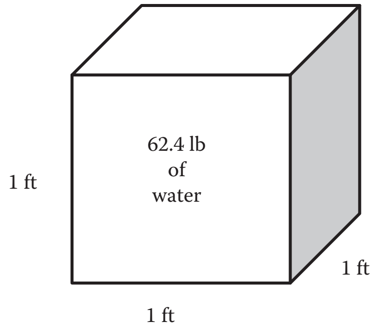

FIGURE 4.2 One cubic foot of water weighs 62.4 pounds.

Thus,

$$1 \text{ gal water} = 8.34 \text{ lb}$$

> ***Note:*** Convert cubic feet to gallons simply by multiplying the number of cubic feet by 7.48 gal/ft^3.

■ Example 4.1

Problem: Find the number of gallons in a reservoir that has a volume of 855.5 ft^3.

Solution:

$$855.5 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 6399 \text{ gal (rounded)}$$

> ***Note:*** The term *head* is used to designate water pressure in terms of the height of a column of water in feet; for example, a 10-ft column of water exerts 4.3 psi. This can be referred to as 4.3-psi pressure or 10 feet of head.

Stevin's Law

Stevin's law deals with water at rest. Specifically, it states: "The pressure at any point in a fluid at rest depends on the distance measured vertically to the free surface and the density of the fluid." Stated as a formula, this becomes

$$p = w \times h \tag{4.1}$$

where

p = Pressure in pounds per square foot (lb/ft^2, or psf).
w = Density in pounds per cubic foot (lb/ft^3).
h = Vertical distance in feet.

■ Example 4.2

Problem: What is the pressure at a point 18 ft below the surface of a reservoir?

Solution: To calculate this, we must know that the density (w) of the water is 62.4 lb/ft^3.

$$p = w \times h = 62.4\ lb/ft^3 \times 18\ ft = 1123\ lb/ft^2\ (psf)$$

Water practitioners generally measure pressure in pounds per square *inch* rather than pounds per square *foot*; to convert, divide by 144 $in.^2/ft^2$ (12 in. × 12 in. = 144 $in.^2$):

$$p = 1123\ lb/ft^2 \div 144\ in.^2/ft^2 = 7.8\ lb/in.^2$$

Properties of Water

Table 4.3 shows the relationships among temperature, specific weight, and the density of water.

Density and Specific Gravity

When we say that iron is heavier than aluminum, we say that iron has greater density than aluminum. In practice, what we are really saying is that a given volume of iron is heavier than the same volume of aluminum.

Note: What is density? *Density* is the *mass per unit volume* of a substance.

Suppose you had a tub of lard and a large box of cold cereal, each having a mass of 600 grams. The density of the cereal would be much less than the density of the lard because the cereal occupies a much larger volume than the lard occupies. The density of an object can be calculated by using the formula:

TABLE 4.3
Water Properties (Temperature, Specific Weight, and Density)

Temperature (°F)	Specific Weight (lb/ft^3)	Density ($slugs/ft^3$)	Temperature (°F)	Specific Weight (lb/ft^3)	Density ($slugs/ft^3$)
32	62.4	1.94	130	61.5	1.91
40	62.4	1.94	140	61.4	1.91
50	62.4	1.94	150	61.2	1.90
60	62.4	1.94	160	61.0	1.90
70	62.3	1.94	170	60.8	1.89
80	62.2	1.93	180	60.6	1.88
90	62.1	1.93	190	60.4	1.88
100	62.0	1.93	200	60.1	1.87
110	61.9	1.92	210	59.8	1.86
120	61.7	1.92			

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \tag{4.2}$$

Perhaps the most common measures of density are pounds per cubic foot (lb/ft^3) and pounds per gallon (lb/gal):

- 1 ft^3 of water weighs 62.4 lb; density = 62.4 lb/ft^3.
- 1 gal of water weighs 8.34 lb; density = 8.34 lb/gal.

The density of dry material, such as cereal, lime, soda, or sand, is usually expressed in pounds per cubic foot. The density of a liquid, such as liquid alum, liquid chlorine, or water, can be expressed either as pounds per cubic foot or as pounds per gallon. The density of a gas, such as chlorine gas, methane, carbon dioxide, or air, is usually expressed in pounds per cubic foot. As shown in Table 4.3, the density of a substance such as water changes slightly as the temperature of the substance changes. This occurs because substances usually increase in volume by expanding as they become warmer. Because of this expansion with warming, the same weight is spread over a larger volume, so the density is lower when a substance is warm rather than when it is cold.

Note: What is specific gravity? Specific gravity is the weight (or density) of a substance compared to the weight (or density) of an equal volume of water. The specific gravity of water is 1.

This relationship is easily seen when a cubic foot of water, which weighs 62.4 lb, is compared to a cubic foot of aluminum, which weighs 178 lb. Aluminum is 2.7 times as heavy as water. It is not that difficult to find the specific gravity of a piece of metal. All you have to do is weigh the metal in air, then weigh it under water. Its loss of weight is the weight of an equal volume of water. To find the specific gravity, divide the weight of the metal by its loss of weight in water:

$$\text{Specific gravity} = \frac{\text{Weight of substance}}{\text{Weight of equal volume of water}} \tag{4.3}$$

■ Example 4.3

Problem: Suppose a piece of metal weighs 150 lb in air and 85 lb under water. What is the specific gravity?

Solution:

$$150 \text{ lb} - 85 \text{ lb} = 65 \text{ lb loss of weight in water}$$

$$\text{Specific gravity} = 150 \div 65 = 2.3$$

DID YOU KNOW?

In a calculation of specific gravity, it is *essential* that the densities be expressed in the same units.

The specific gravity of water is 1, which is the standard, the reference against which all other liquid or solid substances are compared. Specifically, any object that has a specific gravity greater than 1 will sink in water (e.g., rocks, steel, iron, grit, floc, sludge). Substances with a specific gravity of less than 1 will float (e.g., wood, scum, gasoline). Considering the total weight and volume of a ship, its specific gravity is less than 1; therefore, it can float. The most common use of specific gravity in water operations is in gallon-to-pound conversions. In many cases, the liquids being handled have a specific gravity of 1 or very nearly 1 (between 0.98 and 1.02), so a value of 1 may be used in the calculations without introducing significant error. For calculations involving a liquid with a specific gravity of less than 0.98 or greater than 1.02, however, the conversions from gallons to pounds must consider specific gravity. The technique is illustrated in the following example.

■ Example 4.4

Problem: A basin contains 1455 gal of a liquid. If the specific gravity of the liquid is 0.94, how many pounds of liquid are in the basin?

Solution: Normally, for a conversion from gallons to pounds, we would use the factor 8.34 lb/gal (the density of water) if the specific gravity of the substance is between 0.98 and 1.02; in this instance, however, the substance has a specific gravity outside this range, so the 8.34 factor must be adjusted. Multiply 8.34 lb/gal by the specific gravity to obtain the adjusted factor:

$$8.34 \text{ lb/gal} \times 0.94 = 7.84 \text{ lb/gal (rounded)}$$

Then convert 1455 gal to pounds using the correction factor:

$$1455 \text{ gal} \times 7.84 \text{ lb/gal} = 11{,}407 \text{ lb (rounded)}$$

Force and Pressure

Water exerts force and pressure against the walls of its container, whether it is stored in a tank or flowing in a pipeline. Force and pressure are different, although they are closely related. Force and pressure are defined below. Force is the push or pull influence that causes motion. In the English system, force and weight are often used in the same way. The weight of 1 ft^3 of water is 62.4 lb. The force exerted on the bottom of a 1-ft cube is 62.4 lb (see Figure 4.2). If we stack two 1-ft cubes on top of one another, the force on the bottom will be 124.8 lb. Pressure is the force per unit of area. In equation form, this can be expressed as:

$$P = \frac{F}{A} \tag{4.4}$$

where:

P = Pressure.
F = Force.
A = Area over which the force is distributed.

Pounds per square inch (lb/in.^{2} or psi) or pounds per square foot (lb/ft^2 or psf) are commonly used to express pressure. The pressure on the bottom of our 1-ft cube is 62.4 lb/ft^2 (see Figure 4.2). It is normal to express pressure in pounds per square inch. This is easily accomplished by determining the weight of 1 in.^{2} of a 1-ft cube. If we have a cube that is 12 in. on each side, the number of square inches on the bottom surface of the cube is 12 × 12 = 144 in.^{2}. Dividing the weight by the number of square inches determines the weight on each square inch:

$$\text{Pounds per square inch (psi)} = \frac{62.4 \text{ lb}}{144 \text{ in.}^2} = 0.433 \text{ psi}$$

This is the weight of a column of water 1 in. square and 1 ft tall. If the column of water were 2 ft tall, the pressure would be 2 ft × 0.433 psi/ft = 0.866.

Note: 1 ft of water = 0.433 psi.

With this information, feet of head can be converted to psi by multiplying the feet of head times 0.433 psi/ft.

■ Example 4.5

Problem: A tank is mounted at a height of 90 ft. Find the pressure at the bottom of the tank.

Solution:

$$90 \text{ ft} \times 0.433 \text{ psi/ft} = 39 \text{ psi (rounded)}$$

Note: To convert psi to feet, divide the psi by 0.433 psi/ft.

■ Example 4.6

Problem: Find the height of water in a tank if the pressure at the bottom of the tank is 22 psi.

Solution:

$$\text{Height} = 22 \text{ psi} \div 0.433 \text{ psi/ft} = 51 \text{ ft (rounded)}$$

DID YOU KNOW?

One of the problems encountered in a hydraulic system is storing the liquid. Unlike air, which is readily compressible and is capable of being stored in large quantities in relatively small containers, a liquid such as water cannot be compressed. It is not possible to store a large amount of water in a small tank; 62.4 lb of water occupies a volume of 1 cubic foot, regardless of the pressure applied to it.

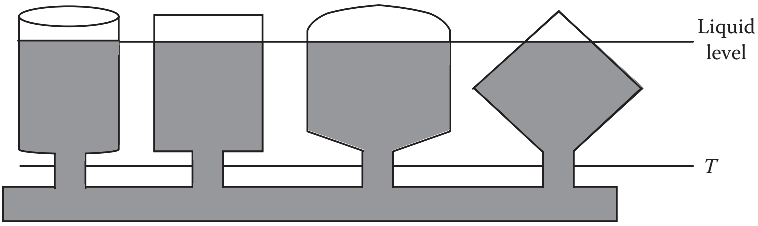

FIGURE 4.3 Hydrostatic pressure.

Hydrostatic Pressure

Figure 4.3 shows a number of differently shaped, connected, open containers of water. Note that the water level is the same in each container, regardless of the shape or size of the container. This occurs because pressure is developed, within water (or any other liquid), by the weight of the water above. If the water level in any one container is momentarily higher than that in any of the other containers, the higher pressure at the bottom of this container would cause some water to flow into the container having the lower liquid level. In addition, the pressure of the water at any level (such as line *T*) is the same in each of the containers. Pressure increases because of the weight of the water. The farther down from the surface, the more pressure is created. This illustrates that the *weight*, not the volume, of water contained in a vessel determines the pressure at the bottom of the vessel. Some important principles that always apply for hydrostatic pressure include the following (Nathanson, 1997):

1. The pressure depends only on the depth of water above the point in question (not on the water surface area).
2. The pressure increases in direct proportion to the depth.
3. The pressure in a continuous volume of water is the same at all points that are at the same depth.
4. The pressure at any point in the water acts in all directions at the same depth.

Head

Head is defined as the vertical distance the water must be lifted from the supply tank to the discharge, or as the height a column of water would rise due to the pressure at its base. A perfect vacuum plus atmospheric pressure of 14.7 psi would lift the water 34 ft. If the top of the sealed tube is open to the atmosphere and the reservoir is enclosed, the pressure in the reservoir is increased; the water will rise in the tube. Because atmospheric pressure is essentially universal, we usually ignore the first 14.7 psi of actual pressure measurements and measure only the difference between the water pressure and the atmospheric pressure; we call this *gauge pressure*. Water in an open reservoir, for example, is subjected to the 14.7 psi of atmospheric pressure, but subtracting this 14.7 psi leaves a gauge pressure of 0 psi. This shows that the water would rise 0 ft above the reservoir surface. If the gauge pressure in a water main is 120 psi, the water would rise in a tube connected to the main:

$$120 \text{ psi} \times 2.31 \text{ ft/psi} = 277 \text{ ft (rounded)}$$

Total Dynamic Head (Total System Head)

The total dynamic head includes the vertical distance the liquid must be lifted (*static head*), the loss to friction (*friction head*), and the energy required to maintain the desired velocity (*velocity head*):

$$\text{Total dynamic head} = \text{Static head} + \text{Friction head} + \text{Velocity head} \tag{4.5}$$

Static Head

Static head is the actual vertical distance the liquid must be lifted:

$$\text{Static head} = \text{Discharge elevation} - \text{Supply elevation} \tag{4.6}$$

■ Example 4.7

Problem: A supply tank is located at elevation 118 ft. The discharge point is at elevation 215 ft. What is the static head in feet?

Solution:

$$\text{Static head} = 215\text{ ft} - 118\text{ ft} = 97\text{ ft}$$

Friction Head

Friction head is the equivalent distance of the energy that must be supplied to overcome friction. Engineering references include tables showing the equivalent vertical distances for various sizes and types of pipes, fittings, and valves. The total friction head is the sum of the equivalent vertical distances for each component. For friction head,

$$\text{Friction head (ft)} = \text{Energy losses due to friction} \tag{4.7}$$

Velocity Head

Velocity head is the equivalent distance of the energy consumed in achieving and maintaining the desired velocity in the system:

$$\text{Velocity head (ft)} = \text{Energy losses to maintain velocity} \tag{4.8}$$

Pressure and Head

The pressure exerted by water is directly proportional to its depth or head in the pipe, tank, or channel. If the pressure is known, the equivalent head can be calculated as follows:

$$\text{Head (ft)} = \text{Pressure (psi)} \times 2.31\text{ (ft/psi)} \tag{4.9}$$

■ Example 4.8

Problem: The pressure gauge on the discharge line from the influent pump reads 72.3 psi. What is the equivalent head in feet?

Solution:

$$\text{Head} = 72.3 \times 2.31 \text{ ft/psi} = 167 \text{ ft}$$

Head and Pressure

If the head is known, the equivalent pressure can be calculated as follows:

$$\text{Pressure (psi)} = \frac{\text{Head (ft)}}{2.31 \text{ ft/psi}} \tag{4.10}$$

■ Example 4.9

Problem: A tank is 22 ft deep. What is the pressure in psi at the bottom of the tank when it is filled with water?

Solution:

$$\text{Pressure} = \frac{22 \text{ ft}}{2.31 \text{ ft/psi}} = 9.52 \text{ psi (rounded)}$$

Flow and Discharge Rates: Water in Motion

The study of fluid flow is much more complicated than that of fluids at rest, but it is important to have an understanding of these principles because the water used in hydropower applications is nearly always in motion (e.g., the water is used to propel turbine blades). *Discharge* (or flow) is the quantity of water passing a given point in a pipe or channel during a given period. Stated another way for open channels, the flow rate through an open channel is directly related to the velocity of the liquid and the cross-sectional area of the liquid in the channel:

$$Q = A \times V \tag{4.11}$$

where:

Q = Flow, or discharge in cubic feet per second (cfs).
A = Cross-sectional area of the pipe or channel (ft^2).
V = Water velocity in feet per second (fps or ft/s).

■ Example 4.10

Problem: A channel is 6 ft wide, and the water depth is 3 ft. The velocity in the channel is 4 fps. What is the discharge or flow rate in cubic feet per second?

Solution:

$$\text{Flow} = 6 \text{ ft} \times 3 \text{ ft} \times 4 \text{ ft/s} = 72 \text{ cfs}$$

Discharge or flow can be recorded as gal/day (gpd), gal/min (gpm), or cubic feet per second (cfs). Flows treated by many hydropower systems are large and are often expressed in million gallons per day (MGD). The discharge or flow rate can be converted from cfs to other units such as gpm or MGD by using appropriate conversion factors.

■ Example 4.11

Problem: A 12-in.-diameter pipe has water flowing through it at 10 fps. What is the discharge in (a) cfs, (b) gpm, and (c) MGD?

Solution: Before we can use the basic formula, we must determine the area (A) of the pipe. The formula for the area of a circle is

$$\text{Area } (A) = \pi \times (D^2/4) = \pi \times r^2 \tag{4.12}$$

where

π = Constant value 3.14159, or simply 3.14.
D = Diameter of the circle (ft).
r = Radius of the circle (ft).

Therefore, the area of the pipe is

$$A = \pi \times (D^2/4) = 3.14 \times (1 \text{ ft}^2/4) = 0.785 \text{ ft}^2$$

(a) Now we can determine the discharge in cfs:

$$Q = V \times A = 10 \text{ fps} \times 0.785 \text{ ft}^2 = 7.85 \text{ ft}^3\text{/s (cfs)}$$

(b) We need to know that 1 cfs is 449 gpm, so 7.85 cfs × 449 gpm/cfs = 3525 gpm (rounded).

(c) Finally, 1 million gallons per day is 1.55 cfs, so

$$7.85 \text{ cfs} \div 1.55 \text{ cfs/MGD} = 5.06 \text{ MGD}$$

Area and Velocity

The *law of continuity* states that the discharge at each point in a pipe or channel is the same as the discharge at any other point (if water does not leave or enter the pipe or channel). That is, under the assumption of steady-state flow, the flow that enters the pipe or channel is the same flow that exits the pipe or channel. In equation form, this becomes:

$$Q_1 = Q_2 \quad \text{or} \quad A_1V_1 = A_2V_2 \tag{4.13}$$

■ Example 4.12

Problem: A pipe 12 inches in diameter is connected to a 6-in.-diameter pipe. The velocity of the water in the 12-in. pipe is 3 fps. What is the velocity in the 6-in. pipe?

Solution: Using the equation $A_1V_1 = A_2V_2$, we need to determine the area of each pipe:

$$\text{Area } (A) = \pi \times (D^2/4)$$

$$\text{12-in. pipe area} = 3.14 \times (1 \text{ ft}^2/4) = 0.785 \text{ ft}^2$$

$$\text{6-in. pipe area} = 3.14 \times (0.5 \text{ ft}^2/4) = 0.196 \text{ ft}^2$$

The continuity equation now becomes:

$$0.785 \text{ ft}^2 \times 3 \text{ ft/s} = 0.196 \text{ ft}^2 \times V_2$$

Solving for V_2:

$$V_2 = \frac{0.785 \text{ ft}^2 \times 3 \text{ ft/s}}{0.196 \text{ ft}^2} = 12 \text{ ft/s (fps)}$$

Pressure and Velocity

In a closed pipe flowing full (under pressure), the pressure is indirectly related to the velocity of the liquid.

$$\text{Velocity}_1 \times \text{Pressure}_1 = \text{Velocity}_2 \times \text{Pressure}_2 \quad (4.14)$$

or

$$V_1P_1 = V_2P_2$$

Piezometric Surface and Bernoulli's Theorem

The volume of water flowing past any given point in the pipe or channel per unit time is called the *flow rate* or *discharge*—or just *flow*. The *continuity of flow* and the *continuity equation* have been discussed (see Equation 4.13). Along with the continuity of flow principle and continuity equation, the law of conservation of energy, piezometric surface, and Bernoulli's theorem (or principle) are also important to our study of water hydraulics.

Conservation of Energy

Many of the principles of physics are important to the study of hydraulics. When applied to problems involving the flow of water, few of the principles of physical science are more important and useful to us than the *law of conservation of energy*. Simply, the law of conservation of energy states that energy can be neither created nor destroyed, but it can be converted from one form to another. In a given closed system, the total energy is constant.

Energy Head

Hydraulic systems have two types of energy—kinetic and potential—and they have three forms of mechanical energy—potential energy due to elevation, potential energy due to pressure, and kinetic energy due to velocity. Energy has the

units of foot pounds (ft-lb). It is convenient to express hydraulic energy in terms of *energy head* in feet of water. This is equivalent to foot-pounds per pound of water (ft-lb/lb = ft).

Energy Available

Energy available is directly proportional to flow rate and to the hydraulic head. As mentioned, the head is equivalent to stored potential energy. This is shown as

$$\text{Head} = m \times g \times h$$

where

m = Mass of water.
g = Acceleration due to gravity (can be taken as 10 m/s^2 in most applications).
h = Head difference.

The diameter of a pipe must be large enough to handle the volume of water flowing. Friction in the pipes will reduce the effective head of water so larger diameters are used, although cost is a factor. Ideally, the pipes should narrow as they proceed downhill; however, friction losses are highest where the velocity is highest, so usually the pipe diameter changes very little. Friction losses in piping are classified as either major head loss or minor head loss (Tovey, 2005).

Major Head Loss

Major head loss consists of pressure decreases along the length of pipe caused by friction created as water encounters the surfaces of the pipe. It typically accounts for most of the pressure drop in a pressurized or dynamic water system. The components that contribute to major head loss are roughness, length, diameter, and velocity:

- *Roughness*—Even when new, the interior surfaces of pipes are rough. The roughness varies, of course, depending on pipe material, corrosion (tuberculation and pitting), and age. Because normal flow in a water pipe is turbulent, the turbulence increases with pipe roughness, which, in turn, causes pressure to drop over the length of the pipe.
- *Pipe length*—With every foot of pipe length, friction losses occur. The longer the pipe, the greater the head loss. Friction loss because of pipe length must be factored into head loss calculations.
- *Pipe diameter*—Generally, small-diameter pipes have more head loss than large-diameter pipes. In large-diameter pipes, less of the water actually touches the interior surfaces of the pipe (thus encountering less friction) than in a small-diameter pipe.
- *Water velocity*—Turbulence in a water pipe is directly proportional to the speed (or velocity) of the flow; thus, the velocity head also contributes to head loss.

DID YOU KNOW?

For the same diameter pipe, when flow increases, head loss increases.

Calculating Major Head Loss

Darcy, Weisbach, and others developed the first practical equation used to determine pipe friction in about 1850. The formula now known as the *Darcy–Weisbach* equation for circular pipes is

$$h_f = f \frac{LV^2}{D^2 g} \tag{4.15}$$

In terms of the flow rate (Q), the equation becomes

$$h_f = \frac{8fLQ^2}{\pi^2 g D^5} \tag{4.16}$$

where

h_f = Head loss (ft).
f = Coefficient of friction.
L = Length of pipe (ft).
Q = Flow rate (ft^3/s).
D = Diameter of pipe (ft).
g = Acceleration due to gravity (32.2 ft/s^2).

The Darcy–Weisbach formula was meant to apply to the flow of any fluid, and into this friction factor was incorporated the degree of roughness and an element called the *Reynold's number*, which is based on the viscosity of the fluid and the degree of turbulence of flow. The Darcy–Weisbach formula is used primarily for determining head loss calculations in pipes. For open channels, the *Manning equation* was developed during the later part of the 19th century. Later, this equation was used for both open channels and closed conduits.

In the early 1900s, a more practical equation, the *Hazen–Williams* equation, was developed for use in making calculations related to water pipes and wastewater force mains:

$$Q = 0.435 \times C \times D^{2.63} \times S^{0.54} \tag{4.17}$$

where

Q = Flow rate (ft^3/s).
C = Coefficient of roughness (C decreases with roughness).
D = Hydraulic radius R (ft).
S = Slope of energy grade line (ft/ft).

C Factor

The C factor, as used in the Hazen–Williams formula, designates the coefficient of roughness. C does not vary appreciably with velocity, and by comparing pipe types and ages it includes only the concept of roughness, ignoring fluid viscosity and

TABLE 4.4
***C* Factors**

Type of Pipe	*C* Factor
Asbestos cement	140
Brass	140
Brick sewer	100
Cast iron	
10 years old	110
20 years old	90
Ductile iron (cement lined)	140
Concrete or concrete lined	
Smooth, steel forms	140
Wooden forms	120
Rough	110
Copper	140
Fire hose (rubber lined)	135
Galvanized iron	120
Glass	140
Lead	130
Masonry conduit	130
Plastic	150
Steel	
Coal-tar enamel lined	150
New unlined	140
Riveted	110
Tin	130
Vitrified	120
Wood stave	120

Source: Adapted from Lindeburg, M.R., *Civil Engineering Reference Manual*, 4th ed., Professional Publications, San Carlos, CA, 1986.

Reynold's number. *C* factor values have been established for various types of pipe (see Table 4.4). Generally, the *C* factor decreases by one with each year of pipe age. Flow for a newly designed system is often calculated with a *C* factor of 100, based on averaging it over the life of the pipe system.

DID YOU KNOW?

A high *C* factor means a smooth pipe. A low *C* factor means a rough pipe.

DID YOU KNOW?

An alternative to calculating the Hazen–Williams formula, called an *alignment chart*, has become quite popular for fieldwork. The alignment chart can be used with reasonable accuracy.

Slope

Slope is defined as the head loss per foot. In open channels, where the water flows by gravity, slope is the amount of incline of the pipe and is calculated as feet of drop per foot of pipe length (ft/ft). Slope is designed to be just enough to overcome frictional losses, so the velocity remains constant, the water keeps flowing, and solids will not settle in the conduit. In piped systems, where pressure loss for every foot of pipe is experienced, slope is not provided by slanting the pipe but instead by pressure added to overcome friction.

Minor Head Loss

In addition to the head loss caused by friction between the fluid and the pipe wall, losses also are caused by turbulence created by obstructions (i.e., valves and fittings of all types) in the line, changes in direction, and changes in flow area.

Reservoir Stored Energy

A major component of a hydroelectric dam is the area behind the dam, its reservoir. The water temporarily stored there is called *gravitational potential energy*. The water is stored above the rest of the dam facility so gravity can carry the water down to the turbines. Because this higher altitude is not where the water would naturally be, the water is considered to be at an altered equilibrium. The result is stored energy of position, or gravitational potential energy. The water has the potential to do work because of the position it is in. As shown in Figure 4.4, gravity will force the water to fall to a lower position through the intake and the control gate. When the control gate is opened, the water from the reservoir moves through the intake and becomes translational kinetic energy as it falls through the next main part of the system, the penstock. *Translational kinetic energy* is the energy due to motion from one location to another. The water moves (falls) from the reservoir through the long shaft of the penstock toward the turbines, where the kinetic energy becomes mechanical energy. The force of the water is used to turn the turbines, which turn the generator shaft. The generators convert the energy of water into electricity and then step-up transformers increase the voltage produced to higher voltage levels.

DID YOU KNOW?

In practice, if minor head loss is less than 5% of the total head loss, it is usually ignored.

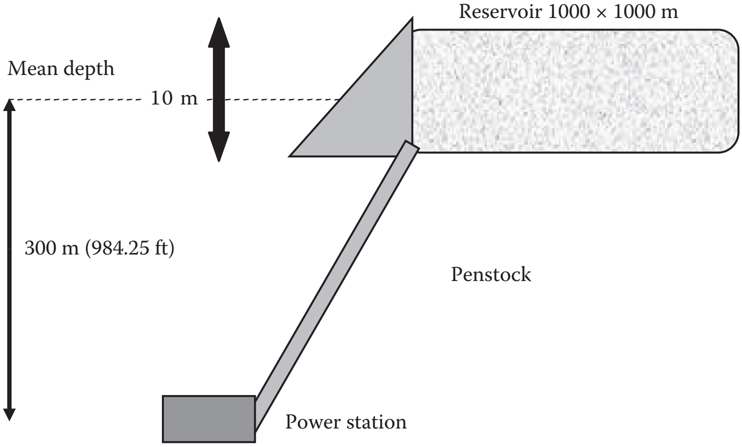

FIGURE 4.4 Schematic representation of a hydropower station. (Adapted from Tovey, N.K., *ENV-2E02 Energy Resources (2004–2005)*, University of East Anglia, Norwich, UK, 2005.)

Because the potential energy stored in the reservoir is converted into kinetic energy at the inlet to the water turbine, we can equate:

$$m \times g \times h = mV^2 \tag{4.18}$$

where:
- m = Mass of water.
- g = Acceleration due to gravity (can be taken as 10 m/s^2 in most applications).
- h = Head difference.
- V = Velocity of water at the inlet.

■ Example 4.13*

Problem: A reservoir has an area of 1 km^2, and the difference between the crest of the dam and the inlet to a hydro station is 10 m (see Figure 4.4). The station runs at an overall efficiency of 80% and is situated 305 m below the crest of the dam. The rainfall is 1000 mm per annum, the catchment area of the reservoir is 10 times the area of the reservoir, and the run is 50%. What should the rated output of the turbine be if its maximum output is designed to be 5 times the mean output at the site? What is the maximum time the station could operate at full power during a sustained drought?

Solution: Mean head between maximum and minimum levels = 305 – 10/2 = 300 m. Average annual flow into the reservoir is equal to 50% of 10 times the area multiplied by the rainfall:

$$\text{Average annual flow} = 0.5 \times 10 \times 1000 \times 1000 \times 1 = 5{,}000{,}000 \text{ m}^3$$

* Adapted from Tovey, N.K., *ENV-2E02 Energy Resources (2004–2005)*, University of East Anglia, Norwich, UK, 2005, p. 109.

$$\text{Mean energy per annum at 80\% efficiency} = m \times g \times h \times 0.8$$
$$= 5{,}000{,}000 \times 1000 \times 10 \times 300 \times 0.8$$
$$= 12{,}000{,}000 \text{ MJ}$$

$$\text{Rated output (i.e., mean power)} = \frac{12{,}000{,}000}{60 \times 60 \times 24 \times 365} = 0.381 \text{ MW}$$

So, maximum power out = 5 × 0.381 = 190 MW, and the time at maximum power assuming the reservoir falls by 10 m is

$$\text{Days} = \frac{\text{Area} \times \text{Depth} \times \text{Density} \times g \times h \times 0.8}{\text{Maximum power}}$$
$$= \frac{1000 \times 1000 \times 10 \times 1000 \times 300 \times 0.8}{1{,}900{,}000 \times 60 \times 60 \times 24}$$
$$= 146.2 \text{ days}$$

Hydroturbines

The two main types of hydroturbines are *impulse* and *reaction* (EERE, 2008). The type of hydropower turbine chosen for a project is based on the height of standing water—referred to as *head*—and the flow, or volume of water, at the site. Cost, efficiency desired, and how deep the turbine must be set are other deciding factors. A cutaway view of a hydroturbine, shafting, and generator connection is provided in Figure 4.5, and a typical turbine blade is shown in Figure 4.6. Figure 4.7 shows the generator end of installed turbines, Figure 4.8 shows the Glen Canyon Dam, and Figure 4.9 shows the Grand Coulee Dam spillway.

Impulse Turbine

The impulse turbine uses the velocity of the water to move the runner and discharges to atmospheric pressure. The water stream hits each bucket on the runner. There is no suction on the down side of the turbine, and water flows out of the bottom of the turbine housing after hitting the runner. An impulse turbine is generally suitable for high-head, low-flow applications.

Reaction Turbine

A reaction turbine develops power from the combined action of pressure and moving water. The runner is placed directly in the water stream flowing over the blades rather than striking each individually. Reaction turbines are generally used for sites with lower head and higher flows than compared with impulse turbines.

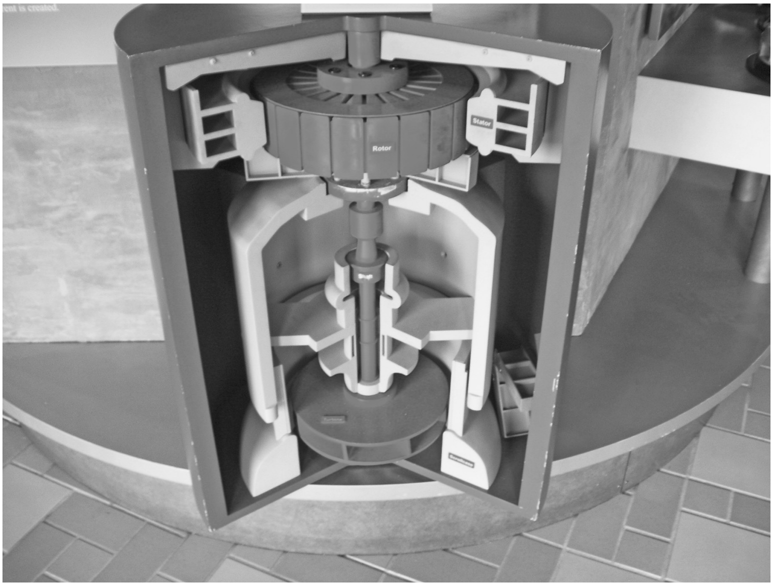

FIGURE 4.5 Cutaway view of a hydroturbine, shafting, and generator (Grand Coulee Dam, Columbia River, Washington).

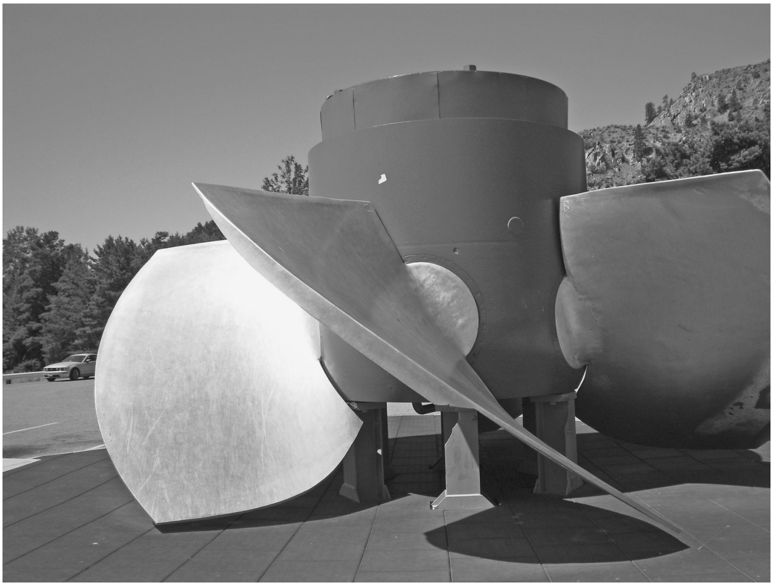

FIGURE 4.6 Turbine blade from the Rocky Reach Dam on the Columbia River in Washington.

FIGURE 4.7 Generator end of a hydroturbine assembly at the Rocky Reach Dam on the Columbia River in Washington.

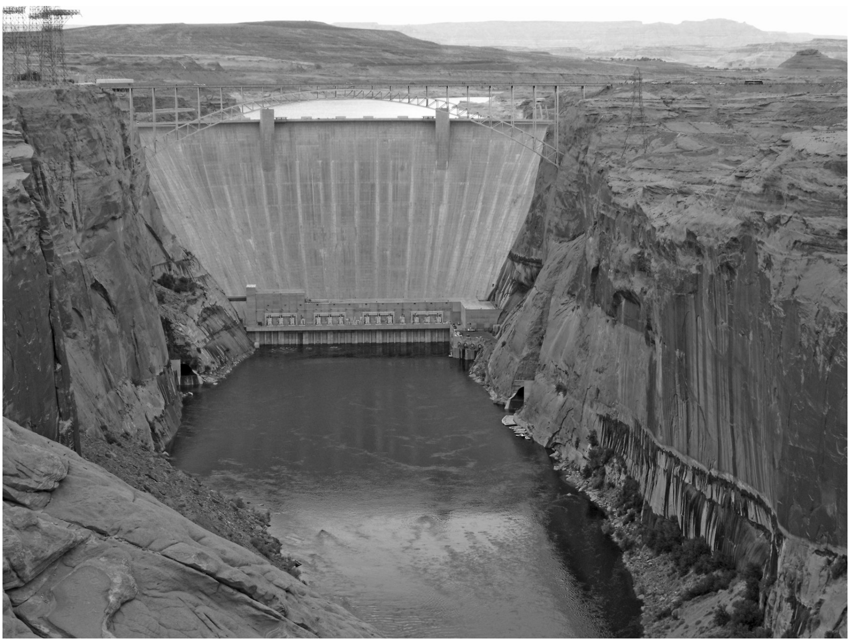

FIGURE 4.8 Glen Canyon Dam on the Colorado River in Arizona.

FIGURE 4.9 The dam and spillway of the Grand Coulee Dam on the Columbia River in Washington.

ADVANCED HYDROPOWER TECHNOLOGY

The U.S. Department of Energy (USDOE, 2008) and its associated technical activities support the development of technologies that will enable existing hydropower facilities to generate more electricity with less environmental impact. This will be done by (1) developing new turbine systems that have improved overall performances; (2) developing new methods to optimize hydropower operations at the unit, plant, and reservoir system levels; and (3) conducting research to improve the effectiveness of the environmental mitigation practices required at hydropower projects.

The main objective of its research into advanced hydropower technology is to develop new system designs and operation modes that will enable both better environmental performance and competitive generation of electricity. The products of USDOE research will allow hydropower projects to generate cleaner electricity, and USDOE-sponsored projects will develop new equipment and operational techniques to optimize water-use efficiency, increase generation, and improve environmental performance and mitigation practices at existing plants. Ongoing research efforts contributing to the success of these objectives will enable up to a 10% increase in the hydropower generation at existing dams; these objectives include the following:

- Test a new generation of large turbines in the field to demonstrate that these turbines are commercially viable, compatible with today's environmental standards, and capable of balancing environmental, technical, operational, and cost considerations.

- Develop new tools to improve water use efficiency and operations optimization within hydropower units, plants, and river systems with multiple hydropower facilities.
- Identify improved practices that can be applied at hydropower plants to mitigate for environmental effects of hydro development and operation.

Hydropower Generation: Dissolved Oxygen Concerns

The benefits derived from the use of hydropower include: (1) it is a clean fuel source; (2) it is a fuel source that is domestically supplied; (3) it relies on the water cycle and thus is a renewable power source; (4) it is generally available as needed; (5) it creates reservoirs that offer a variety of recreational opportunities, such as fishing, swimming, and boating; and (6) it creates a supply of water where needed and assists in flood control. Many of these benefits are well known and often taken for granted.

Coins are two sided, of course; that is, the good side of anything is generally accompanied by a bad side. Many view this to be the case with hydropower. The bad side or disadvantages of hydropower include the impact on fish populations, such as salmon, when the fish cannot migrate upstream past impoundment dams to their spawning grounds or migrate downstream to the ocean. Hydropower can also be impacted by drought, because when water is not available the plant cannot produce electricity. Hydropower plants also compete with other uses for the land.

Other lesser known negatives of hydropower plants concern their impact on water flow and quality; hydropower plants can cause low water levels that impact riparian habitats. Water quality is also affected by hydropower plants. Low dissolved oxygen (DO) levels in the water, which are harmful to riparian habitats, can result when reservoirs stratify; that is, they develop layers of water of different temperatures (see Figure 4.10). Stratification can affect the water temperature, thus causing changes in dissolved oxygen levels, nutrient levels, productivity, and the bioavailability of heavy metals. During the summer, the natural process of stratification can divide a reservoir into distinct vertical strata, such as a warm, well-mixed upper layer (epilimnion) over a cooler, relativity stagnant lower layer (hypolimnion). Plant and animal respiration, bacterial decomposition of organic matter, and chemical oxidation can all act to progressively remove dissolved oxygen from hypolimnetic waters. This decrease in hypolimnetic dissolved oxygen is not generally offset by the renewal mechanisms of atmospheric diffusion, circulation, and photosynthesis that operate

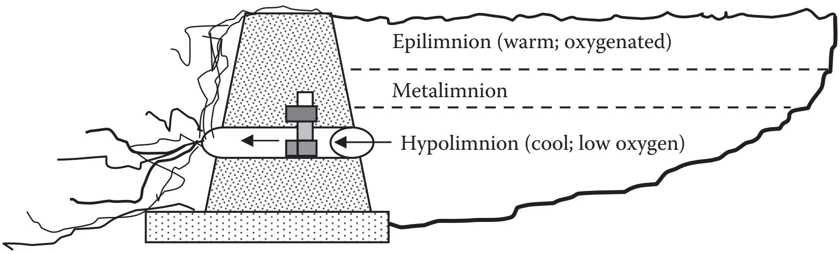

FIGURE 4.10 Thermal stratification of a hydropower reservoir.

in the epilmnion (Spellman, 1996, 2008). In temperate regions, the decline in hypolimnetic dissolved oxygen concentrations begins at the onset of stratification (spring or summer) and continues until either anaerobic conditions predominate or reoxygenation occurs during the fall turnover of the water body.

Numerous structural, operational, and regulatory techniques are available to resolve low dissolved oxygen issues. Levels of dissolved oxygen can be increased through modifications in dam operations that include such techniques as fluctuating the timing and duration of flow releases, spilling or sluicing water, increasing minimum flows, flow mixing, and turbine aeration; at some sites, injection of air or oxygen for weir aeration has proven effective. The most effective strategy for addressing the dissolved oxygen problem depends on the site.

ECOLOGICAL IMPACTS OF HYDROPOWER

During operation, adverse ecological effects could result from disturbance of wildlife by equipment noise, site inspection and maintenance activities, exposure of biota to contaminants, and mortality of birds due to collisions with the project facilities and/or electrocution by transmission lines. During operation, wildlife could still be affected by habitat fragmentation or the presence of barriers in fenced areas, canals, or above-ground pipelines, utility rights-of-way (ROWs), and access roads. In addition, the presence of the hydropower project and its associated access roads and ROWs may increase the human use of surrounding areas, which could, in turn, impact ecological resources in the surrounding areas through

- Introduction and spread of invasive vegetation
- Disturbance of habitats
- Mortality of wildlife from vehicles
- Increase in hunting (including poaching)
- Increased potential for fire
- Physical barriers to fish migration
- Flow alteration and fluctuations
- Biological impacts of flow fluctuations

In the discussion that follows, for the purposes of this text, we concentrate on the last three impacts listed above related to the Pacific Northwest region of the United States.

Physical Barrier to Fish Migration

The presence of a dam could impose a physical barrier to fish migration. As described earlier in the Rachel River account, this could be mitigated by construction of a fish ladder (see Figure 4.11). Figure 4.12 shows a window view of salmon climbing a fish ladder to their spawning grounds in the Pacific Northwest. In this area, salmon runs include sockeye salmon in June (see Figure 4.13), Chinook salmon (see Figure 4.14) and coho salmon (see Figure 4.15) in September and October, and steelhead (see Figure 4.16) in late fall and winter in Lake Washington, Seattle, Washington.

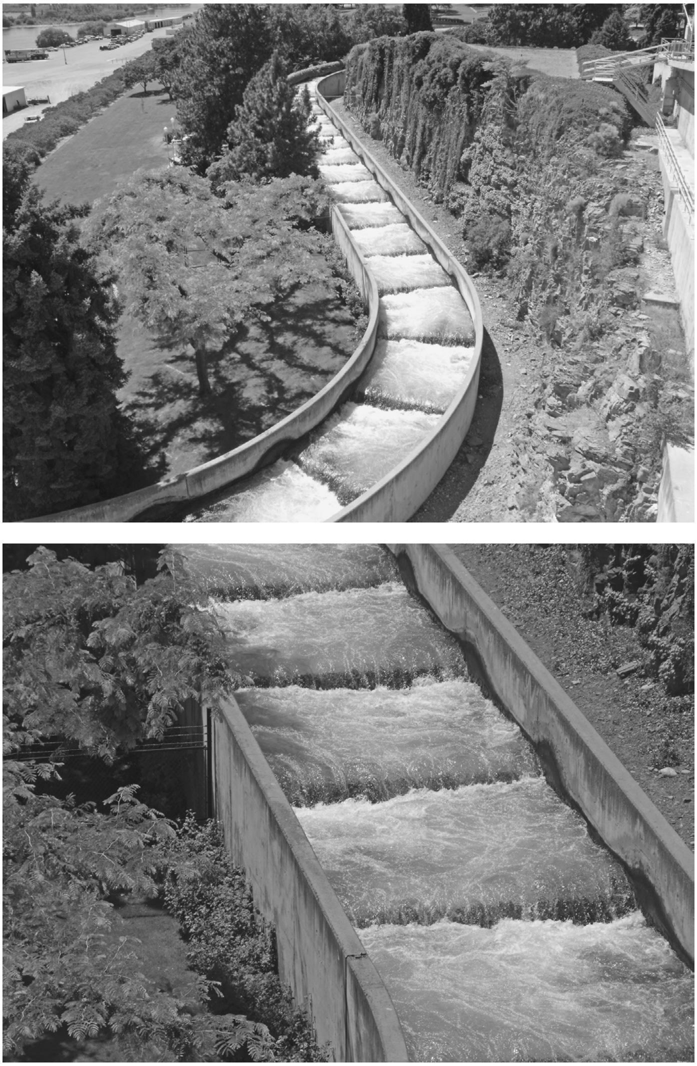

FIGURE 4.11 Fish ladder at Rocky Reach Dam on the Columbia River in Washington.

Flow Alterations, Flow Fluctuations, and Regulated and Unregulated Rivers and Salmonids*

Hydropower plants can, to varying capacities, change instream flow patterns in rivers below the dams and powerhouses. These changes can be classified into two categories: *flow alterations* and *flow fluctuations*. Flow alterations are changes in flow

* Adapted from Hunter, M.A., *Hydropower Flow Fluctuations and Salmonids: A Review of the Biological Effects, Mechanical Causes, and Options for Mitigation*, Washington Department of Fisheries, Olympia, 1992.

FIGURE 4.12 Window view of salmon climbing a fish ladder.

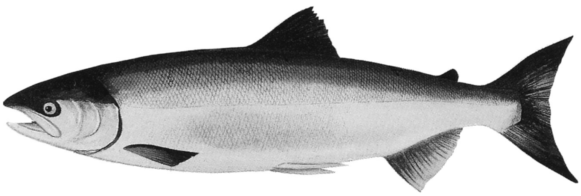

FIGURE 4.13 Sockeye salmon typically found in Lake Washington, Seattle, WA.

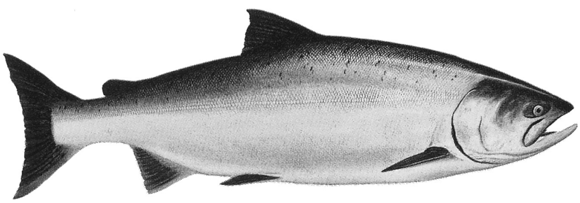

FIGURE 4.14 Chinook salmon typically found in Lake Washington, Seattle, WA.

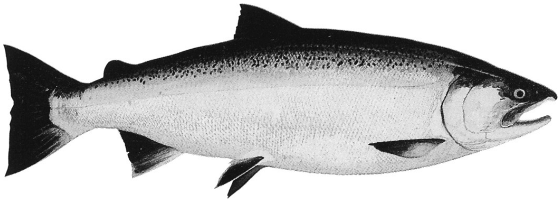

FIGURE 4.15 Coho salmon typically found in Lake Washington, Seattle, WA.

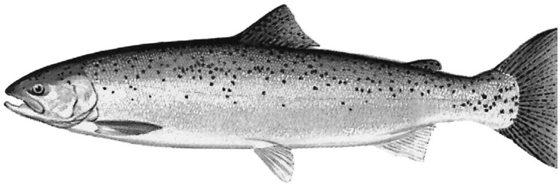

FIGURE 4.16 Steelhead typically found in Lake Washington, Seattle, WA.

over long periods of time (weeks, months, or seasons) resulting from the storage of water, irrigation diversions, municipal diversions, or the reactions of flow between dams and powerhouses. These changes in net flow usually change the availability of fish habitat and thus change the fish production potential of a river. Flow alterations are evaluated by studying the fish habitat requirements and estimating the changes in habitat area at different flows using a hydraulic model. The Instream Flow Incremental Methodology (IFIM) (Bovee, 1982) has become a standard method for estimating habitat changes resulting from flow alterations. The IFIM that was developed under the guidance of the U.S. Fish and Wildlife Service (USFWS) is a process utilizing various technical methodologies to evaluate changes in the amount of estimated usable habitat for various species or groups of species as flow changes (Stalnaker et al., 1995). The IFIM methodology is routinely used to facilitate negation of instream flow requirements, usually minimum flow requirements that meet the habitat needs of economically important or threatened fish species.

Flow fluctuations are unnaturally rapid changes in the flow over periods of minutes, hours, and days. Flow fluctuations can be immediately lethal or have indirect and delayed biological effects. Flow fluctuations can be measured either by changes in *flow*, which is the volume of water passing a specific river transect, or by changes in *stage*, which is the water surface elevation or gauge height. Both units are needed to understand the problem, and the terms are used interchangeably in this text. Hydrologists and engineers require flow measurements for many applications; however, the biological impact of flow fluctuations is best measured by stage. These two units do not have a simple functional relationship, thus *rating tables* or *rating curves* are used to define the flow at each stage for a specific river transect.

Flows in *unregulated rivers* respond to changes in precipitation and snow melt. West of the Cascade Range, the peak flows occur from heavy rain storms in November, December, and January. A lesser but more sustained peak occurs from a combination of rain and snow melt in the spring. The lowest flows coincide with the

dry season that occurs in late summer and early fall. Glacial streams and streams on the east side of the Cascades have a somewhat different pattern. Here, the highest flows often occur in the spring and extend into the early summer. The lowest flows in some years occur during cold periods in the winter. In either case, periods of heavy rainfall or dry weather can create flows that are above or below seasonal averages. These natural flow variations indirectly affect fish production as a result of changes in the quantity and quality of instream habitat.

On a shorter time scale, individual storms can rapidly increase river stage in less than a day. After the storm, the stage declines to a relatively stable level over a longer period of time, usually days or weeks. In addition to storm events, limited daily stage changes sometimes occur during sunny weather as a result of snow-melt runoff.

Flows in *regulated rivers* respond to measures taken to improve river channels so that they can be used more efficiently in the national economic interest. When properly engineered and constructed, river regulation ensures the creation of favorable conditions for navigation and timber rafting, the maintenance of the necessary water levels at water intake works, the protection of populated areas and agricultural land from flooding during spring floods and high water, the slow movement of river sediment, and the smooth flow of water toward the openings of hydraulic engineering structures such as dams.

BIOLOGICAL IMPACTS OF FLOW FLUCTUATIONS

Increases in Flow

Evidence of biological impacts from rapid flow increases is scarce. Some impacts associated with rapid flow increases might be more appropriately associated with high flows. Eggs and alevins (fry) can be killed when gravel scour occurs, and juvenile fish may be physically flushed down the river (Rochester et al., 1984). Some

DID YOU KNOW?

River stage is an important concept when analyzing how much water is moving in a stream at any given moment. *Stage* is the water level above some arbitrary point in the river, usually with the zero height being near the river bed, and is commonly measured in feet. For example, on a normal day when no rain has fallen for a while, a river might have a stage of 2 feet (baseflow conditions). If a big storm hits, the river stage could rise to 15 or 20 feet, sometimes very quickly. This is important because, from past records, we might know that when the stage hits 21 feet the water will start flowing over its banks and into the basements of houses along the river. How high and how fast a river will rise during a storm depends on many things. Most important, of course, is how much rain is falling, but we also have to look at other things, such as the stage of the river when the storm begins, what the soil is like in the drainage basin where it is raining (is the soil already saturated with water from a previous storm?), and how hard and in what parts of the watershed the rain is falling (USGS, 2014b).

DID YOU KNOW?

With the advent of modern computer and satellite technology, the U.S. Geological Survey can monitor the stage of many streams almost instantly. Because some streams, especially those in the normally arid western United States, can rise dramatically in a matter of minutes during a major storm, it is important to be able to remotely monitor how fast water is rising in real time in order to warn people that might be affected by a dangerous flood (USGS, 2014b).

species of aquatic insects that swim in pools can be physically flushed downstream from a sudden increase in flow (Trotzky and Gregory, 1974). The biological effects of unnatural flow increases are usually irrelevant in regulating hydropower operations because public safety concerns justify more stringent regulations than biological concerns. Flow increases can strand and occasionally drown fishermen and other people located on bars, rocks, or in confined canyons. Boaters might also be at risk under some circumstances.

Stranding

Stranding is the separation of fish from flowing surface water as a result of declining river stage. Stranding can occur during any drop in stage. It is not exclusively associated with complete or substantial dewatering of a river. Stranding can be classified into two categories: *Beaching* is when fish flounder out of the water on the substrate. *Trapping* is the isolation of fish in pockets of water with no access to the free-flowing surface water. Stranding cannot always be neatly classified as beaching or trapping. Thus, in this text we use the term stranding unless a more specific term is appropriate. Salmonid stranding associated with hydropower operations has been widely documented in Washington and Oregon (e.g., Bauersfeld, 1977, 1978a; Becker et al., 1981; Fiscus, 1977; Olson, 1990; Phinney, 1974a,b; Satterthwaite, 1987; Thompson, 1970; Witty and Thompson, 1974). Stranding can occur many miles downstream of the powerhouse (Phillips, 1969; Woodin, 1984). The estimated numbers of fish stranded in flow fluctuation events range from negligible to 120,000 fry (Phinney, 1974a). Stranding mortality is difficult or impossible to estimate. Estimates are usually very conservation or highly variable. Stranding can also occur as a result of other events, including natural declines in flow (author's observation of Colorado River over time), ship wash (Bauersfeld, 1977), municipal water withdrawals, and irrigation withdrawals. Many factors affect the incidence of stranding. A recurrent theme in much of the following discussion is the high vulnerability of small salmonid fry.

DID YOU KNOW?

Salmonids are a family of ray-finned fish that includes salmon, trout, chars, freshwater whitefishes, and graylings.

Juvenile salmonids are more vulnerable to stranding than adults. Salmonid fry that have just absorbed the yolk sac and have recently emerged from the gravel are by far the most vulnerable. They are poor swimmers and settle along shallow margins of rivers (Phinney, 1974a; Woodin, 1984), where they seek refuge from currents and larger fish. Once Chinook attain the size of 50 to 60 mm in length, vulnerability drops substantially. For steelhead, vulnerability drops significantly when the fry reach 40 mm (Beck Associates, 1989). Larger juveniles are more inclined to inhabit pools, glides, overhanging banks, and midchannel substrates, where they are less vulnerable to stranding; however, many juveniles still inhabit shoreline areas and remain vulnerable to stranding until they emigrate to saltwater (Hamilton and Buell, 1976). Adult stranding as a result of hydropower fluctuations has been documented (Hamilton and Buell, 1976).

The river channel configuration is a major factor in the incidence of stranding. A river channel with many side channels, potholes, and low gradient bars will have a much greater incidence of stranding than a river confined to a single channel with steep banks. Large numbers of small fry die from beaching on gravel bars when unnatural flow fluctuations occur (Phillips, 1969; Phinney, 1974a; Woodin, 1984). Bauersfeld (1978a) observed beaching primarily on bars with slopes less than 4%. Beck Associates (1989) determined that beaching occurred primarily on bars with slopes less than 5%. Under laboratory conditions, Monk (1989) determined that Chinook fry stranded in significantly larger numbers on 1.8% slopes than on 5.1% slopes, but the results were not significant for steelhead. Stranding on steep gravel bars (>5% slope) has not been thoroughly studied.

Long side channels with intermittent flows are notorious for trapping juvenile fish. Substantial trapping can occur even with unregulated flows (Hunter, 1992). Side channels are valuable rearing habitats, and juveniles of several species prefer side channels over the main channel; however, unnatural fluctuations will repeatedly trap fish, eventually killing some or all of them (Hamilton and Buell, 1976; Olson, 1990; Witty and Thompson, 1974; Woodin, 1984). Side channels can trap substantial numbers of fingerlings and smolts (up to 150 cm) as well as fry.

As water recedes from river margins, juvenile salmonids may become trapped in deep pools called *potholes* (Woodin, 1984). River potholes are formed at high flows from scouring (a process called *corrosion*; see Figure 4.17) around boulders and rootwads and where opposing flows meet. Potholes may remain watered for hours or months depending on the depth of the pothole and the river stage. Beck Associates (1989) extensively studied pothole stranding in the Skagit River (Washington State). Among the conclusions were that (1) only a small fraction of the potholes in a river channel posed a threat to fish if fluctuations are limited in range, (2) the incidence of stranding is independent of the rate of stage decrease, and (3) the incidence of stranding is inversely related to the depth of water over the top of each pothole at the start of the decline in flow.

Most documented observations of stranding have occurred on gravel; however, stranding has also occurred in mud (Becker et al., 1981) and vegetation (Phillips, 1969; Satterthwaite, 1987). Under laboratory conditions, Monk (1989) found significantly different rates of stranding on different types of gravel. In fact, substrate was statistically the most significant factor contributing to the stranding of Chinook

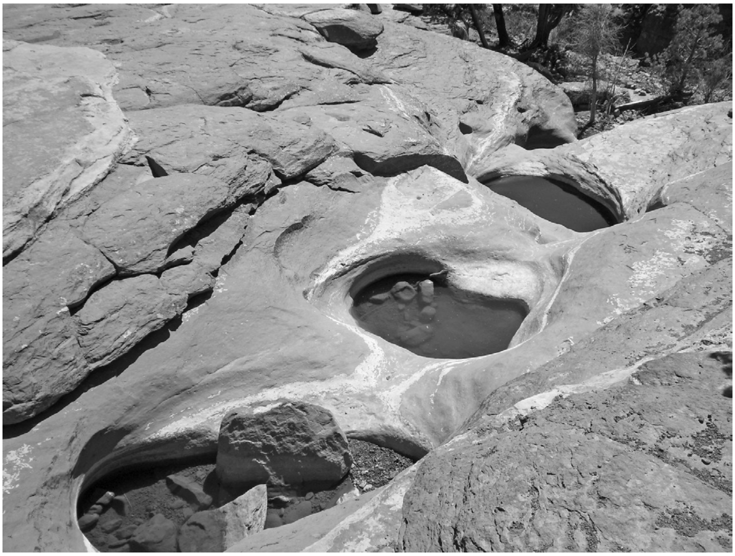

FIGURE 4.17 Potholes in an ancient river bed (Red Rock Canyon, Sedona, Arizona).

and steelhead fry. On cobble substrate, fry (especially steelhead fry) were inclined to maintain a stationary position over the streambed (i.e., rheotaxis); whereas, over small gravel, fry swam around, often in schools. When the water surface dropped, fry maintaining their position became trapped in pockets of water between cobbles, whereas mobile fish were more included to retreat with the water margin. When beaching became imminent, fry over cobble substrate retreated into inter-gravel cavities, where they became trapped. The difference in stranding rate was facilitated by the flow of water along a receding margin of the stream. On cobble substrate, the water drained into the substrate, whereas on finer substrates a significant portion of the water flowed off on the surface.

Fry of some species are more vulnerable to stranding than others. In Washington State, stranding of Chinook and steelhead fry has been frequently observed. Although pink salmon fry and chum salmon fry occur in the same rivers, they strand

DID YOU KNOW?

We cannot say that because a stream rises (doubles) from a 10-foot stage to a 20-foot stage that the amount of water flowing also doubles. When a river flows out of main river banks and spreads out along the flatter landscape, even a 1-inch rise in stage can mean a huge rise in streamflow. So, the amount of water flowing in a stream might double when the stage rises from 5 to 10 feet of stage, but then it might quadruple when it goes from 15 to 20 feet. A graphic called a *rating curve* is used to illustrate typical river stage–discharge (streamflow) relationships.

DID YOU KNOW?

To find out how much water is flowing in a stream or river, USGS personnel have to go out and make a *discharge measurement*—a measurement of streamflow at that instant in time. USGS uses the term *discharge* to refer to how much water is flowing, and discharge is usually expressed in cubic feet per second. The term *streamflow* can be used instead of discharge.

in lower numbers than Chinook fry and steelhead fry (Woodin, 1984). However, Beck Associates (1989) determined that the rate of chum and pink fry stranding per the available fry was substantially higher than for Chinook. The low numbers of pink and chum salmon stranding is a result of the short freshwater residency; they emigrate to saltwater shortly after emergence, whereas Chinook and steelhead remain in the river for months or years.

Hamilton and Buell (1976) observed extensive coho stranding in the Campbell River (British Columbia), and coho stranding has been observed in incidental numbers in other studies (Olsen, 1990). The overall incidence of coho stranding is rather low in the studies conducted to date. The likely reason for this is that coho prefer streams for spawning and breeding, whereas the formal research and evaluation have taken place in large and medium rivers. Juvenile coho rear for a full year in freshwater; thus, it is reasonable to assume that stranding would occur at rates similar to those for Chinook and steelhead.

The total drop in stage from an episode of flow fluctuation (known as *ramping range*) affects the incidence of stranding by increasing the gravel bar area exposed. In addition, it increases the number of side channels and potholes that become isolated from surface flow (Beck Associates, 1989). Stranding increases dramatically when flow drops below a certain water level, defined as the *critical flow* (Bauersfeld, 1978a; Phinney, 1974a; Thompson, 1970; Woodin, 1984). In hydropower mitigation settlements, the critical flow is defined as the minimum operating discharge, or as an upper end of a flow range where more restrictive operation criteria are applied. The factors that likely account for this response have been discussed above. The exposure of the lowest gradient gravel bars often occurs in a limited range of flows. The exposure of spawning gravel from which fry are emerging may also account for the higher incidence of stranding.

In rivers with seasonal side channels and off-channel sloughs (slews, slues), even a natural flow reduction can trap fry and smolts. Under normal circumstances, the natural population can sustain a small loss several times a year; however, when a hydropower facility causes repeated flow fluctuations, these small losses can accumulate to a very significant cumulative loss (Bauersfeld, 1978a).

The *ramping rate* is the rate of change in stage resulting from regulated discharges. Unless otherwise noted, it refers to the rate of state decline. The faster the ramping rate, the more likely fish are to be stranded (Bauersfeld, 1978a; Phinney, 1974). Ramping rates less than 1 inch per hour were needed to protect steelhead fry on the Sultan River. Olson (1990) determined that a ramping rate of 1 inch per hour

DID YOU KNOW?

To measure instantaneous discharge, USGS hydrologic technicians stand in the stream, on a bridge, or in a boat and measure the depth and how fast the water is moving at many places across the stream. By doing this many times and at many stream stages, over the years the USGS has developed a relation between stream state and discharge.

was adequate to protect steelhead fry; however, the ramping rate was measured at a confined river transect, whereas the stranding was observed on lower gradient bars farther downstream. Thus, the effective ramping rate at these bars was less than 1 inch per hour.

Although many hydropower mitigation settlements specify ramping rates, some research has indicated that ramping rates cannot always protect fish from stranding. Woodin (1984) determined that *any* daytime ramping stranded Chinook fry. Beck Associates (1989) could not find any correlation between ramping and the incidence of pothole trapping, nor was there any correlation between the ramping rate and steelhead fry stranding during the summer. In both cases, stranding occurred regardless of the ramping rate.

Small fry are highly vulnerable to stranding and are present in streams only at certain times of the year. Chinook, coho, pink, and chum fry emerge during late winter and early spring, while steelhead emerge in late spring through early fall (Olson, 1989). Fingerlings, smolts, and adults are vulnerable to stranding in other seasons; however, less restrictive ramping criteria are often sufficient to protect them.

For at least some species, the incidence of stranding is influenced by the time of day. Chinook fry are less dependent on substrate for cover at night and thus are less vulnerable to stranding at night (Woodin, 1984). Two studies (Olson, 1990; Stober et al., 1982) concluded that steelhead fry are less vulnerable during the day, presumably because this species feeds during the day. However, two other studies (Beck Associates, 1989; Monk, 1989) found no difference in the rate of steelhead fry stranding relative to day and night.

Salmonids respire using their gills and do not survive out of water for more than 10 minutes; thus, beaching is always fatal. Juvenile salmonids trapped in side channels and potholes can survive for hours, days, or under favorable circumstances for months (Hunter, 1992). However, many trapped fish die from predation, temperature shock, or oxygen depletion. Survivors that are rescued by higher flows are probably in poorer condition than fish in the free-flowing channel.

Some observations suggest that a highly stable flow regime for a week or more prior to a flow fluctuation will increase the incidence of fry stranding (Phinney, 1974b). Two hypotheses might explain this observation. One hypothesis states that after long periods of stable flow more fry are available for stranding. In other words, a major flow reduction after a week of stable flows strands seven daily cohorts of emerging fry at once, rather than one cohort when fluctuations occur daily. An alternative hypothesis is that juveniles become accustomed to residing and feeding along the margins

of a stream, either as a behavioral response to stable flows or in response to aquatic invertebrate populations that thrive along the water's edge under stable flows. These hypotheses should be thoroughly tested before they are applied to mitigation practices.

Juvenile Emigration (Salmonid Drift)

Flow fluctuations in an experimental stream channel caused juvenile Chinook to emigrate downstream (McPhee and Brusven, 1976). The pre-test rate of emigration under stable flows was about 1% a day. Severe flow fluctuations (from 51 L/s to 17 to 3 to 51, with each flow being held for 24 hours) caused 60% of the Chinook to emigrate. A high rate of emigration continued even after initial flows were reestablished. A less severe daily fluctuation in flow (between 51 and 17 L/s for four 24-hour periods) caused 14% of the Chinook to emigrate. Alternating flows between 51 L/s and 17 L/s every 24 hours cause a greater rate of emigration than alternating the same flows every 12 hours. Most of the emigration occurred at night, a behavior observed in aquatic invertebrates. The behavioral response to flow fluctuations and how this may affect the juvenile salmonid rearing capacity is not well understood. Under conservative ramping requirements, flow fluctuations may cause downstream emigration, driving many fish to habitats that may be less desirable or overcrowded and leaving upstream rearing habitats underutilized. This could be a particular concern in a stream with a falls or other barrier that prevents juveniles from returning upstream.

Increased Predation

It has been suggested that juvenile fish forced from the river margins as a result of declining flows suffer from predation by larger fish (Phillips, 1969). This effect does not appear to have been documented anywhere, but it is a credible hypothesis under some circumstances.

Aquatic Invertebrates

Like fish, aquatic invertebrates are not necessarily adapted to unnatural drops in flow. Cushman (1985) extensively reviewed the effects of flow fluctuations on aquatic life, especially aquatic invertebrates. Interested readers are encouraged to

DID YOU KNOW?

Stream stages are not always cooperative, so it's not uncommon for someone to have to go measure a stream at 2:00 in the morning during a storm, sometimes in freezing conditions. Also, the stream can be uncooperative in that it changes—a big storm may come along and scour out bottom material of a creek or lodge a big log sideways in the creek, or sometimes do both at the same time. These kind of changes result in changes in the relationship between stage and discharge (USGS, 2014b).

refer to this review. Research on the effects of flow fluctuations on aquatic invertebrates in the Pacific Northwest is limited, although more information is available elsewhere in North America. The studies that have been done suggest that aquatic invertebrates can be severely impacted by flow fluctuations. Fluctuations substantially reduce invertebrate diversity and total biomass and change the species composition under most circumstances. One study from the Skagit River found that flow fluctuations had a greater adverse impact on the aquatic invertebrate community than a substantial reduction in average flow (Gislason, 1985). The reduction in aquatic invertebrate production can impact salmonid production as a result of reduced feeding (Cushman, 1985).

Additional research is needed on the effects of flow fluctuations on aquatic invertebrates in the Pacific Northwest; however, a thorough study would be a formidable task. It would involve many species with different life cycles, behavioral responses, lethal responses, and contributions as prey to salmonids. Populations of some species may change rapidly under normal conditions, thus it may be difficult to associate cause and effect. Flow fluctuations can impact the aquatic invertebrates in the following ways:

- *Stranding*—Flow fluctuations can strand many species of aquatic invertebrates, much in the same way fish can become stranded (Gislason, 1985; Phillips 1969). Death may result from suffocation, desiccation, temperature shock, or predation.
- *Increased drift*—Many aquatic invertebrates are sensitive to reductions in flow and respond by leaving the substrate and floating downstream. This floating behavior is drift. Nighttime drift is normal; however, drift becomes highly elevated under unnatural fluctuations in flow (McPhee and Brusven, 1975; Cushman, 1985). This elevated drift may be an emergency response to avoid stranding, a response to overcrowding of the inter-gravel habitat, or a response by aquatic species that are adapted to a narrow range of water velocity. This response may temporarily increase fish food supply (McPhee and Brusven, 1975), but when repeated fluctuations occur many species are flushed out of the river and the aquatic invertebrate biomass usually declines, often substantially (Cushman, 1985; Gislason, 1985). Elevated drift also occurs in response to sudden increases in flow, capturing terrestrial insects from the river banks and scouring some aquatic invertebrates from the river substrate (Mundie and Mounce, 1976).
- *Detritus feeders*—Under stable flow conditions, floating detritus (leaves, woody debris) accumulates on the shores of the river as a result of current and wind action on sand or gravel substrate. This detritus remains close to the river margin and often remains damp for days or weeks at a time. Under fluctuating flows, this organic detritus becomes suspended (Mundie and Mounce, 1976) and is flushed out of the river or redeposited at the high waterline where it desiccates during low flow periods. As a result the invertebrate detritus community is less capable of exploiting this resource.

- *Herbivorous invertebrates*—Impacts are similar to those on the detritus community. Algae grows on exposed rock surfaces on which herbivorous aquatic invertebrates graze. Fluctuations desiccate and disrupt the growth of the exposed algae (Gislason, 1985) and reduce access by herbivores.

Redd Dewatering

Research has extensively documented the lethal impact of redd dewatering on salmonid eggs and alevins (i.e., larval fish) (Frailey and Graham, 1982; Fraser 1972; Fustish et al., 1988; Satterthwaite et al., 1985). Salmonid eggs can survive for weeks in dewatered gravel (Becker and Neitzel, 1985; Neitzel et al., 1985; Reiser and White, 1983; Stober et al., 1982), if they remain moist and are not subjected to freezing or high temperatures. The necessary moisture may originate from subsurface river water or from groundwater. If the subsurface water level drops too far, the inter-gravel spaces will dry out, and the eggs will desiccate and die. Thus, redd dewatering is not always lethal or even harmful to eggs; however, site conditions, weather, and duration of exposure will all affect survival. Because alevins rely on gills to respire, dewatering is lethal (Neitzel et al., 1985; Stober et al., 1982). Alevins can survive in subsurface, inter-gravel flow from a river or groundwater source. If inter-gravel spaces are not obstructed with pea gravel, sand, or fines, some alevins will survive by descending through inter-gravel spaces with the declining water surface (Strober et al., 1982). Both alevins and eggs may die from being submerged in stagnant water. Standing inter-gravel water may lose its oxygen to biotic decay, and metabolic wastes may build up to lethal levels. A redd can be dewatered between spawning and hatching without harm to the eggs under some circumstances, and in one situation a hydropower facility is operated to allow limited redd dewatering (Neitzel et al., 1985). However, in most Pacific Northwest rivers, anadromous fish spawn over an extended period. Different species spawn in different seasons and individual species may spawn over a range of 2 to 6 months. As a result, when eggs are present, alevins and fry are also present, both of which are highly vulnerable to flow fluctuations.

Spawning Interference

Bauersfeld (1978b) found that repeated dewatering caused Chinook salmon to abandon attempts to spawn and move elsewhere, often to less desirable or crowded locations. Hamilton and Buell (1976) performed a highly detailed study using observation towers situated over spawning beds to track activity on the spawning bed and to observe individual tagged fish. They observed that spawning Chinook were frequently interrupted by flow fluctuations. Females repeatedly initiated redd digging and then abandoned the redd sites when flows changed. The authors concluded that flow fluctuations decrease viability due to untimely release of eggs, failure to cover eggs once they were released, and a failure of males to properly fertilize eggs laid in incomplete redds. Other researchers offered conflicting conclusions. Stober et al. (1982) noted that Chinook salmon successfully spawned in an area that was dewatered several hours a day, and Chapman et al. (1986) found that 8 hours a day of dewatering still permitted successful spawning.

Hydraulic Response to Flow Fluctuations

The ramping rate attenuates as a function of the distance downstream from the source of a fluctuation event (Nestler et al., 1989). The characteristics of the river greatly influence this attenuation. A fluctuation in flow passing through a narrow bedrock river channel will experience little or no attenuation. Pools, side-channels, and gravel bars attenuate the ramping rate by storing water from higher flows and release this water gradually. Tributary inflow will attenuate the ramping rate and the ramping range. Hydraulic equations (e.g., unsteady flows; see Chow, 2009, for one of the best texts written on open-channel hydraulics) exist to describe these responses. The time it takes for a fluctuation to pass from one place to another on a river is known as *lag time*. The river channel configuration, gradient, and flow all influence the speed at which the fluctuation travels downstream. Lag time can be determined by field observations as several flows. For projects with long penstocks, the term *bypass lag time* refers to the time that flow fluctuations take to pass down the natural stream channel from the dam to the powerhouse tailrace.

Types of Hydropower Activity That Cause Flows to Fluctuate

Hydropower facilities cause flow fluctuations in a variety of ways. A brief overview of mechanical causes is provided in the following.

- *Load following*—Load following occurs when a hydropower plant follows daily changes in power demand and adjusts its power output as demand for electricity fluctuates throughout the day.
- *Peaking*—A peaking hydropower plant operates only during times of peak demand. Peaking is the most widely documented source of fish stranding. Biologists and fishermen have observed major fish kills from peaking (Bauersfeld, 1977, 1978a; Becker et al., 1981; Graybill et al., 1979; Phinney, 1974a; Thompson, 1970).
- *Low-flow shutdowns*—When turbine flow is below the level for practical turbine operation, the plant must take various turbines offline. In addition, a minimum flow is usually required to maintain the aquatic habitat in the bypass reach. Dam facilities with seasonal storage can operate for years without a low-flow shutdown.
- *Low-flow startups*—Run-of-river plants will cause a drop in flow in the bypass and downstream reaches during powerhouse start-ups. In these situations, operators must ramp flows at the start of power generation to reduce stranding.
- *Powerhouse failures*—Powerhouse failures are rare disruptions of the penstock flow originating from the powerhouse. These disruptions usually result from mechanical problems but can also occur due to load rejection, which is the inability of the utility line to receive power generated from the turns. Powerhouse failures can occur at any facility. This type of failure can cause a sudden drop in flow level in the downstream reach.

- *Flow continuation*—Flow continuation is the mechanical capacity to maintain flow through the penstock during powerhouse failures.
- *Intake failures*—Intake failures are all penstock flow disruptions that occur at the intake structure. Intake failures are less frequent than powerhouse failures; they usually occur as a result of the accumulation of debris, the failure of fish screen cleaning equipment, or failure of the dam and associated gates to deliver water into the intake.
- *Cycling*—A way to generate power when flow is not enough for continuous or efficient operation; it is not an attempt to follow load demands. Cycling will normally occur at low stream flows when the salmonids would be most vulnerable to fluctuations.
- *Multiple turbine operations*—If a powerhouse has two or more turbines, operators can cause abrupt changes in flow when changing the number of turbines in operation.
- *Forebay surges*—Forebay surges occur when the powerhouse of some run-of-the-river plants start generation and are probably caused by a drop in head at the intake during start-up.
- *Reservoir stranding*—In large reservoirs, stranding is routinely anticipated as one of the consequences of drawdowns, and it is sometimes employed as a method of eradicating undesirable fish.
- *Tailwater maintenance and repair activities*—All hydropower plants will eventually require inspection, maintenance, and repair. However, it is often impossible to inspect or repair the structure or equipment submerged in the tailwater without completely or substantially disrupting flow to the river.

LOW WATER LEVELS AND EVAPORATION OF RESERVOIRS

They say a picture is worth a thousand words. Well, from the photographs shown in Figure 4.18, it should be obvious to even the most casual observer that Lake Mead, the reservoir formed by the Hoover Dam and the Colorado River, has a very distinctive bathtub ring along the channel cliffs that hold the reservoir water in place until the water passes through the dam's penstocks to its turbines and then back into the Colorado River below. The obvious conclusion to be drawn from the photographs is that Lake Mead is much lower than it has been in the past. This conclusion is correct, of course. As of October 2010, Lake Mead was only about 40% full. The lake has dropped 130 ft since 1999 and in 2010 was at 1084 ft, depths not seen since 1956.

Observers, hydrologists, critics, and laypersons (i.e., non-scientists) have differing opinions as to the causes of Lake Mead's current low water level. Most of these opinions have some merit. For example, the USGS (2013) observed that the bathtub rings and lower water level in Lake Mead are the result of a "stealth disaster." Drought is the culprit. Drought is a stealthy incremental disaster that is much more costly to the national economy than most people suspect. A prolonged dry spell, lasting over a decade, is steadily draining the water sources that power Hoover Dam's turbines. The Southwest and vast stretches of the High Plains region have suffered lengthy drought conditions for the past several years.

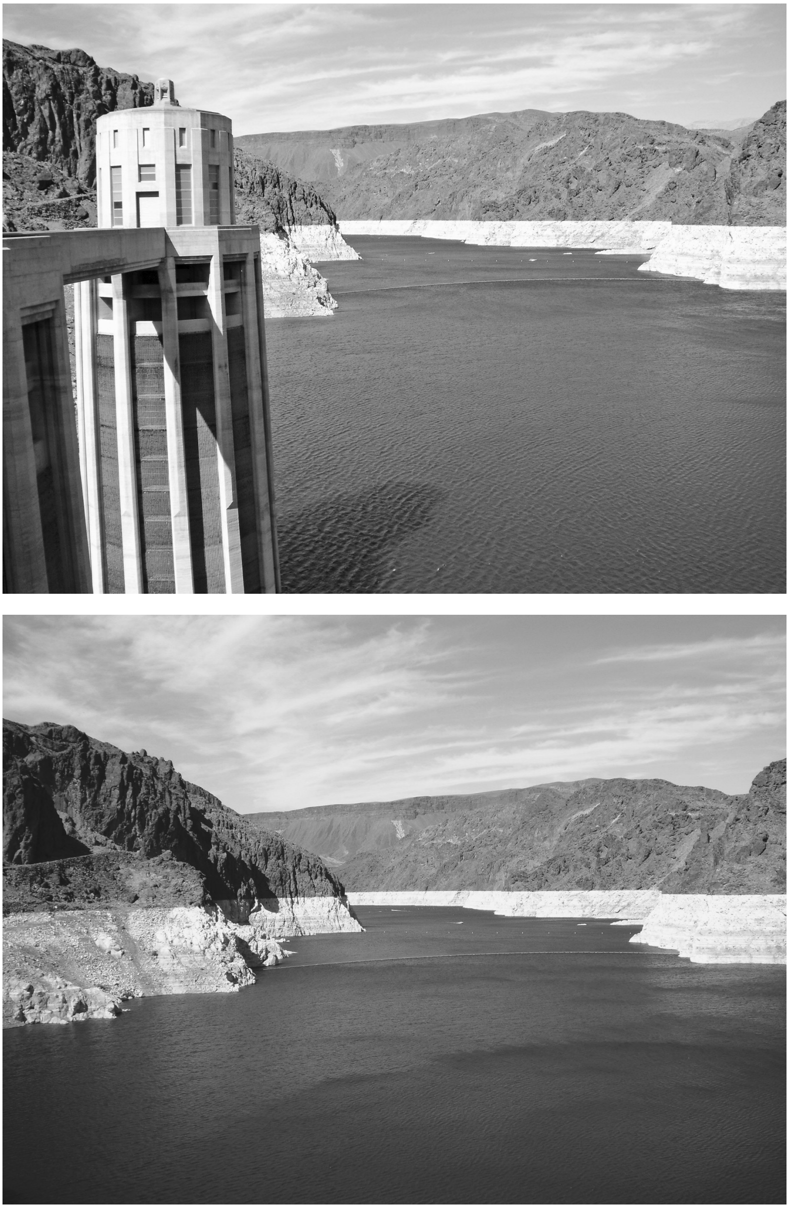

FIGURE 4.18 Lake Mead bathtub ring on the steep, barren, rocky cliffs surrounding the lake.

In addition to drought, heavy usage of the Colorado and Green Rivers has contributed to Lake Mead's low water level. For example, residents along the river use the water for showers, meals, hydration, and lawns. Farms use the water for their crops, livestock, and cleaning. Industrial facilities use the water for production, for cleaning their facilities, and for their employees.

In arid regions such as the Hoover Dam on the Arizona/Nevada border there is another reason for Lake Mead's low water levels: evaporation. This is a major issue and concern of the USGS and others. If water totals are at a premium to begin with (and they are), the evaporation rate of the remaining water is important and must be closely monitored. As a case in point, consider the following USGS 1997–1999 report on the impact of evaporation on Lake Mead.

Estimating Evaporation from Lake Mead*

Lake Mead is one of a series of large Colorado River reservoirs operated and maintained by the Bureau of Reclamation. The Colorado River system of reservoirs and diversions is an important source of water for millions of people in seven Western states and Mexico. The U.S. Geological Survey, in cooperation with the Bureau of Reclamation, conducted a study from 1997 to 1999 to estimate evaporation from Lake Mead. For this study, micrometeorological and hydrologic data were collected continually from instrumented platforms deployed at four locations on the lake: open-water areas of Boulder Basin, Virgin Basin, and Overton Arm and a protected cove in Boulder Basin. Data collected at the platforms were used to estimate Lake Mead evaporation by solving an energy-budget equation. The average annual evaporation rate at open-water stations from January 1998 to December 1999 was 7.5 ft. Because the spatial variation of monthly and annual evaporation rates was minimal for the open-water stations, a single open-water station in Boulder Basin would provide data that are adequate to estimate evaporation from Lake Mead.

Lake Mead is the largest reservoir by volume in the United States and was formed when Hoover Dam was completed in 1935. It took until July 1941 for water to fill Lake Mead, which has a maximum surface elevation of 1229 ft, a maximum surface area of 162,700 acres, and a maximum available capacity of 27,377,000 acre-ft (Bureau of Reclamation, 1967). At the maximum elevation of 1229 ft, Lake Mead extends 65.9 miles upstream of Hoover Dam and has a maximum width of 9.3 miles (LaBounty and Horn, 1997). The average lake elevation from 1942 (first complete calendar year of full pool) to 1995, based on monthly end-of-month elevations, is 1169.9 ft, which corresponds to a lake surface area of 125,600 acres.

The drainage area of Lake Mead at Hoover Dam is about 171,700 m^2 (Tadayon et al., 2000). Ninety-seven percent of the inflow into Lake Mead is from the Colorado River (13.12 million acre-ft/yr (Tadayon et al., 2000), with the remaining 2% coming from the combined flow of the Las Vegas Wash (148,000 acre-ft/yr) and the Virgin River (176,000 acre-ft/yr) (Jones et al., 2000), as well as ephemeral streams. The average annual release from Hoover Dam from 1935 to 1999 was about 10.1 million acre-ft (Tadayon et al., 2000). Flow of the Colorado River at Diamond Creek (130 miles upstream of Hoover Dam) in calendar year 1999 was 12.69 million acre-ft, while the release from Hoover Dam was 11.04 million acre-ft (Tadayon et al., 2001). Retention time for Lake Mead averages 3.9 years, depending on release and flow patterns.

* Adapted from Westennberg, C.I. et al., *Estimating Evaporation from Lake Mead (1997–99)*, USGS Scientific Investigation Report 2006-5252, U.S. Geological Survey, Washington, DC, 2006.

Lake Mead is in an environment with a warm, arid climate. From 1961 to 1990, the average maximum air temperature was 105.9°F for Las Vegas, Nevada, and 107.8°F for Overton, Nevada, whereas the average minimum air temperatures were 33.6°F and 28.0°F, respectively. Average annual precipitation (1961–1990) was 4.13 in. for Las Vegas and 3.31 in. for Overton. This warm, arid environment is conducive to high rates of evaporation. Sparsely vegetated, gentle to moderately sloping alluvial fans, and steep, barren, rocky cliffs surround the lake. Generally, the adjacent hills rise to low or moderated height above the lake surface. The vast majority of lake is exposed to winds from the southwest to southeast.

Computation Methods

Lake Mead evaporation was computed using micrometeorological data collected at four floating instrumented platforms deployed in Water Barge Cove near Callville Bay, Boulder Basin near Sentinel Island, the Virgin Basin, and in the Overton Arm near Echo Bay. The platform in Water Barge Cove was in a relatively shallow cove protected from prevailing winds. The platforms in Boulder Basin near Sentinel Island, Virgin Basin, and Overton Arm were in different areas of the lake that are representative of open-water conditions in each basin. The depth of water at the four platforms fluctuated during the study due to water-level changes of Lake Mead. Lake elevation ranged from less than 1196 ft in February 1997 to almost 1216 ft in September 1998. Each floating platform was equipped with instruments to measure and record meteorological data and water temperature. Air temperature and relative humidity were measured with a temperature–humidity probe (THP), wind speed and direction were measured with an anemometer and wind monitor, net radiation was measured with a net radiometer, and water temperature was measured at various depths with temperature probes. A two-point mooring system was used to secure each barge to prevent drifting and maintain the directional aspect of the wind monitor and net radiometer.

Energy-Budget Method to Measure Evaporation

The energy-budget method was used to measure evaporation from Lake Mead. This method also was used to quantify evaporation from western reservoirs in the 1950s and has been used by the USGS on a few long-term lake studies (Rosenberry et al., 1993; Sturrock and Rosenberry, 1992). The energy-budget method is the most accurate method for measuring lake evaporation (Winter, 1981). Use of the energy-budget method requires a large amount of data collection, but the effort is important because accurate measurements of lake evaporation are rare. An energy budget is similar to a water budget in that the change in stored energy is equal to the fluxes in and out of the

> **DID YOU KNOW?**
>
> The amount of heat necessary to change 1 kilogram of a liquid into a gas is called the *latent heat of vaporization*. When this point is reached, the entire mass of substance is in the gas state. The temperature of the substance at which this change from liquid to gas occurs is known as the *boiling point*.

system. Energy drives the process of evaporation because the water at the surface of the lake must absorb a certain amount of energy (latent heat of vaporization; approximately 580 calories per gram) before the water will evaporate. After some derivation, the following equation is used to calculate evaporation from the lake:

$$E = \frac{Q_s - Q_r - Q_b - Q_v - Q_\theta}{\rho L(R + 1)} \tag{4.19}$$

where

E = Evaporation rate.
Q_s = Solar radiation incident to the water surface.
Q_r = Reflected solar radiation.
Q_b = Net energy lost by the body of water through the exchange of long-wave radiation between the atmosphere and the body of water.
Q_v = Net energy advected into the body of water.
Q_θ = Change in energy stored in the body of water.
ρ = Density of evaporated water.
L = Latent heat of vaporization.
R = Bowen ratio.

The Bowen ratio (R) can be expressed as

$$R = \gamma \; \frac{T_0 - T_a}{e_0 - e_a} \; P \tag{4.20}$$

where

γ = Empirical constant.
T_0 = Temperature of the water surface.
T_a = Temperature of the air.
e_0 = Vapor pressure of saturated air at the temperature (T_0).
e_a = Vapor pressure of the air above the water surface.
P = Atmospheric pressure.

Net radiation (Q_n) was measured at Lake Mead evaporation platforms and replaces three energy terms (Q_s, Q_r, and Q_b) in Equation 4.19. Net advected energy (Q_v) is disregarded based on the assumption that advected energy is negligible during a 20-minute evaporation period. Thus, after modifying Equation 4.19 by substituting for net radiation, removing the net advected energy term, and replacing R with Equation 4.20, evaporation can be estimated from measured meteorological and hydrological parameters:

$$E = \frac{Q_n - Q_\theta}{\rho L \gamma_c \; \dfrac{T_0 - T_a}{e_0 - e_a} \; + 1} \tag{4.21}$$

where γ_c is a psychrometric constant, a product of γ and P (Laczniak et al., 1999).

Meteorological Data

Meteorological and water temperature data were used to compute evaporation rates for Lake Mead. Measurements were made every 10 to 30 seconds and were averaged for 20-minute periods. Some of the missing or incorrect 20-minute data were estimated or computed to maximize the amount of data available for the evaporation computation. Where data were missing for short periods, they were estimated from trends of the data before and after the periods of missing or incorrect data. Where data were missing or incorrect for longer periods, they were computed from other available data at that station, data from another station, or data for another year. Typically, a regression was developed with two sets of measurements for a different period, but for similar environmental conditions, using a complete set of data. The regression was then used to estimate the missing incorrect data from a complete set of data.

Monthly values of meteorological data and water temperatures were computed from 20-minute averaged data collected at each station for 1997, 1998, and 1999. Average daily air temperature was about the same at all four platforms, whereas relative humidity and water temperature were similar at the open-water platforms. Generally, water temperature was higher and relative humidity was lower at the sheltered cove platform (Water Barge Cove) than at the open-water platforms.

Daily air temperature, water temperature, and relative humidity at the Sentinel Island station were compared for 1997, 1998, and 1999. Air temperature varied from year to year, but the seasonal pattern was consistent. The maximum daily air temperature occurred about mid-July, with some daily average air temperatures exceeding 95°F, and the minimum daily air temperature occurred from late December through February. Water temperature did not vary much from year to year. Maximum daily water temperature occurred in late July to early August, and the minimum daily water temperature occurred in late February. Relative humidity fluctuated from day to day and differed greatly from year to year; however, there was a seasonal pattern of high relative humidity in January that gradually decreased to a low at the end of June, followed by a gradual increase to higher relative humidity in December.

Daily average wind speed for 1999 was 5 mph. Wind direction was predominately from the southeast to the southwest, occasionally from the northwest, and rarely from the northeast. Most daily wind speeds were less than 10 mph. The Virgin Basin location experienced more daily wind greater than 10 mph than other locations.

Evaporation Rates

Evaporation rates were computed at 20-minute intervals to evaluate diurnal fluctuations of lake evaporation. The 20-minute period evaporation rates were also used to identify periods of poor or missing energy-budget data. Daily evaporation rates are the sum of 20-minute periods, monthly rates are the sum of daily evaporation, and annual rates are the sum of monthly evaporation.

Daily Rates

The daily evaporation rates at the four evaporation stations were compared for calendar year 1999, and they showed similar daily fluctuations. However, the magnitude of fluctuations in daily evaporation was greater at Virgin basin and Sentinel

Island than at Overton Arm or Water Barge Cove. Daily evaporation was greatest from late June through early July and was least from mid-December through late January.

Monthly Rates

To evaluate the temporal (size of) variation in monthly evaporation at each station, monthly evaporation rates for each station were averaged and compared to the total evaporation rate for each month of data collection. Temporal data were available for Water Barge Cove, Sentinel Island, and Virgin Basin stations (see Table 4.5); however, monthly data were insufficient for the Overton Arm station to compute average monthly evaporation. Total monthly evaporation rates at three stations, with some exceptions, generally were within 10% of average monthly rates; consequently, annual variation in monthly evaporation typically was minimal between 1997 and 1999. Some months, however, exhibited significant differences between average and total evaporation. These differences were as great as 31% at Water Barge Cove (February 1997), 14% at Sentinel Island (January 1998 and 1999), and 22% at Virgin Basin (December 1998 and 1999). Some of the difference in monthly evaporation rates from year to year may be due to errors in meteorological and water-temperature data collected at each station, but year-to-year differences for most months likely are due to actual differences in evaporation.

To evaluate the spatial variation in evaporation, total monthly evaporation rates at all four stations were averaged for every month of data collection, and the average was compared to the total monthly evaporation rate at each station. For each station, total monthly evaporation rates compared well to average monthly rates with correlation coefficients of 0.96 or higher. However, total monthly evaporation at Water Barge Cove generally was less than total evaporation rates at the open-water stations when rates were less the 6.5 in. Total monthly evaporation rates for all three open-water stations were nearly equal and compared well to average evaporation rates; the correlation coefficient for Sentinel Island and for Overton Arm was 0.98, and for Virgin Basin it was 0.96. This evaluation suggests that the spatial variation in evaporation is minimal for open-water areas of Lake Mead.

The monthly volume of evaporated water was computed using the average monthly open-water evaporation rate, in feet, and the average monthly surface area of Lake Mead for July 1997 through December 1999, in acres. The volume of water evaporated in 1 month ranged from 46,000 acre-ft in February 1998 to 126,000 acre-ft in July 1998.

Annual Rates

The average monthly rates for the Lake Mead open-water evaporation stations were computed for 1998 and 1999. For open-water stations, the sum of the average monthly rates for 1998 was 88.9 in. (7.4 ft), and the sum for 1999 was 90.7 in. (7.6 ft). For these 2 years, the average annual Lake Mead evaporation rate was 89.9 in. (7.5 ft). Monthly evaporation rates were available for only the Sentinel Island station for January to March 1998, and those rates are used instead of an average rate. Evaporation rates at the Sentinel Island station are generally representative of evaporation of the lake as a whole. For April 1998 through November 1999, the total

TABLE 4.5
Evaporation from Lake Mead at Four Floating Instrumented Platforms, Arizona and Nevada, 1999–1999

Site	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Monthly Evaporation, 1997 (inches)												
Water Barge Cove	—	5.4	9.1	7.9	—	10.8	10.8	9.2	8.3	7.6	4.1	2.6
Sentinel Island	—	—	—	—	—	—	9.1	9.1	8.8	8.7	6.4	4.6
Virgin Basin	—	—	—	—	—	—	—	—	—	—	—	—
Overton Arm	—	—	—	—	—	—	—	—	—	—	—	—
Total Monthly Evaporation, 1998 (inches)												
Water Barge Cove	2.9	3.2	6.6	8.2	8.9	10.2	10.1	8.8	8.5	6.7	3.7	2.6
Sentinel Island	3.7	3.6	7.1	7.4	9.9	9.4	10.0	8.9	8.9	8.5	7.3	6.0
Virgin Basin	—	—	—	8.6	9.7	9.1	9.9	8.7	9.7	7.1	5.9	4.1
Overton Arm	—	—	—	—	—	—	—	—	—	—	—	—
Average Evaporation, 1998 (inches)												
All available sites	3.3	3.4	6.9	8.0	9.5	9.6	10.0	8.8	9.0	7.4	5.6	4.2
Open-water sites	3.7	3.6	7.1	8.0	9.8	9.2	9.9	8.8	9.3	7.8	6.6	5.0
Total Monthly Evaporation, 1999 (inches)												
Water Barge Cove	3.0	3.8	7.4	6.8	9.2	10.5	9.4	8.7	9.4	8.0	4.3	3.1
Sentinel Island	5.0	4.4	8.1	6.9	9.0	9.2	8.4	8.6	9.9	8.8	6.7	—
Virgin Basin	4.0	5.3	7.9	7.1	9.6	9.3	8.8	8.7	9.1	8.0	7.3	6.5
Overton Arm	—	—	7.8	6.9	9.5	9.5	9.4	8.6	9.5	8.7	7.0	4.1
Average Evaporation, 1999 (inches)												
All available sites	4.0	4.5	7.8	6.9	9.3	9.6	9.0	8.6	9.5	8.4	6.3	4.5
Open-water sites	4.5	4.8	8.0	7.0	9.4	9.4	8.9	8.6	9.5	8.5	7.0	5.3

Source: USGS, *Estimating Evaporation from Lake Mead*, U.S. Geological Survey, Washington, DC, 2006 (http://pubs.usgs.gov/sir/2006/5252/section3.html).

evaporation at the Sentinel Island station was 161.3 in., whereas, the total of average monthly evaporation for the open-water stations was 159.9 in. The difference of 1.4 in. is less than 1% of the total average open-water evaporation. The annual volume of water evaporated from Lake Mead exceeded 1.1 million acre-ft in 1998 and 1999, which probably is higher than a long-term average annual evaporation due to higher-than-normal lake elevations and corresponding larger-than-normal surface area for the period. For example, the average surface area of Lake Mead was 125,000 acres from 1942 to 1995 and the computed average annual evaporation rate was 7.5 ft from 1997 to 1998, which would equal a long-term average annual volume of 937,500 acre-ft of evaporated water.

IMPACTS ON HUMAN HEALTH AND SAFETY

Possible impacts on health and safety during operations include exposure to electromagnetic fields (EMFs) and accidental worker injury or death during operation and maintenance activities. Working around, with, or on hydropower facilities and equipment presents many of the same hazards to the installers, operators, and maintenance personnel as for wind turbine and solar operators and maintenance personnel. Hydropower safety issues include the following:

- Falls
- Confined space entry
- Fire
- Lockout/tagout
- Medical and first aid
- Crane, derrick, and hoist safety
- Electrical safety
- Machine guarding
- Respiratory protection

In addition, worker health and safety issues also include working in potential weather extremes and possible exposure to the hazards of nature, such as uneven terrain and dangerous plants, animals, and insects. Risk to the public of accidental death or injury is unlikely, as the facilities are fenced and guarded from unlawful entry; however, access to the impoundment or tailrace would be a potential source for accidents.

HYDROPOWER: THE BOTTOM LINE

Hydropower offers advantages over the other energy sources but presents unique environmental challenges. As mentioned, the advantages of using hydropower begin with that fact that hydropower does not pollute the air like power plants that burn fossil fuels, such as coal and natural gas. Moreover, hydropower does not have to be imported into the United States like foreign oil does; it is produced in the United States. Because hydropower relies on the water cycle, driven by the sun, it is a

renewable resource that will be around for at least as long as humans. Hydropower is controllable; that is, engineers can control the flow of water through the turbines to produce electricity on demand. Finally, hydropower impoundment dams create huge lake areas for recreation, irrigation of farm lands, reliable supplies of potable water, and flood control.

Hydropower, though, also has some disadvantages; it is these disadvantages or environmental impacts that have been the focus of this text. For example, fish populations can be impacted if fish cannot migrate upstream past impoundment dams to spawning grounds or if they cannot migrate downstream to the ocean. Many dams have installed fish ladders or elevators to aid upstream fish passage. Downstream fish passage is aided by diverting fish from turbine intakes using screens or racks or even underwater lights and sounds, and by maintaining a minimum spill flow past the turbine. Hydropower can also impact water quality and flow. Hydropower plants can cause low dissolved oxygen levels in the water, a problem that is harmful to riparian habitats and is addressed using various aeration techniques that oxygenate the water. Maintaining minimum flows of water downstream of a hydropower installation is also critical for the survival of riparian habitats. Hydropower is also susceptible to drought. When water is not available, the hydropower plants cannot produce electricity. Typical activities during operation of a hydropower plant include operation of the facility, power generation, and associated maintenance activities that would require vehicular access and heavy equipment operation when components are being replaced. Finally, construction of new hydropower facilities impacts investors and others by competing with other uses of the land. Preserving local flora and fauna and historical or cultural sites is often more highly valued than electricity generation.

THOUGHT-PROVOKING QUESTIONS

4.1 A few environmentalist groups advocate tearing down existing hydroelectric dams in the United States to allow affected rivers to run free. Do you support or oppose this argument? Why?

4.2 Do we have any more water on Earth today than yesterday or 1000 years ago?

4.3 According to the Rachel River account, the scientists and environmental scientists devised several recommendations to alleviate the downward trend in salmon population. What additional recommendations would you make to mitigate the situation?

4.4 In the Rachel River account, what is the meaning of the statement: “Notice they didn’t try to ask the Native Americans. They also would have known what to do. The salmon had already told them.”

4.5 Explain why an increase in water temperature affects salmon populations.

4.6 When you compare the pros and cons of hydroelectric power it sounds great—so why don’t we use it to produce all of our power?

4.7 Does the Rachel River account and the indicated mitigation procedures indicate to you that science and scientists can solve all problems?

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5 Biomass/Bioenergy

I'm the Lorax who speaks for the trees, which you seem to be chopping as fast as you please.

—Dr. Seuss (*The Lorax*)

Even on the eve of the end of the world, plant a tree.

—Koran

The wretched and the poor look for water and find none,
Their tongues are parched with thirst;
But I the Lord will give them an answer,
I, the god of Israel, will not forsake them.
I will open rivers among the sand-dunes
And wells in the valleys;
I will turn the desert into pools.
And the dry land into springs of water;
I will plant cedars in the wastes,
And acacia and myrtle on the barren heath
Side by side with fir and box.

—*Isaiah* 41:17–20

A nation that runs on oil can't afford to run short.

—Old oil industry slogan

Study: Fuels from corn waste not better, greener than gas.

Biofuels made from the leftovers of harvested corn plants are worse than gasoline for global warming in the short term, a study shows, challenging the Obama administration's conclusions that they are a much cleaner oil alternative and will help fight climate change.

Cappielo (2014)

INTRODUCTION

In an article in *The New York Times*, Thomas Friedman (2010) stated that, "The fat lady has sung." Specifically, Friedman was speaking about America's transition from the "Greatest Generation" to what Kurt Anderson referred to as the "Grasshopper Generation." According to Friedman, we are "going from the age of government handouts to the age of citizen givebacks, from the age of companions fly free to the age of paying for each bag." Friedman goes on to say that we all accept that our parents were the greatest generation, but it is us that we are concerned about and that it is the "we" that comprise the Grasshopper Generation: "We have been eating through the prosperity that was bequeathed us like hungry locusts."

What we are eating through, among other things, is our readily available, relatively inexpensive source of energy. The point is that we can, like the grasshopper, gobble it all up until it is all gone or we can find alternatives—renewable alternatives of energy. The nation is aggressively developing the capacity to meet some of our energy needs through biofuels and biopower. The Energy Independence and Security Act of 2007 (EISA) called for the use of 36 billion gallons per year (BGY) of renewable fuels by 2011 and established new categories of renewable fuels, each with specific volume requirements and life-cycle greenhouse gas (GHG) performance thresholds (USDA, 2012).

One of the promising sources of energy is biomass (biofuel) or bioenergy (biopower). *Biomass* is the feedstock used to produce *bioenergy*, a general term for energy derived from materials such as straw, wood, or animal wastes (i.e., biomass), which, in contrast to fossil fuels, were living matter relatively recently. Such materials can be burned directly as solids (biomass) to produce heat or power, but they can also be converted into liquid biofuels. In the last few years, interest has grown considerably in bioenergy fuels such as biofuels (biodiesel and bioethanol) that can be used for transport. At the moment, transport has taken center stage in our search for renewable, alternative fuels to eventually replace hydrocarbon fuels. Unlike biofuels, solid biomass fuel is used primarily for electricity generation or heat supply.

Even though we have stated that bioenergy is a promising source of energy for the future, it is rather ironic whenever the experts (or anyone else for that matter) make this point without qualification. Keep in mind that only 100 years ago our economy was based primarily on bioenergy from biomass, or carbohydrates, rather than from hydrocarbons. In the late 1800s, the largest selling chemicals were alcohols made from wood and grain, the first plastics were produced from cotton, and about 65% of the nation's energy came from wood (USDOE, 2004). By the 1920s, the economy started shifting toward the use of fossil resources, and after World War II this trend accelerated as technology breakthroughs were made. By the 1970s, fossil energy was established as the backbone of the U.S. economy, and all but a small portion of the carbohydrate economy remained. In the industrial sector, plants accounted for about 16% of input in 1989, compared with 35% in 1925.

Processing costs and the availability of inexpensive fossil energy resources continue to be driving factors in the dominance of hydrocarbon resources. In many cases, it is still more economical to produce goods from petroleum or natural gas than from plant matter. This trend is about to shift dramatically as we reach peak oil and as the world continues to demand unprecedented amounts of petroleum supplies from an ever-dwindling supply. The technological advances being made in the biological sciences and engineering, political change, and concern for the environment have begun to swing the economy back toward carbohydrates on a number of fronts. Consumption of biofuels in vehicles, for example, rose from zero in 1977 to nearly 1.5 billion gallons by 1999. The use of inks produced from soybeans in the United States increased fourfold between 1989 and 2000 and is now at more than 22% of total use (Morris, 2002).

Technological advances are also beginning to make an impact on reducing the cost of producing industrial products and fuels from biomass, making them more competitive with those produced from petroleum-based hydrocarbons.

Developments in pyrolysis, ultracentrifuges, and membranes, as well as the use of enzymes and microbes as biological factories, are enabling the extraction of valuable components from plants at a much lower cost. As a result, industry is investing in the development of new bioproducts that are steadily gaining a share of current markets (USDOE, 2004).

New technologies are helping the chemical and food processing industries to develop new processes that will enable more cost-effective production of all kinds of industrial products from biomass. One example is a plastic polymer derived from corn that is now being produced at a 300-million-pound-per-year plant in Nebraska, a joint venture between Cargill, the largest grain merchants, and Dow Chemical, the largest chemical producer (Fahey, 2001).

Other chemical companies are exploring the use of low-cost biomass processes to make chemicals and plastics that are now made from more expensive petrochemical processes (USDOE, 2006a). In this regard, new innovative processes such as biorefineries may become the foundation of the new bioindustry. A biorefinery is similar in concept to a petroleum refinery, except that it is based on conversion of biomass feedstocks rather than crude oil. Biorefineries in theory would use multiple forms of biomass to produce a flexible mix of products, including fuels, power, heat, chemicals, and materials (see Figure 5.1). In a biorefinery, biomass would be converted into high-value chemical products and fuels (both gas and liquid). Byproducts and residues, as well as some portion of the fuels produced, would be used to fuel onsite power generation or cogeneration facilities producing heat and power. The biorefinery concept has already proven successful in the U.S. agricultural and forest products industries, where such facilities now produce food, feed fiber, or chemicals, as well as heat and electricity to run plant operations. Biorefineries offer the most potential for realizing the ultimate opportunities of the bioenergy industry. Table 5.1 shows the energy consumption by energy source for 2008; in that year, biomass (biofuels, waste, wood, and wood-derived fuels) accounted for 3852 quadrillion Btu.

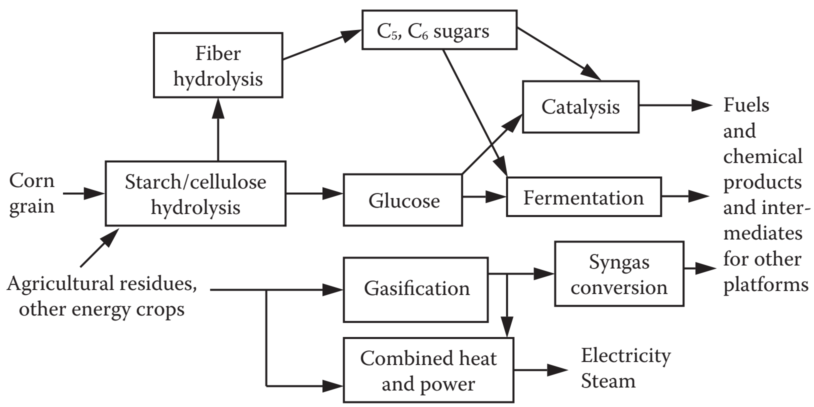

FIGURE 5.1 A biorefinery.

TABLE 5.1
U.S. Energy Consumption by Energy Source (2008)

Energy Source	Energy Consumption (quadrillion Btu)
Total	99.438
Renewable	7.367
Biomass (total)	**3.852**
Biofuels	**1.372**
Waste	**0.436**
Wood and wood-derived fuels	**2.044**
Geothermal energy	0.360
Hydroelectric conventional	2.512
Solar thermal/PV energy	0.097
Wind energy	0.546

Source: EIA, *U.S. Energy Consumption by Energy Source*, Environmental Investigation Agency, Washington, D.C., 2007 (http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/table1.html).

DID YOU KNOW?

In 2004, it was estimated that in the United States alone more than 100 billion gallons of light fuel oil per year can be produced from waste and biomass. The source waste and biomass included in this estimation included municipal solid waste, municipal sewage sludge, hazmat waste, agricultural crop waste, feedlot manure, plastics, tires, heavy oil or tar sands, forestry waste, restaurant grease, and biomass crops (switchgrass) grown on idle land and cropland.

It is important to note that biomass-produced bioenergy is not the panacea for solving our energy needs now and for the future. There are environmental impacts associated with biomass technology. There are tradeoffs. Are these tradeoffs significant? Are they worth it? Will biomass eventually replace fossil fuel usage? The jury is still out; however, with proper technology, proper planning, proper usage, and proper operation, biomass conversion to bioenergy can and will make a difference, eventually. There are probably more benefits than non-benefits to be derived from the use of biomass, but this book is about the environmental impacts of renewable energy, including biomass-to-bioenergy conversion. Later, after a brief introduction to what biomass is, how it is currently used, plant basics, feedstocks, biodiesel, and biogas, the environmental impacts of biomass production, refining, and usage are discussed.

DID YOU KNOW?

With regard to electricity, biomass energy cost per kilowatt hour (kWh) is about 5 to 10 cents, which amounts to approximately $1500 to $1800 per kilowatt peak (kWp). However, the cost of electricity generated from biomass energy differs as it is also dependent on certain factors as listed below:

- Kind of the biofuel used
- Method adopted to generate biomass energy form biofuel
- Size of the plant for generating biomass energy
- System design of the plant (Karthik, 2010)

BIOMASS*

Biomass (all Earth's living matter) consists of the energy from plants and plant-derived organic-based materials; it is essentially stored energy from the sun. Biomass can be biochemically processed to extract sugars, thermochemically processed to produce biofuels or biomaterials, or combusted to produce heat or electricity. Biomass is also an input into other end-use markets, such as forestry products (pulpwood) and other industrial applications. This complicates the economics of biomass feedstock and requires that we differentiate between what is technically possible from what is economically feasible, taking into account relative prices and intermarket competition.

Biomass has been used since people began burning wood to cook food and keep warm. Trees have been the principal fuel for almost every society for over 5000 years, from the Bronze Age until the middle of the 19th century (Perlin, 2005). Wood is still the largest biomass energy resource today, but other sources of biomass can also be used. These include food crops, grassy and woody plants, residues from agriculture or forestry, and the organic component of municipal and industrial wastes. Even the fumes from landfills (which are methane, a natural gas) can be used as a biomass energy source. This category excludes organic material that has been transformed by geological processes into substances such as coal or petroleum.

Feedstock Types

A variety of biomass feedstocks can be used to produce transportation fuels, biobased products, and power. Feedstocks refer to the crops or products, such as waste vegetable oil, that can be used as or converted into biofuels and bioenergy. With regard to the advantages or disadvantages of one type of feedstock as compared to another, this is gauged in terms of how much usable material they yield, where they can grow, and how energy and water intensive they are. Feedstock types are

* Adapted from Spellman, F.R. and Bieber, R., *The Science of Renewable Energy*, CRC Press, Boca Raton, FL, 2011.

FIGURE 5.2 Stored corn biomass feedstock.

categorized as first-generation or second-generation feedstocks. First-generation feedstocks include those that are already widely grown and used for some form of bioenergy or biofuel production, which means that food vs. fuel conflicts could arise. First-generation feedstocks include sugars (sugar beets, sugar cane, sugar palm, sweet sorghum, and *Nypa* palm), starches (cassava, corn, milo, sorghum, sweet potato, and wheat), waste feedstocks such as whey and citrus peels, and oils and fats (coconut oil, oil palm, rapeseed, soy beans sunflower seed, castor beans, *Jatropha*, jojoba, karanj, waste vegetable oil, and animal fat). Second-generation feedstocks include crops that offer high potential yields of biofuels but are not widely cultivated or not cultivated as an energy crop. Examples are cellulosic feedstocks or conventional crops such as *Miscanthus* grasses, prairie grass and switchgrass, and willow and hybrid poplar trees. Algae and halophytes (saltwater plants) are other second-generation feedstocks.

Currently, a majority of the ethanol produced in the United States is made from corn or other starch-based crops (see Figure 5.2). The current focus, however, is on the development of cellulosic feedstocks—non-grain, non-food-based feedstocks such as switchgrass, corn stover, and wood material—and on technologies to convert cellulosic material into transportation fuels and other products. Using cellulosic feedstocks not only can alleviate the potential concern of diverting food crops to produce fuel but can also offers a variety of environmental benefits (EERE, 2008). Because such a wide variety of cellulosic feedstocks can be used for energy production, potential feedstocks are grouped into categories—or pathways. Figure 5.3 shows some of the specific feedstocks in each of these areas.

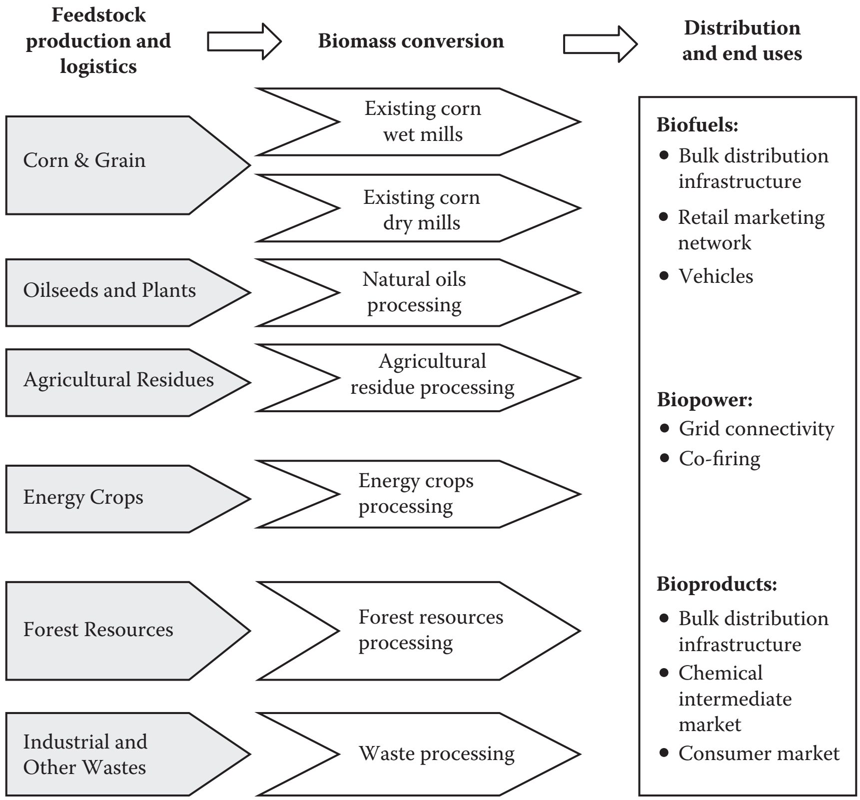

FIGURE 5.3 Resource-based biorefinery pathways.

Composition of Biomass

The ease with which biomass can be converted to useful products or intermediates is determined by the composition of the biomass feedstock. Biomass contains a variety of components, some of which are readily accessible and others that are much more difficult and costly to extract. The composition and subsequent conversion issues for current and potential biomass feedstock compounds are listed and described below:

- *Starch* (glucose) is readily recovered and converted from grain (corn, wheat, rice) into products. Starch from corn grain provides the primary feedstock for today's existing and emerging sugar-based bioproducts, such as polylactide, as well as the entire fuel ethanol industry. Corn grain serves as the primary feedstock for starch used to manufacture today's biobased products. Corn wet mills use a multistep process to separate starch from the germ, gluten (protein), and fiber components of corn grain. The starch streams generated by wet milling are very pure, and acid or enzymatic hydrolysis is used to break the glycosidic linkages of starch to yield glucose. Glucose is then converted into a multitude of useful products.

- *Lignocellulosic biomass* is the non-grain portion of biomass (e.g., cobs, stalks), often referred to as agricultural stover or residues. Energy crops such as switchgrass also contain valuable components, but they are not as readily accessible as starch. These lignocellulosic biomass resources (also called *cellulosic*) are comprised of cellulose, hemicellulose, and lignin. Generally, lignocellulosic material contains 30 to 50% cellulose, 20 to 30% hemicellulose, and 20 to 30% lignin. Some exceptions to this are cotton (98% cellulose) and flax (80% cellulose). Lignocellulosic biomass is perceived as a valuable and largely untapped resource for the future bioindustry; however, recovering the components in a cost-effective way presents a significant technical challenge.
- *Cellulose* is one of nature's polymers and is composed of glucose, a six-carbon sugar. The glucose molecules are joined by glycosidic linkages, which allow the glucose chains to assume an extended ribbon conformation. Hydrogen bonding between chains leads to the formation of the flat sheets that lie on top of one another in a staggered fashion, similar to the way staggered bricks add strength and stability to a wall. As a result, cellulose is very chemically stable and insoluble and serves as a structural component in plant walls.
- *Hemicellulose* is a polymer containing primarily 5-carbon sugars such as xylose and arabinose, with some glucose and mannose dispersed throughout. It forms a short-chain polymer that interacts with cellulose and lignin to form a matrix in the plant wall, strengthening it. Hemicellulose is more easily hydrolyzed than cellulose. Much of the hemicellulose in lignocellulosic material is solubilized and hydrolyzed to pentose and hexose sugars.
- *Lignin* helps bind the cellulosic/hemicellulose matrix while adding flexibility to the mix. The molecular structure of lignin polymers is very random and disorganized and consists primarily of carbon ring structures (benzene rings with methoxyl, hydroxyl, and propyl groups) interconnected by polysaccharides (sugar polymers). The ring structures of lignin have great potential as valuable chemical intermediates; however, separation and recovery of the lignin are difficult.
- *Oils* and *proteins* are obtained from the seeds of certain plants (e.g., soybeans, castor beans) and have great potential for bioproducts. These oils and proteins can be extracted in a variety of ways. Plants raised for this purpose include soy, corn, sunflower, safflower, rapeseed, and others. A large portion of the oils and proteins recovered from oilseeds and corn is processed for human or animal consumption, but they can also serve as raw materials for lubricants, hydraulic fluids, polymers, and a host of other products.
- *Vegetable oils* are composed primarily of triglycerides, also referred to as triacylglycerols. Triglycerides contain a glycerol molecule as the backbone with three fatty acids attached to glycerol's hydroxyl groups.
- *Proteins* are natural polymers with amino acids as the monomer unit. They are incredibly complex materials and their functional properties depend on molecular structure. There are 20 amino acids, each differentiated by their side chain or R-group, and they can be classified as nonpolar and

hydrophobic, polar uncharged, or ionizable. The interactions among the side chains, the amide protons, and the carbonyl oxygen help create the three-dimensional shape of the protein.

PLANT BASICS*

Biotechnology can not only transform materials extracted from plants but also transform the plants to produce more valuable materials. Selective breeding and genetic engineering can be used to improve production of chemical, as well as food, fiber, and structural products. Plants can be developed to produce high-value chemicals in greater quantity than they do naturally, or even to produce compounds they do not naturally produce (NREL, 2002). To optimize plant biomass for more efficient processing requires a better understanding of plants and plant cell-wall structure and function. The plant kingdom ranks second in importance only to the animal kingdom (at least from the human point of view). The importance of plants and plant communities to humans, bioenergy production, and their environment cannot be overstated. Some of the important things plants provide are listed below:

Aesthetics—Plants add to the beauty of the places where we live.
Medicine—80% of all medicinal drugs originate in wild plants.
Food—90% of the world's food comes from only 20 plant species.
Industrial products—Plants are very important for the goods they provide (e.g., plant fibers provide clothing), and wood is used to build homes.
Recreation—Plants are the basis for many important recreational activities, including fishing, nature observation, hiking, and hunting.
Air quality—The oxygen in the air we breathe comes from the photosynthesis of plants.
Water quality—Plants aid in maintaining healthy watersheds, streams, and lakes by holding soil in place, controlling stream flows, and filtering sediments from water.
Erosion control—Plant cover helps to prevent wind or water erosion of the top layer of soil that we depend on.
Climate—Regional climates are impacted by the amount and type of plant cover.
Fish and wildlife habitat—Plants provide the necessary habitat for wildlife and fish populations.
Ecosystem—Every plant species serves an important role or purpose in its community.
Feedstock for bioenergy production—Some important fuel chemicals come from plants, such as ethanol from corn and soy diesel from soybeans.

Although both are important kingdoms of living things, plants and animals differ in many important aspects. Some of these differences are summarized in Table 5.2. Before discussing the basic specifics of plants, it is important to first define a few key plant terms.

* Adapted from Spellman, F.R., *Biology for the Non-Biologist*, Government Institutes Press, Lanham, MD, 2009.

TABLE 5.2
Comparison of Plants and Animals

Plants	Animals
Plants contain chlorophyll and can make their own food.	Animals cannot make their own food and are dependent on plants and other animals for food.
Plants give off oxygen and take in carbon dioxide given off by animals.	Animals give off carbon dioxide, which plants need to make food, and take in oxygen, which they need to breathe.
Plants generally are rooted in one place and do not move on their own.	Most animals have the ability to move fairly freely.
Plants have either no or a very basic ability to sense.	Animals have a much more highly developed sensory and nervous system.

Plant Terminology

Apical meristem consists of meristematic cells located at the tip (apex) of a root or shoot.
Cambium is the lateral meristem in plants.
Chloroplasts are disk-like organelles with a double membrane that are found in eukaryotic plant cells.
Companion cells are specialized cells in the phloem that load sugars into the sieve elements.
Cotyledons are leaf-like structures (sometimes referred to as a *seed leaf*) present in the seeds of flowering plants.
Dicots are one of the two main types of flowering plants; they are characterized by having two cotyledons.
Diploid refers to having two of each kind of chromosome (2*n*).
Guard cells are specialized epidermal cells that flank stomata and whose opening and closing regulate gas exchange and water loss.
Haploid refers to having only a single set of chromosomes (*n*).
Meristem is a group of plant cells that can divide indefinitely, providing new cells for the plant.
Monocots are one of two main types of flowering plants; they are characterized by having a single cotyledon.
Periderm is a layer of plant tissue derived from the cork cambium and then secondary tissue, replacing the epidermis.
Phloem is a complex vascular tissue that transports carbohydrates throughout the plant.
Sieve cells are conducting cells in the phloem of vascular plants.
Stomata are pores on the underside of leaves that can be opened or closed to control gas exchange and water loss.
Thallus is the main plant body, not differentiated into a stem or leaves.
Tropism is the plant behavior that controls the direction of plant growth.

TABLE 5.3
Main Phyla (Divisions) of Plants

Phylum (Division)	Examples
Bryophyta	Mosses, liverworts, and hornworts
Coniferophyta	Conifers such as redwoods, pines, and firs
Cycadophyta	Cycads, sago palms
Gnetophyta	Shrub trees and vines
Ginkophyta	*Ginkgo* (the only genus)
Lycophyta	Lycopods (look like mosses)
Pterophyta	Ferns and tree-ferns
Anthophyta	Flowering plants, including oak, corn, maize, and herbs

Vascular tissue is found in the bodies of vascular plants that transport water, nutrients, and carbohydrates. The two major kinds are xylem and phloem.

Xylem is vascular tissue of plants that transports water and dissolved minerals from the roots upwards to other parts of plant. Xylem often also provides mechanical support against gravity.

Although not typically acknowledged, plants are as intricate and complicated as animals. Plants evolved from photosynthetic protists and are characterized by photosynthetic nutrition, cell walls made from cellulose and other polysaccharides, lack of mobility, and a characteristic life cycle involving an alternation of generations. The phyla (divisions) of plants and some examples are shown in Table 5.3.

Plant Cell

A brief summary of plant cells is provided here (see Figure 5.4).

- *Plants have all the same organelles that animal cells have* (e.g., nucleus, ribosomes, mitochondria, endoplasmic reticulum, Golgi apparatus).
- *Plants have chloroplasts*, the special organelles that contain chlorophyll and allow plants to carry out photosynthesis.
- *Plant cells can sometimes have large vacuoles for storage.*
- *Plant cells are surrounded by a rigid cell wall made of cellulose,* in addition to the cell membrane that surrounds animal cells. These walls provide support.

DID YOU KNOW?

In the Pacific Northwest and Oregon, biomass energy costs are about 5.2 to 6.7 cents per kWh. This is comparatively costlier than the electricity generated from natural gas, which is only 2.8 cents per kWh (Karthik, 2010).

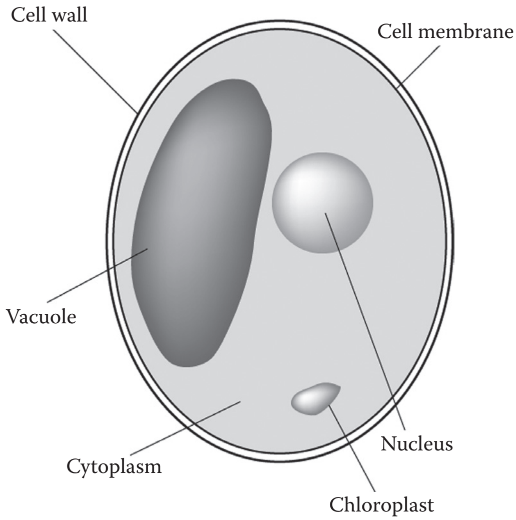

FIGURE 5.4 Plant cell.

Vascular Plants

Vascular plants, also called *tracheophytes*, have special vascular tissue for the transport of necessary liquids and minerals over long distances. Vascular tissues are composed of specialized cells that create "tubes" through which materials can flow throughout the plant body. These vessels are continuous throughout the plant, allowing for the efficient and controlled distribution of water and nutrients. In addition to this transport function, vascular tissues also support the plant. The two types of vascular tissue are xylem and phloem:

- *Xylem* consists of a tube or a tunnel (pipeline) in which water and minerals are transported throughout the plant to leaves for photosynthesis. In addition to distributing nutrients, xylem (wood) provides structural support. After a time, the xylem at the center of older trees ceases to function in transport and takes on a supportive role only.
- *Phloem* tissue consists of cells called *sieve tubes* and *companion cells.* Phloem tissue moves dissolved sugars (carbohydrates), amino acids, and other products of photosynthesis from the leaves to other regions of the plant.

The two most important tracheophytes are gymnosperms (*gymno*, naked; *sperma*, seed) and angiosperms (*angio*, vessel, receptacle, container).

- *Gymnosperms*—The plants we recognize as gymnosperms represent the sporophyte generation (i.e., the spore-producing phase in the life cycle of a plant that exhibits alternation of generation). Gymnosperms were the first tracheophytes to use seeds for reproduction. The seeds develop in protective structures called *cones.* A gymnosperm contains some cones that are

female and some that are male. Female cones produce spores that, after fertilization, become eggs enclosed in seeds that fall to the ground. Male cones produce pollen, which is taken by the wind and fertilizes female eggs by that means. Unlike flowering plants, the gymnosperm does not form true flowers or fruits. Coniferous tress such as firs and pines are good examples of gymnosperms.

- *Angiosperms*—These flowering plants are the most highly evolved plants and the most dominant in present times. They have stems, roots, and leaves. Unlike gymnosperms such as conifers and cycads, the seeds of angiosperms are found in the flowers. Angiosperm eggs are fertilized and develop into a seed in an ovary that is usually in a flower.

The two types of angiosperms are monocots and dicots:

- *Monocots*—These angiosperms start with one seed leaf (cotyledon), thus their name, which is derived from the presence of a single cotyledon during embryonic development. Monocots include grasses, grains, and other narrow-leaved angiosperms. The main veins of their leaves are usually parallel and unbranched, the flower parts occur in multiples of three, and a fibrous root system is present. Monocots include orchids, lilies, irises, palms, grasses, and wheat, corn, and oats.
- *Dicots*—Angiosperms in this group grow two seed leaves (two cotyledons). Most plants are dicots and include maples, oaks, elms, sunflowers, and roses. Their leaves usually have a single main vein or three or more branched veins that spread out from the base of the leaf.

Leaves

The principal function of leaves is to absorb sunlight for the manufacturing of plant sugars in photosynthesis. The broad, flattened surfaces of the leaves gather energy from sunlight, while apertures on their undersides bring in carbon dioxide and release oxygen. Leaves develop as a flattened surface in order to present a large area for efficient absorption of light energy. On its two exteriors, the leaf has layers of epidermal cells that secrete a waxy, nearly impermeable cuticle (chitin) to protect against water loss (dehydration) and fungal or bacterial attack. Gases diffuse in or out of the leaf through *stomata*, small openings on the underside of the leaf. The opening or closing of the stomata occurs through the swelling or relaxing of *guard cells*. If the plant wants to limit the diffusion of gases and the transpiration of water, the guard cells swell together and close the stomata. Leaf thickness is kept to a minimum so that gases that enter the leaf can diffuse easily throughout the leaf cells.

Chlorophyll and Chloroplasts

The green pigment in leaves is *chlorophyll*. Chlorophyll absorbs red and blue light from the sunlight that falls on leaves; therefore, the light reflected by the leaves is diminished in red and blue and appears green. The molecules of chlorophyll are large. They are not soluble in the aqueous solution that fills plant cells. Instead, they

DID YOU KNOW?

Charles Darwin was the first to discuss how plants respond to light. He found that new shoots of grasses bend toward the light because the cells on the dark side grow faster than those on the lighted side.

are attached to the membranes of disc-like structures, called *chloroplasts*, inside the cells. Chloroplasts are the site of photosynthesis, the process in which light energy is converted to chemical energy. In chloroplasts, the light absorbed by chlorophyll supplies the energy used by plants to transform carbon dioxide and water into oxygen and carbohydrates. Chlorophyll is not a very stable compound; bright sunlight causes it to decompose. To maintain the amount of chlorophyll in their leaves, plants continuously synthesize it. The synthesis of chlorophyll in plants requires sunlight and warm temperatures; therefore, during summer chlorophyll is continuously broken down and regenerated in the leaves of trees.

Photosynthesis

Because our quality of life, and indeed our very existence, depends on photosynthesis, it is essential to understand it. In photosynthesis, plants (and other photosynthetic autotrophs) use the energy from sunlight to create the carbohydrates necessary for cell respiration. More specifically, plants take water and carbon dioxide and transform them into glucose and oxygen:

$$6CO_2 + 6H_2O + \text{Light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

This general equation of photosynthesis represents the combined effects of two different stages. The first stage is called the *light reaction* and the second stage is called the *dark reaction*. The light reaction is the photosynthesis process in which solar energy is harvested and ultimately converted into NADPH and adenosine triphosphate (ATP); the light reaction can only occur in light. In the dark reaction, the NADPH and ATP formed by the light reaction reduce carbon dioxide and convert it into carbohydrates; the dark reaction can occur in the dark as long as ATP is present.

Roots

Roots absorb nutrients and water, anchor the plant in the soil, provide support for the stem, and store food. They are usually below ground and lack nodes, shoots, and leaves. There are two major types of root systems in plants. *Taproot systems* have a stout main root with a limited number of side-branching roots. Examples of taproot system plants are nut trees, carrots, radishes, parsnips, and dandelions. Taproots make transplanting difficult. The second type of root system, *fibrous*, has many branched roots. Examples of fibrous root plants are most grasses, marigolds, and beans. Radiating from the roots is a system of root hairs, which vastly increase the absorptive surface area of the roots. Roots also anchor the plant in the soil.

Growth in Vascular Plants

Vascular plants undergo two kinds of growth (growth is primarily restricted to meristems). *Primary growth* occurs relatively close to the tips of roots and stems. It is initiated by apical meristems and is primarily involved in the extension of the plant body. The tissues that arise during primary growth are called primary tissues, and the plant body composed of these tissues is called the *primary plant body.* Most primitive vascular plants are entirely made up of primary tissues. *Secondary growth* occurs in some plants; secondary growth thickens the stems and roots. Secondary growth results from the activity of lateral meristems, or *cambia*, of which there are two types:

1. *Vascular cambium* gives rise to secondary vascular tissues (secondary xylem and phloem). The vascular cambium gives rise to xylem on the inside and phloem on the outside.
2. *Cork cambium* forms the periderm (bark). The periderm replaces the epidermis in woody plants.

Plant Hormones

Plant growth is controlled by plant hormones, which influence cell differentiation, elongation, and division. Some plant hormones also affect the timing of reproduction and germination.

- *Auxins* affect cell elongation (tropism), apical dominance, and fruit drop or retention. Auxins are also responsible for root development, secondary growth in the vascular cambium, inhibition of lateral branching, and fruit development. Auxin is involved in the absorption of vital minerals and fall color. As a leaf reaches its maximum growth, auxin production declines. In deciduous plants this triggers a series of metabolic steps that cause the reabsorption of valuable materials (such as chlorophyll) and their transport into the branch or stem for storage during the winter months. When the chlorophyll is gone, the other pigments typical of fall color become visible.
- *Kinins* promote cell division and tissue growth in the leaf, stem, and root. Kinins are also involved in the development of chloroplasts, fruits, and flowers. In addition, they have been shown to delay senescence (aging), especially in leaves, which is one reason why florists use cytokinins on freshly cut flowers—when treated with cytokinins, they remain green, protein synthesis continues, and carbohydrates do not break down.
- *Gibberellins* are produced in the root growing tips and act as a messenger to stimulate growth, especially elongation of the stem, and can also end the dormancy period of seeds and buds by encouraging germination. Additionally, gibberellins play a role in root growth and differentiation.
- *Ethylene* controls the ripening of fruits. Ethylene may ensure that flowers are carpelate (female), while gibberellin confers maleness on flowers. It also contributes to the senescence of plants by promoting leaf loss and other changes.
- *Inhibitors* restrain growth and maintain the period of dormancy in seeds and buds.

Tropisms

Tropism is the movement (including growth in plants) of an organism in response to an external stimulus. Tropisms controlled by hormones are a unique characteristic of sessile organisms such as plants that enable them to adapt to different features of their environment—gravity, light, water, and touch—so they can flourish. The three main types of tropisms are

- *Phototropism*—The tendency of plants to grow or bend (move) in response to light. Phototropism results from the rapid elongation of cells on the dark side of the plant, which causes the plant to bend in the opposite direction. For example, the stems and leaves of a geranium plant growing on a windowsill always turn toward the light.
- *Gravitropism*—The tendency of plants to grow toward or against gravity. A plant that displays positive gravitropism (plant roots) will grow downward, toward the center of earth. That is, gravity causes the roots of plants to grow down so that the plant is anchored in the ground and has enough water to grow and thrive. Plants that display negative gravitropism (plant stems) will grow upward, away from the earth. Most plants are negatively gravitropic. Gravitropism is also controlled by auxin. In a horizontal root or stem, auxin is concentrated in the lower half, pulled by gravity. In a positively gravitropic plant, this auxin concentration will inhibit cell growth on the lower side, causing the stem to bend downward. In a negatively gravitropic plant, this auxin concentration will inspire cell growth on that lower side, causing the stem to bend upward.
- *Thigmotropism*—The tendency of plants to grow or bend in response to touch. Some people notice that their houseplants respond to thigmotropism by growing better when they are touched and have attention paid to them. Touch causes parts of the plant to thicken or coil as they touch or are touched by environmental entities. For example, tree trunks grow thicker when exposed to strong winds and vines tend to grow straight until they encounter a substrate to wrap around.

Photoperiodism

Photoperiodism is the response of an organism, such as plants, to naturally occurring changes in light during a 24-hour period. The site of perception of photoperiod in plants is leaves. Sunflowers are particularly well known for their photoperiodism, or their ability to open and close in response to the changing position of the sun throughout the day. All flowering plants have been placed in one of three categories with respect to photoperiodism:

- *Short-day plants*—Flowering is promoted by day lengths shorter than a certain critical day length; includes poinsettias, chrysanthemums, goldenrod, and asters.

- *Long-day plants*—Flowering is promoted by day lengths longer than a certain critical day length; includes spinach, lettuce, and most grains.
- *Day-neutral plants*—Flowering response is insensitive to day length; includes tomatoes, sunflowers, dandelions, rice, and corn.

Plant Reproduction

Plants can reproduce both sexually and asexually. Each type of reproduction has its benefits and disadvantages. A comparison of sexual and asexual plant reproduction is provided in the following text.

Sexual Reproduction

- Sexual reproduction occurs when a sperm nucleus from the pollen grain fuses with an egg cell from the ovary of the pistil (the female reproductive structures in flowers, consisting of the stigma, style, and ovary).
- Each brings a complete set of genes and produces genetically unique organisms.
- The resulting plant embryo develops inside the seed and grows when the seed is germinated.

Asexual Reproduction

- Asexual reproduction occurs when the vegetative part of a plant, root, stem, or leaf gives rise to a new offspring plant whose genetic content is identical to the parent plant. An example would be a plant reproducing by root suckers, shoots that come from the root system. The breadfruit tree is an example.
- Asexual reproduction is also called *vegetative propagation*. It is an important way for plant growers to get many identical plants from one very quickly.
- By asexual reproduction plants can spread and colonize an area quickly (e.g., crabgrass).

Plant Cell Walls

Figure 5.5 shows the basic organelles within a standard plant cell, including the cell wall. It should be pointed out, however, that plants can have two types of cell walls, primary and secondary. Primary cell walls contain cellulose consisting of hydrogen-bonded chains of thousands of glucose molecules, in addition to hemicellulose and other materials all woven into a network. Certain types of cells, such as those in vascular tissues, develop secondary walls inside the primary wall after the cell has stopped growing. These cell-wall structures also contain lignin, which provides rigidity and resistance to compression. The area formed by two adjacent plant cells, the middle lamella, typically is enriched with pectin. Cellulose in higher plants is organized into microfibrils, each measuring about 3 to 6 nm in diameter and containing up to 36 glucan chains having thousands of glucose residues. Like steel

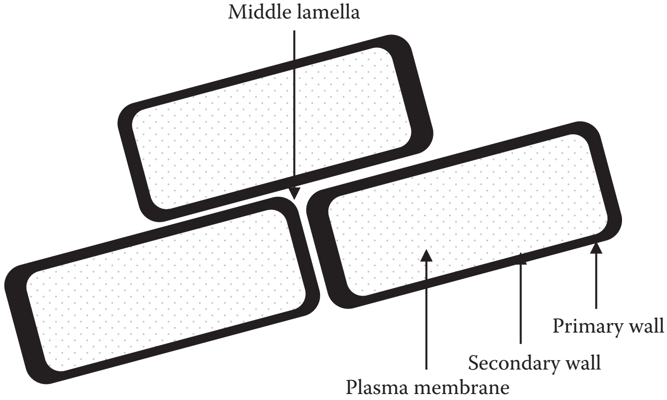

FIGURE 5.5 Plant cell walls.

> **DID YOU KNOW?**
>
> Cellulose microfibrils are composed of parallel and linear chains of glucose molecules that are tightly cross-linked by intermolecular hydrogen bonds.

girders stabilizing a skyscraper's structure, the mechanical strength of the primary cell wall is due mainly to the microfibril scaffold (i.e., crystalline cellulose core) (USDOE, 2007).

FEEDSTOCKS*

First-Generation Feedstocks

For first-generation feedstocks, the type of major end-use product is easily categorized (see Table 5.4). Corn and sugarcane are the most commonly used feedstocks for ethanol production. Soybean and other vegetable oils and animal fats are used for the production of biodiesel (and bioproducts). Manure and landfill organic waste are used for methane production and the generation of electricity. Corn is used for ethanol production and currently is the leading feedstock used in the United States. Several factors favor a positive outlook for further near-term growth in corn ethanol production. Continued high oil prices will provide economic support for the expansion of all alternative fuel programs, including corn ethanol. Technology improvements that increase feedstock productivity and fuel conversion yields and positive spillovers from second-generation technologies (biomass gasification in ethanol refiners) will also help to lower production costs for corn ethanol. Among the factors likely to limit future growth of corn ethanol production are increased feedstock and

* Adapted from BR&Di, *The Economics of Biomass Feedstocks in the United States: A Review of the Literature*, Biomass Research and Development Initiative, Washington, DC, 2008.

other production costs, increased competition from unconventional liquid fossil fuels (e.g., oil sands, coal, heavy oil, shale), the emergence of cellulosic ethanol as a low-cost competitor, and new policies to reduce greenhouse gas (GHG) emissions that could favor advanced biofuels over corn ethanol.

Biodiesel is another type of biofuel experiencing expansion. Although its production costs are higher than ethanol, biodiesel has some environmental advantages, including biodegradability and lower sulfur and carbon dioxide emissions when burned. Biodiesel production in the United States increased rapidly from less than 2 million gallons in 2000 to about 500 million gallons in 2007. Policy incentives in the Energy Independence and Security Act of 2007 are expected to sustain demand for 1 billion gallons per year of this fuel after 2011. A variety of oil-based feedstocks are converted to biodiesel using a process known as *transesterification*. This is the process of exchanging the organic group R'' of an ester with the organic group R' of an alcohol. These reactions are often catalyzed by the addition of an acid or base as shown below:

Transesterification: Alcohol + Ester → Different alcohol + Different ester

The oil-based feedstocks include vegetable oils (mostly soy oil), recycled oils and yellow grease, and animal fats such as beef tallow. It takes 3.4 kg of oil/fat to produce 1 gallon of biodiesel (Baize, 2006). Biodiesel production costs are high compared to ethanol, with feedstocks accounting for 80% or more of total costs.

The biodiesel industry consists of many small plants that are highly dispersed geographically. Decisions about plant location are primarily determined by local availability and access to the feedstock. Recent expansion in biodiesel production is affecting the soybean market. Achieving a nationwide target of 2% biodiesel blend in diesel transportation fuel, for example, would require 2.8 million metric tons (MT) of vegetable oil, or about 30% of current U.S. soybean oil production (USDA, 2012).

One of the key biodiesel byproducts is glycerin. At the present time there is concern about producing glycerin mainly because there are no existing markets for the product; however, recent technological developments include an alternative chemical process that would produce biodiesel without glycerin. In addition, new processes are being tested that further transform glycerin into propylene glycol, which is used in the manufacture of antifreeze.

Second-Generation Feedstocks: Short-Term Availability

Agricultural residues, a second-generation biomass feedstock, offer a potentially large and readily available biomass resource, but sustainability and conservation constraints could place much of it out of reach. Given current U.S. cropland use, corn and wheat offer the most potentially recoverable residues; however, these residues play an important role in recycling nutrients in the soil and maintaining long-term fertility and land productivity. Removing too much residue could aggravate soil erosion and deplete the soil of essential nutrients and organic matter.

Safe removal rate methodologies, based on soil erosion, have been developed. Methodologies to determine removal rates while safeguarding soil fertility and meeting conservation objectives still need to be developed. Studies have shown that

TABLE 5.4
Biomass Feedstocks and Major Bioenergy End-Use Applications

Feedstocks		First-Generation Fuels			Second-Generation Fuels	
		Ethanol	Biodiesel	Methane	Cellulosic Ethanol	Thermoch Fuels (e.g., Ethanol, Diesel, Butanol)
First-generation						
Starch and sugar feedstock for ethanol	Corn	X				
	Sugarcane	X				
	Molasses	X				
	Sorghum	X				
Vegetable oil and fats and biodiesel	Vegetable oils		X			
	Recycled fats and grease		X			
	Beef tallow		X			
Second-generation (short-term)						
Agricultural residues and livestock byproducts	Corn stover				X	
	Wheat straw				X	
	Rice straw				X	
	Bagasse				X	
	Manure			X		
Forest biomass	Logging residues				X	X
	Fuel treatments				X	X
	Conventional wood				X	X

Urban woody waste and landfills	Primary wood products		X	X
	Secondary mill residues		X	X
	Municipal solid wastes	X	X	X
	Construction/ demolition wood			
	Landfills	X	X	
Second-generation (long-term)				
Herbaceous energy crops	Switchgrass		X	X
	Miscanthus		X	X
	Reed canary grass		X	X
	Sweet sorghum			
	Alfalfa		X	X
Short-rotation woody crops	Willow		X	X
	Hybrid poplar		X	X
	Cottonwood		X	X
	Sycamore pines		X	X
	Eucalyptus		X	X

under current tillage practices the national average safe removal rate based on soil erosion for corn stover is less than 30%. Actual rates vary widely depending on local conditions. In other words, much of the generated crop residues may be out of reach for biomass use if soil conservation goals are to be achieved (Graham et al., 2007).

The estimated delivery costs for agricultural residues vary widely depending on crop type, load resource density, storage and handling requirements, and distance and transportation costs. Moreover, existing estimates are largely derived from engineering models, which may not account for economic conditions. Agricultural residue feedstocks (such as corn stover) have a significant advantage in that they can be readily integrated into the expanding corn ethanol industry; however, dedicated energy crops (such as switchgrass) may have more benign environmental impacts.

Another significant biomass source is *forest biomass*, which can be immediately available should the bioenergy market develop. Logging residues are associated with timber industry activities and constitute significant biomass resources in many states, particularly in the Northeast, North Central, Pacific Northwest, and Southeast. In the western states, the predominance of public lands and environmental pressure reduce the supply potential for logging residues, but there is a vast potential for biomass from thinning undertaken to reduce the risk of forest fires. However, the few analyses that have examined recoverability of logging residues cite the need to account for factors such as the scale and location of biorefineries and biopower plants, as well as regional resource density.

The potential for forest residues may be large but the actual quantities available for biomass conversion may be low due to the economics of harvesting, handling, and transporting the residues from forest areas to locations where they could be used. It is not clear how these residues compete with fossil fuels in the biopower and co-firing industries. In addition, there are competing uses for these products in the pulp and paper industry, as well as different bioenergy end uses. Economic studies of logging residues suggest a current lack of competitiveness with fossil fuels (coal, gas), but logging residues could become more cost competitive with further improvements in harvesting and transportation technologies and with policies that require a fuller accounting of the social and environmental benefits from converting forest residues to biopower or biofuels.

Another source of forest residues that could be recovered in significant quantities is biomass from fuel treatments and thinnings. Fuel treatment residues are the byproduct of efforts to reduce the risk of loss from fire, insects, and disease and therefore present substantially different challenges than do logging residues. The overall value of forest health benefits such as clean air and water is generally believed to exceed the cost of treatment. However, treated forests are often distant from end-use markets, resulting in high transportation costs to make use of the harvested material. Road or trail access, steep terrain, and other factors commonly limit thinning operations in western forests.

Transportation costs can be a significant factor in the cost of recovering biomass. As much as half the cost of the material delivered to a manufacturing facility may be attributed to transportation. The offset to the high-cost transportation of forest thinnings is onsite densification of the biomass. This could entail pelletization, fast pyrolysis (to produce bio-oil), or baling. The economics of transporting thinned woody residues vs. onsite densification depend on the distance to end-use markets. Densification may be

more economical if power generation facilities are far away. In addition to co-firing or co-generation facilities, improvements in thermochemical conversion efficiency and establishment of small-scale conversion facilities using gasification and/or pyrolysis may favor the use of forest residues for biofuel production (Polagye et al., 2007).

A third major category of immediately available second-generation biomass is wood residues from *secondary mill products* and *urban wood waste*. Urban wood waste provides a relatively cheap feedstock to supplement other biomass resources (Wiltsee, 1998). Urban wood waste encompasses the biomass portion of commercial, industrial, and municipal solid waste (MSW), while secondary mill residues include sawdust, shavings, wood trims, and other byproducts generated from processing lumber, engineered wood products, or wood particles. Both urban wood waste and secondary mill residues have several primary uses and disposal methods. Urban wood waste not used in captive markets (such as the pulpwood industry) could be used as a biomass either to generate electricity or to produce cellulosic ethanol when it becomes commercially viable.

The amount of urban wood wastes produced in the United States is significant and their use as biomass could be economically viable, particularly in large urban centers (Wiltsee, 1998). Several national availability estimates exist for various types of urban wood wastes, but estimates vary depending on methodology, product coverage, and assumptions about alternative uses (McKeever, 2004; Wiltsee, 1998). One of the challenges with regard to the potential availability of urban woody waste is to sort out the portion that is available (not currently used) and determine alternative uses, including those used by captive markets (not likely to be diverted to bioenergy). One assessment of urban wood waste finds that 36% of total biomass generated is currently sold to noncaptive markets, and 50% of the unused residues are not available due to contamination, quality, or recoverability.

One source of recurring and potentially available carbon feedstock is municipal solid waste. The U.S. Environmental Protection Agency (USEPA) estimated that in 2005 245.7 million tons of MSW were generated in the United States, of which 79 million tons were recycled, 33.4 millions tons were diverted to energy recovery, and 133.3 million tons were disposed of in landfills. As such, landfilled material represents a potentially significant source of renewable carbon that could be used for fuel/energy production or in support of biofuel production.

Attributes of the Perfect Energy Crop

The perfect energy crop has

- High biomass
- Improved composition and structure
- Disease and pest resistance
- Optimized architecture
- Salt, pH, and aluminum tolerance
- Rapid and cost-effective propagation
- Stand establishment (cold germination and cold growth)
- Perennial
- Deep roots

Second-Generation Feedstocks: Long-Term Availability

Large-scale biofuels production, in the long run, will require other resources, including dedicated energy crops. Dedicated feedstocks are perennial grasses and trees grown as crops specifically to provide the required raw materials to bioenergy producers. A steady supply of low-cost, uniform, and consistent-quality biomass feedstock will be critical for the economic viability of cellulosic ethanol production. During the late 1980s, the Department of Energy sponsored research on perennial herbaceous (grassy) biomass crops, particularly switchgrass, which is considered a model energy crop because of its many perceived advantages: (1) native to North America, (2) high biomass yield per acre, (3) wide regional coverage, and (4) adaptability to marginal land conditions. An extensive research program on switchgrass in the 1990s generated a wealth of information on high-yielding varieties, regional adaptability, and management practices. Preliminary field trials show that the economic viability of switchgrass cultivation depends critically on the initial establishment success. During this phase, seed dormancy and seedling sensitivity to soil and weed conditions require that recommended practices be closely followed by growers. Viable yields require fertilization rates at about half the average for corn.

Switchgrass (*Panicum virgatum*) is a hardy, deep-rooted, perennial, rhizomatous, warm-season grass native to North America. It is believed to be most suitable for cultivation in marginal lands, low-moisture lands, and lands with lower opportunity costs such as pastures, including lands under the Conservation Reserve Program (CRP) where the federal government pays landowners annual rent for keeping land out of production (McLaughlin and Kzos, 2005). Additionally, a large amount of highly erodible land in the Corn Belt is unsuitable for straw or stover removal but is potentially viable for dedicated energy crops such as switchgrass. Factors favoring adoption of switchgrass include selection of suitable lands, environmental benefits (carbon balances, improved soil nutrients and quality), and the use of existing hay production techniques to grow the crop. Where switchgrass is grown on CRP lands, payments help to offset production costs. Factors discouraging switchgrass adoption include no possibility for crop rotation; farmers' risk aversion for producing a new crop because of lack of information, skills, and know-how; potential conflict with on-farm and off-farm scheduling activities; and a lack of compatibility with long-term land tenure. Overall, production budget and delivery cost assessments suggest that switchgrass is a high-cost crop (undercurrent technology and price conditions) and may not compete with established crops, except in areas with low opportunity costs (e.g., pasture land, marginal lands).

Substantial variability is apparent in the economics of switchgrass production and assessments of production budgets and delivered costs. Factors at play include methods for storage and handling, transport distances, yields, and types of land used (cropland vs. grassland). When delivered costs of switchgrass are translated into break-even prices (compared with conventional crops), it becomes apparent that cellulosic ethanol or biopower plants would have to offer relatively high prices for switchgrass to induce farmer to grow it (Rinehart, 2006). However, the economics of switchgrass could improve if growers benefited from CRP payments and other payments tied to environmental services (such as carbon credits). In the long run,

DID YOU KNOW?

With regard to establishing switchgrass, no single method can be suggested for all situations (Parrish et al., 2008). No-till and conventional tillage can be used to establish the crop. When seeded as part of a diverse mixture, planting guidelines for warm-season grass mixtures for conservation plantings should be followed. Several key factors can increase the likelihood of success for establishing switchgrass, including the following:

- Plant switchgrass after the soil is well warmed during the spring.
- Use seeds that are highly germinable and plant 0.6 to 1.2 cm deep, or up to 2 cm deep in sandy soils.
- Pack or firm the soil both before and after seeding.
- Provide no fertilization at planting to minimize competition.
- Control weeds with chemical or cultural control methods.

the viability of an energy crop such as switchgrass hinges on continued reductions in cellulosic ethanol conversion costs and sustained improvements in yield and productivity through breeding, biotechnology, and agronomic research.

Although it is an important biofuels crop, switchgrass does have limitations. Switchgrass is not optimally grown everywhere. For example, in the upper Midwest under wet soils, reed canarygrass (*Phalaris arundinacea*) is more suitable, while semitropical grass species are better adapted to the Gulf Coast region. State and local efforts are testing alternatives to switchgrass, including reed canarygrass, a tall, perennial grass that forms extensive single-species stands along the margins of lakes and streams; *Miscanthus* (often confused with "elephant grass"), which is a rapid-growth, low-mineral-content, high-biomass-yield plant; and other species.

With regard to long-run sustainability, the ecology of perennial grassy crops favors a multiplicity of crops or even a mix of species within the same area. Both ecological and economic sustainability favor the development of a range of herbaceous species for optimal use of local soil and climatic conditions. A mix of several energy crops in the same region would help reduce the risk of epidemic pests and disease outbreak and optimize the supply of biomass to an ethanol or biopower plant because different grasses mature and can be harvested at different times. Moreover, development of future energy crops must be evaluated from the standpoint of their water use efficiency, impact on soil nutrient cycling, effect on crop rotations, and environmental benefit (improved energy use efficiency and reduced greenhouse gas

DID YOU KNOW?

The main advantage of using switchgrass over corn as an ethanol feedstock is that its cost of production is generally about half that of grain corn and more biomass energy per hectare can be captured in the field (Samson et al., 2008).

emissions, nutrient runoff, pesticide runoff, and land-use impacts). In the long run, developing a broad range of grassy crops for energy use is compatible with both sustainability and economic viability criteria.

Short-rotation woody crops (SRWCs) represent another important category of future dedicated energy crops. Among the SRWCs, hybrid poplar, willow, American sycamore, sweetgum, and loblolly have been extensively researched for their very high biomass yield potential. Breeding programs and management practices continue to be developed for these species. SRWCs are based on a high-density plantation system and more frequent harvesting (every 3 to 4 years for willow and 7 years for hybrid poplar). Following is a summary of short-rotation crops:

- *Hybrid poplar*—This species is very site specific and has a limited growing niche. It requires an abundant and continuous supply of moisture during the growing season. Soils should be moist but not continually saturated and should have good internal drainage. It prefers damp, well-drained, fine sandy-loam soils located near streams, where coarse sand is first deposited as flooding occurs. Hybrid poplars are among the fastest-growing trees in North America—in just six growing seasons, hybrid poplars can reach 60 feet or more in height. They are well suited for the production of bioenergy, fiber, and other biobased products.
- *Willow species (Salix)*—In folklore and myth, a willow tree is believed to be quite sinister, capable of uprooting itself and stalking travelers. The reality is that willows are used for biofiltration, constructed wetlands, ecological wastewater treatment systems, hedges, land reclamation, landscaping, phytoremediation, stream bank stabilization (bioengineering), slope stabilization, soil erosion control, shelterbelt and windbreak, soil building, soil reclamation, tree bog composting toilets, and wildlife habitat. Willow is grown for biomass or biofuels in energy forestry systems as a consequence of its high energy-in/energy-out ratio, large carbon mitigation potential, and fast growth (Aylott, 2008). Willow is also grown and harvested for making charcoal.
- *American sycamore*—Sycamores prefer alluvial soils along streams in bottomlands. Sycamore growth and yield are less than those of poplars and willows.
- *Sweetgum (Liquidambar styraciflua)*—Sweetgum is a species tolerant of a variety of soils, but it grows best on rich, moist, alluvial clay and loam soils of river bottoms.
- *Loblolly pine (Pinus taeda)*—Loblolly pine is quite adaptable to a variety of sites. It performs well on both poorly drained bottomland flats and modestly arid uplands. Biomass for energy is currently being obtained from precommercial thinnings and from logging residues in loblolly pine stands. Utilization will undoubtedly increase, and loblolly pine energy plantations may become a reality.

In many parts of the country, plantations of poplar, willow, pines, and cottonwood have been established and are being commercially harvested. Willows are being planted in New York, particularly following enactment of the Renewable Portfolio

DID YOU KNOW?

Fermentation is a series of chemical reactions that convert sugars to ethanol. The fermentation reaction is caused by yeast or bacteria, which feed on the sugars. Ethanol and carbon dioxide are produced as the sugar is consumed. The simplified fermentation reaction equation for the 6-carbon sugar glucose is

$$\underset{\text{Glucose}}{C_6H_{12}O_6} \rightarrow 2\ \underset{\text{Ethanol}}{CH_3CH_2OH} + 2\ \underset{\text{Carbon dioxide}}{CO_2}$$

Standard (RPS) and other state incentives. Over 30,000 hectares of poplars are being grown in Minnesota, and several thousand hectares are also grown as part of a DOE-funded project to provide biomass for a power utility company in southern Minnesota. The Pacific Northwest has large plantations of hybrid poplars, estimated at 60,000 hectares as of 2007. Most of these plantations are currently used for pulp wood, with little volume being used for bioenergy. Because SRWCs can be used either for biomass or as feedstock for pulp and other products, pulp demand will influence the cost of using it for bioenergy production.

An important consideration for energy crops (e.g., switchgrass, poplar, willow) is the potential for increasing yields and developing other desirable characteristics. Most energy crops are unimproved or have been bred only recently for biomass yield, whereas corn and other commercial food crops have undergone substantial improvements in yield, disease resistance, and other agronomic traits. A more complex understanding of biological systems and application of the latest biotechnological advances would accelerate the development of new biomass crops with desirable attributes. These attributes include increased yields and processability, optimal growth in specific microclimates, better pest resistance, efficient nutrient use, and greater tolerance to moisture deficits and other sources of stress. Agronomic and breeding improvements of these new crops could provide a significant boost to future energy crop production.

Biothanol Production by Dry Corn Mill Process

Ethanol production from dry corn milling follows a seven-step process as shown in Figure 5.6. First, corn feedstock is cleaned and milled (ground into corn meal), and the milled corn is then converted to a slurry. The slurry is liquefied (slurried with water to form a mash), and the enzymes yield glucose. Yeast is then added to the mash to convert starch into a simple sugar (dextrose) in a process known as *saccharification*. After liquefaction, the mash is cooked in a saccharification tank to reduce bacterial levels and it then moves through several fermenters where fermentation takes place (sugar is converted to ethanol by yeast). The resulting "beer" containing 2 to 12% ethanol is then distilled into ethanol at 95% alcohol and 5% water. The remaining solids (stillage) are collected during distillation, dried, and sold as an animal feed known as dried distillers' grain (DDG). The final removal of water from the ethanol to less than 1% (dehydration) allows it to be blended with gasoline.

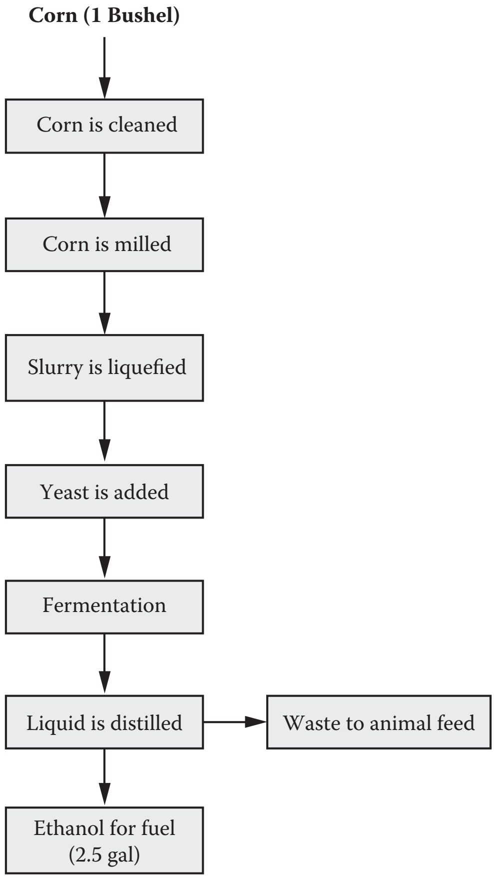

FIGURE 5.6 Flow diagram for production of ethanol from corn.

Gasoline Gallon Equivalent (GGE)

Before beginning our discussion about alternative renewable fuels used for transportation purposes, it is important that the reader has a fundamental understanding of the difference between conventional gasoline and diesel fuel energy output as compared to non-conventional renewable products. Typically, this comparison is made utilizing a standard engineering parameter known as the *gasoline gallon equivalent* (GGE), which is the ratio of the number of British thermal units (Btu) available in 1 U.S. gallon (1 gal) of gasoline to the number of British thermal units available in 1 gal of the alternative substance in question. NIST (2012) defined a gasoline gallon equivalent as 5660 pounds of natural gas. The GGE parameter allows consumers to compare the energy content of competing fuels against a commonly known fuel—gasoline. Table 5.5 provides GGE and Btu/unit value comparisons for various fuels.

TABLE 5.5
Gasoline Gallon Equivalent (GGE)

Fuel	GGE	Btu
Gasoline (base)	1.0000 gal	114,000 Btu/gal
Gasoline (conventional, summer)	0.9960 gal	114,500 Btu/gal
Gasoline (conventional, winter)	1.0130 gal	112,500 Btu/gal
Gasoline (reformulated gasoline, ethanol)	1.0190 gal	111,836 Btu/gal
Gasoline (reformulated gasoline, ETBE)	1.0190 gal	111,811 Btu/gal
Gasoline (reformulated gasoline, MTBE)	1.0200 gal	111,745 Btu/gal
Gasoline (10% MBTE)	1.0200 gal	112,000 Btu/gal
Gasoline (regular unleaded)	1.0000 gal	114,100 Btu/gal
Diesel #2	0.8800 gal	129,500 Btu/gal
Biodiesel (B100)	0.9600 gal	118,300 Btu/gal
Biodiesel (B20)	0.9000 gal	127,250 Btu/gal
Liquid natural gas (LNG)	1.5362 gal	75,000 Btu/gal
Compressed natural gas	1.26 ft^3 (3.587 m^3)	900 Btu/ft^3
Hydrogen at 101.325 kPa	357.37 ft^3	319 Btu/ft^3
Hydrogen by weight	0.997 kg (2.198 lb)	119.9 MJ/kg (51,500 Btu/lb)
Liquefied petroleum gas (LPG)	1.3500 gal	84,300 Btu/gal
Methanol fuel (M100)	2.0100 gal	56,800 Btu/gal
Ethanol fuel (E100)	1.5000 gal	76,100 Btu/gal
Ethanol fuel (E85)	1.3900 gal	81,800 Btu/gal
Jet fuel (naphtha)	0.9700 gal	118,700 Btu/gal

Source: USEPA, *Fuel Economy Impact Analysis of RFG*, U.S. Environmental Protection Agency, Washington, DC, 2007.

Note: ETBE, ethyl *tert*-butyl ether; MTBE, methyl *tert*-butyl ether.

Pros and Cons of Bioethanol

With regard to the use of ethanol for transportation (propulsion), it can be used as an extender and octane enhancer in conventional gasoline. Its primary advantage is that its feedstock (plants) is renewable. It can also be used as a primary fuel (in E85), thus reducing dependence on petroleum products. Ethanol is an important player in the ongoing effort to reduce environmental pollution from carbon monoxide (CO) gas and global carbon dioxide (CO_2). In some locations, E85 and gasohol are less expensive per gallon than conventional gasoline. As the production and use of ethanol as a fuel increase, farmers will benefit from the increased demand for their products. From the practical and safety and health point of view, ethanol can be used to prevent gasline freeze in extremely cold weather, and because it is not as flammable as gasoline it is less likely to cause accidental explosions.

Ethanol use for transportation purposes does have a few negatives. Probably the most obvious shortcoming is its lack of availability at local gas stations. Gas stations selling E85 as part of their normal products are not as abundant as

conventional gas stations. In some locations, E85 and gasohol are more expensive per gallon than conventional gasoline. E85 can damage vehicles that are not designed to burn it as a fuel. Also, ethanol contains less energy than gasoline. This means that a car will not go as far on a gallon of E85, and fuel economy will decrease by 20 to 30%. Ethanol is produced from plant matter that could otherwise be consumed as human and animal food products. Critics argue that food products used for fuel instead of to feed people and animals will contribute indirectly to mass world hunger. Moreover, it will lead to higher food prices. However, even though higher corn prices increase animal feed and ingredient costs for farmers and food manufacturers, these costs are passed through to retail at a rate less than 10% of the change in corn price.

Corn for Ethanol Production or Food Supply?*

In 2007, record U.S. trade driven by economic growth in developing countries and favorable exchange rates, combined with tight global grain supplies, resulted in record or near-record prices for corn, soybeans, and other food and feed grains. For corn, these factors, along with increased demand for ethanol, helped push prices from under $2 per bushel in 2005 to $3.40 per bushel in 2007. By the end of the 2006–2007 crop year, over 2 billion bushels of corn (19% of the harvested crop) were used to produce ethanol, a 30% increase from the previous year. Higher corn prices motivated farmers to increase corn acreage at the expense of other crops, such as soybeans and cotton, raising their prices as well.

The pressing and pertinent question becomes: What effect do these higher commodity costs have on retail food prices? In general, retail food prices are much less volatile than farm-level prices and tend to rise by a fraction of the change in farm prices. The magnitude of response depends on both the retailing costs beyond the raw food ingredients and the nature of competition in retail food markets. The impact of ethanol on retail food prices depends on how long the increased demand for corn drives up farm corn prices and the extent to which higher corn prices are passed through to retail.

Retail food prices adjust as the cost of inputs into retail food production change and the competitive environment in a given market evolves. Strong competition among three to five retail store chains in most U.S. markets has had a moderating effect on food price inflation. Overall, retail food prices have been relatively stable over the past 20 years, with prices increasing an average of 3.0% per year from 1987 through 2007, just below the overall rate of inflation. Since then, food price inflation has averaged just 2.5% per year.

Field corn is the predominant corn type grown in the United States, and it is primarily used for animal feed. Currently, less than 10% of the U.S. field corn crop is used for direct domestic human consumption in corn-based foods such as corn meal, corn starch, and corn flakes; the remainder is used for animal feed, exports,

* Adapted from Leibtag, E., Corn prices near record high, but what about food costs? *Amber Waves*, February, 2008 (http://webarchives.cdlib.org/sw1vh5dg3r/http://ers.usda.gov/AmberWaves/February08/Features/CornPrices.htm).

ethanol production, seed, and industrial uses. Sweet corn, both white and yellow, is usually consumed as immature whole-kernel corn by humans and also as an ingredient in other corn-based foods, but it makes up only about 1% of the total U.S. corn production.

Because U.S. ethanol production uses field corn, the most direct impact of increased ethanol production should be on field corn prices and on the price of food products based on field corn. However, even for those products heavily based on field corn, the effect of rising corn prices is dampened by other market factors. For example, an 18-ounce box of corn flakes contains about 12.9 ounces of milled field corn. When field corn is priced at $2.28 per bushel (the 20-year average), the actual value of corn represented in the box of corn flakes is about 3.3 cents (1 bushel = 56 pounds). (The remainder of the price represents packaging, processing, advertising, transportation, and other costs.) At $3.40 per bushel, the average price in 2007, the value is about 4.9 cents. The 49% increase in corn prices would be expected to raise the price of a box of corn flakes by about 1.6 cents, or 0.5%, assuming no other cost increases.

In the 1980s, Coca-Cola made the shift from sugar to corn syrup in most of its U.S.-produced soda, and many other beverage makers followed suit. Currently, about 4.1% of U.S.-produced corn is made into high-fructose corn syrup. A 2-liter bottle of soda contains about 15 ounces of corn in the form of high-fructose corn syrup. At $3.40 per bushel, the actual value of corn represented is 5.7 cents, compared with 3.8 cents when corn is priced at $2.28 per bushel. Assuming no other cost increases, the higher corn price in 2007 would be expected to raise soda prices by 1.9 cents per 2-liter bottle, or 1%. These are notable changes in terms of price measure and inflation, but relatively minor changes in the average household budget.

In addition to the impact on corn flakes and soda beverage prices, livestock prices are also impacted. This stands to reason when you consider that livestock rations traditionally contain a large amount of corn; thus, a bigger impact would be expected in meat and poultry prices due to higher feed costs than in other food products. Currently, 55% of corn produced in the United States is used as animal feed for livestock and poultry. However, estimating the actual corn used as feed to produce retail meat is a complicated calculation. Livestock producers have many options when deciding how much corn to include in a feed ration. For example, at one extreme, grass-fed cattle consume no corn, while other cattle may have a diet consisting primarily of corn. For hog and poultry producers, ration variations may be less extreme but can still vary quite a bit. To estimate the impact of higher corn prices on retail meat prices, it is necessary to make a series of assumptions about feeding practices and grain conversion rates from animal to final retail meat products. To avoid downplaying potential impacts, this analysis uses upper-bound conversion estimates of 7 pounds of corn to produce 1 pound of beef, 6.5 pounds of corn to produce 1 pound of pork, and 2.6 pounds of corn to produce 1 pound of chicken.

Using these ratios and data from the Bureau of Labor Statistics, a simple pass-through model provides estimates of the expected increase in meat prices given the higher corn prices. The logic of this model is illustrated by an example using chicken prices. Over the past 20 years, the average price of a bushel of corn in the United States has been $2.28, implying that a pound of chicken at the retail level uses 8 cents

DID YOU KNOW?

Although higher commodity costs may have a relatively modest impact on U.S. retail food prices, there may be greater effect on retail food prices in lower-income developing countries. As a relatively low-priced food, grains have historically accounted for a large share of the diet in less developed countries. Even with incomes rising, consumers in such countries consume a less processed diet than is typical in the United States and other industrialized countries, so food prices are more closely tied to swings in both domestic and global commodity prices.

worth of corn, or about 4% of the $2.05 average retail price for chicken breasts. Using the average price of corn for 2007 ($3.40 per bushel) and assuming producers do not change their animal-feeding practices, retail chicken prices would rise 5.2 cents, or 2.5%. Using the same corn data, retail beef prices would go up 14 cents per pound, or 8.7%, while pork prices would rise 13 cents per pound, or 4.1%.

These estimates for meat, poultry, and corn-related foods, however, assume that the magnitude of the corn price change does not affect the rate at which cost increases are passed through to retail prices. It could be the case that corn price fluctuations have little impact on retail food prices until corn prices rise high enough for a long enough time to elicit a large price adjustment by food producers and notably higher retail food prices.

On the other hand, these estimates may be overstating the effect of corn price increases on retail food prices because they do not account for producers potentially switching from more expensive to less costly inputs. Such substitution would dampen the effect of higher corn prices on retail meat prices. Even assuming the upper-bound effects outlined above, the impact of rising corn commodity prices on overall food prices is limited. Given that less than a third of retail food contains corn as a major ingredient, these rising prices for corn-related products would raise overall U.S. retail food prices less than 1 percentage point per year above the normal rate of inflation.

Continuing elevated prices for corn will depend on the extent to which corn remains the most efficient feedstock for ethanol production and ethanol remains a viable source of alternative energy. Both of these conditions may change over time as other crops and biomass are used to produce ethanol and other alternative energy sources develop.

Even if these conditions do not change in the near term, market adjustments may dampen long-run impacts. In 1996, when field corn prices reached an all-time high of $3.55 per bushel due to drought-related tighter supplies in the United States and strong demand for corn from China and other parts of Asia, the effect on food prices was short lived. At that time, retail prices rose for some foods, including pork and poultry, but these effects did not extend beyond the middle of 1997. For the most part, food markets adjusted to the higher corn prices and corn producers increased supply, bringing down price.

Food producers, manufacturers, and retailers may also adjust to the changing market conditions by adopting more efficient production methods and improved technologies to counter higher costs. For example, soft drink manufacturers may consider substituting sugar for corn syrup as a sweetener if corn prices remain high, while livestock and poultry producers may develop alternative feed rations that minimize the corn needed for animal feed. Adjustments by producers, manufacturers, and retailers, along with continued strong retail competition, imply that U.S. retail food prices will remain relatively stable.

The Brazilian Example*

Brazil has the world's second largest ethanol program and is capitalizing on plentiful soybean supplies to expand into biodiesel. More than half of the nation's sugarcane crop is processed into ethanol, which now accounts for about 20% of the country's fuel supply. Initiated in the 1970s after the OPEC oil embargo, Brazil's policy program was designed to promote the nation's energy independence and to create an alternative and value-added market for sugar producers. The government has spent billions to support sugarcane producers, develop distilleries, build up a distribution infrastructure, and promote production of pure-ethanol-burning and, later, flex-fuel vehicles able to run on gasoline, ethanol–gasoline blends, or pure hydrous (wet; 7 to 4% water content) ethanol. Advocates contend that, while the costs were high, the program saved far more in foreign exchange from reduced petroleum imports.

In the mid- to late 1990s, Brazil eliminated direct subsidies and price setting for ethanol. It pursued a less intrusive approach with two main elements—a blending requirement (now about 25%) and tax incentives favoring ethanol use and the purchase of ethanol-using or flex-fuel vehicles. Today, more than 80% of Brazil's newly produced automobiles have flexible fuel capability, up from 30% in 2004. With ethanol widely available at almost all of Brazil's 32,000 gas stations, Brazilian consumers currently choose primarily between 100% hydrous ethanol and a 2% ethanol–gasoline blend on the basis of relative prices.

Approximately 20% of current fuel use (alcohol, gasoline, and diesel) in Brazil is ethanol, but it may be difficult to raise the share as Brazil's fuel demand grows. Brazil is a middle-income economy with per capita energy consumption only 15% that of the United States and Canada. Current ethanol production levels in Brazil are not much higher than they were in the later 1990s. Production of domestic off- and on-shore petroleum resources has grown more rapidly than ethanol and accounts for a larger share of expanding fuel use than does ethanol in the last decade.

BIOMASS FOR BIOPOWER

In addition to advanced fuels, biomass can also be used for the production of biopower. This can be done in several ways, including direct combustion of biomass in dedicated power plants, co-firing biomass with coal, biomass gasification in a combined cycle plant to produce steam and electricity, or via anaerobic digestion

* Adapted from Coyle, W., The future of biofuels: a global perspective. *Amber Waves*, November, 2007 (http://www.thebioenergysite.com/articles/9/the-future-of-biofuels-a-global-perspective).

(EPRI, 1997). Combustion is the burning of biomass in air. This involves the conversion of chemical energy stored in biomass into heat, mechanical power, or electricity (McKendry, 2002). Although it is possible to use all types of biomass, combustion is preferable when the biomass is more than 50% dry. High-moisture biomass is better suited for biological conversion processes. Net bioenergy conversion efficiencies for biomass combustion power plants range from 20 to 40%. Higher efficiencies are obtained with combined heat and power (CHP) facilities and with large size power-only systems (over 100 megawatt-electrical, MWe), or when the biomass is co-fired with coal in power plants (McKendry, 2002).

Co-firing biomass with coal is a straightforward and inexpensive way to diversify the fuel supply, reduce coal plant air emissions (NO_x, SO_2, CO_2), divert biomass from landfills, and stimulate the biomass power industry (Hughes, 2000). Moreover, biomass is the only renewable energy technology that can directly displace coal. Given the dominance of coal-based power plants in U.S. electricity production, co-firing with biomass fuel is the most economical way to reduce greenhouse gas emissions. Possible biomass fuel for co-firing includes wood waste, short-rotation woody crops, switchgrass, alfalfa stems, various types of manure, landfill gas, and wastewater treatment gas (Tillman, 2000). In addition, agricultural residues such as straw can also be used for co-firing.

A promising technology development currently at the demonstration stage is biomass integrated gasification/combined cycle (BIG/CC), where a gas turbine converts the gaseous fuel to electricity with a high conversion efficiency, reaching 40 to 50% of the heating value of the incoming gas (McKendry, 2002). An important advantage of gasification is the ability to work with a wider variety of feedstocks, such as high-alkali fuels that are problematic with direct combustion. High-alkali fuels such as switchgrass, straw, and other agricultural residues often cause corrosion, but the gasification systems can easily remove the alkali species from the fuel gas before it is combusted. High silica, also a problem with grasses, can result in slagging in the reactor. The slagging problem is not unique to one form of biomass but instead is common among many different types of biomass fuels (Miles et al., 1993). Slagging deposits can reduce heat transfer, reduce combustion efficiency, and damage combustion chambers when large particles break off. Research has focused on two alkali metals, potassium and sodium, and on silica, all elements commonly found in living plants. In general, it appears that faster growing plants (or faster growing plant components such as seeds) tend to have higher concentrations of alkali metal and silica. Thus, materials such as straw, nut hulls, fruit pits, weeds, and grasses tend to create more problems when burned than does wood from a slow-growing tree.

Potassium and sodium metals, whether in the form of oxides, hydroxides, or metallo-organic compounds, tend to lower the melting point of ash mixtures containing various other minerals such as silica (SiO_2). The high alkali content (up to 35%) in the ash from burning annual crop residues lowers the fusion or "sticky temperature" of these ashes from 2200°F for wood ash to as low as 1300°F. This results in serious slagging on the boiler grate or in the bed and fouling of convection heat transfer surfaces. Even small percentages (10%) of some of these high-alkali residues burned with wood in conventional boilers will cause serious slagging and fouling in

TABLE 5.6
Alkali Content and Slagging Potential of Biofuels

Fuel	Total Alkali (lb/MMBtu)	Slagging Potential
Wood		
Pine chips	0.07	Minimal
White oak	0.14	Minimal
Hybrid poplar	0.46	Probable
Urban wood waste	0.46	Probable
Clean tree trimmings	0.73	Probable
Pits, nuts, shells		
Almond shells	0.97	Certain
Refuse-derived fuel	1.60	Certain
Grasses		
Switch grass	1.97	Certain
Wheat straw (average)	2.00	Certain
Wheat straw (high-alkali)	5.59	Certain
Rice straw	3.80	Certain

Source: Adapted from Miles, T.R. et al., Alkali slagging problems with biomass fuels. In: *First Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry*, Vol. 1, National Renewable Energy Laboratory, Burlington, VT, 1993.

a day to two, necessitating combustion system shutdown. A method to predict slagging and fouling from combustion of biomass fuels has been adapted from the coal industry. The method involves calculating the weight in pounds of alkali (K_2O + Na_2O) per million Btu in the fuel as follows:

$$\frac{1\times 10^6}{\text{Btu/lb}} \times \%\text{Ash} \times \%\text{Alkali of the ash} = \frac{\text{lb Alkali}}{\text{MMBtu}}$$

This method combines all the pertinent data into one index number. A value below 0.4 lb/MMBtu (MMBtu = thousand thousand Btu) is considered a fairly low slagging risk. Values between 0.4 and 0.8 lb/MMBtu will probably slag with increasing certainty of slagging as 0.8 lb/MMBtu is approached. Above 0.8 lb/MMBtu, the fuel is virtually certain to slag and foul (see Table 5.6).

Another process for biomass is the application of anaerobic digestion to produce biogas (methane) for electricity generation. Recall that anaerobic digestion involves the controlled breakdown of organic wastes by bacteria in the absence of oxygen. Major agricultural feedstocks for anaerobic digestion include food processing wastes and manure from livestock operations. The Energy Information Agency has also projected a significant increase in the generation of electricity from municipal waste and landfill gas—to about 0.5% of U.S. electricity consumption (EIA, 2006).

TABLE 5.7
Common Products from Biomass

Biomass Resource	Uses
Corn	Solvents, pharmaceuticals, adhesives, starch, resins, binders, polymers, cleaners, ethanol
Vegetable oils	Surfactants in soaps and detergents, pharmaceuticals (inactive ingredients), inks, paints, resins, cosmetics, fatty acids, lubricants, biodiesel
Wood	Paper, building materials, cellulose for fibers and polymers, resins, binders, adhesives, coatings, paints, ins, fatty acids, road and roofing pitch

Source: USDOE, *Industrial Bioproducts: Today and Tomorrow*, U.S. Department of Energy, Washington, DC, 2004.

BIOMASS FOR BIOPRODUCTS*

Bioproducts are industrial and consumer goods manufactured wholly or in part from renewable biomass (plant-based resources). Today's industrial bioproducts are amazingly diverse, ranging from solvents and paints to pharmaceuticals, soaps, cosmetics, and building materials (see Table 5.7). Industrial bioproducts are integral to our way of life—few sectors of the economy do not rely in some way or another on products made from biomass. Corn, wood, soybeans, and plant oils are the primary resources used to create this remarkable diversity of industrial and consumer goods. In some cases, it is not readily apparent that a product is derived in part from biomass. Biomass components are often combined with other materials such as petrochemicals and minerals to manufacture the final product. Soybean oil, for example, is blended with other components to produce paints, toiletries, solvents, inks, and pharmaceuticals. Some products, such as starch adhesives, are derived entirely from biomass. The many derivatives of corn illustrate the diversity of products that can be obtained from a single biomass resource (see Figure 5.7). Besides being an important source of food and feed, corn serves as a feedstock for ethanol and sorbitol (a sweetish, crystalline alcohol), industrial starches and sweeteners, citric and lactic acid, and many other products. Biomass, which is comprised of carbohydrates, can be used to produce some of the products that are commonly manufactured from petroleum and natural gas, or hydrocarbons. Both resources contain the essential elements of carbon and hydrogen. In some cases, both resources have captured a portion of market share (see Table 5.8).

Classes of Bioproducts

The thousands of different industrial bioproducts produced today can be categorized into five major areas:

* Adapted from USDOE, *Industrial Bioproducts: Today and Tomorrow*, U.S. Department of Energy, Washington, DC, 2004.

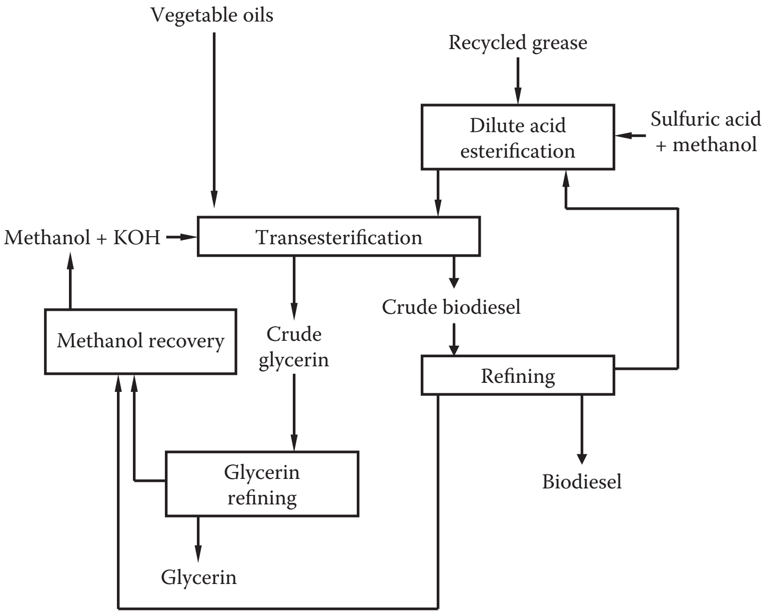

FIGURE 5.7 Biodiesel process.

TABLE 5.8
Products from Hydrocarbons vs. Carbohydrates

Product	Total Production (millions of tons)	% Derived from Plants
Adhesives	5.0	40.0
Fatty acids	2.5	40.0
Surfactants	3.5	35.0
Acetic acid	2.3	17.5
Plasticizers	0.8	15.0
Activated carbon	1.5	12.0
Detergents	12.6	11.0
Pigments	15.5	6.0
Dyes	4.5	6.0
Wall points	7.8	3.5
Inks	3.5	3.5
Plastics	30.0	1.8

Source: ILSR, *Accelerating the Shift to a Carbohydrate Economy: The Federal Role*, Executive Summary of the Minority Report of the Biomass Research and Development Technical Advisory Committee, Institute for Local Self-Reliance, Washington, DC, 2002.

1. *Sugar and starch bioproducts* derived through fermentation and thermochemical processes include alcohols, acids, starch, xanthum gum, and other products derived from biomass sugars. Primary feedstocks include sugarcane, sugarbeets, corn, wheat, rice, potatoes, barley, sorghum grain, and wood.
2. *Oil- and lipid-based bioproducts* include fatty acids, oils, alkyd resins, glycerine, and a variety of vegetable oils derived from soybeans, rapeseed, or other oilseeds.
3. *Gum and wood chemicals* include tall oil (liquid rosin), alkyd resins, rosins, pitch, fatty acids, turpentine, and other chemicals derived from trees.
4. *Cellulose derivatives, fibers, and plastics* include products derived from cellulose, including cellulose acetate (cellophane) and triacetate, cellulose nitrate, alkali cellulose, and regenerated cellulose. The primary sources of cellulose are bleached wood pulp and cotton linters.
5. *Industrial enzymes* are used as biocatalysts for a variety of biochemical reactions in the production of starch and sugar, alcohols, and oils. They are also used in laundry detergents, tanning of leathers, and textile sizing (Uhlig, 1998).

BIODIESEL

The diesel engine is the workhorse of heavy transportation and industrial processes; it is widely used to power trains, tractors, ships, pumps, and generators. Powering the diesel engine is conventional diesel fuel or biodiesel fuel. Biodiesel is a rather viscous liquid fuel made up of fatty acid alkyl esters, fatty acid methyl esters (FAMEs), and long-chain mono-alkyl esters. It is produced from renewable sources such as new and used vegetable oils and animal fats and is a cleaner-burning replacement for petroleum-based diesel fuel. It is nontoxic and biodegradable. This fuel is designed to be used in compression-ignition (diesel) engines similar or identical to those that burn petroleum diesel. Biodiesel has physical properties similar to those of petroleum diesel (see Table 5.9). In the United States, most biodiesel is made from soybean oil or recycled cooking oils. Animal fats, other vegetable oils, and other recycled oils can also be used to produce biodiesel, depending on the costs and availability. In the future, blends of all kinds of fats and oils may be used to produce biodiesel. Before providing a basic description of the vegetable and/or recycled grease to biodiesel process, it is important to define and review a few of the key technological terms associated with the conversion process.

DID YOU KNOW?

There is a reason for the costly side of biomass energy. To generate electricity from biomass, a massive amount of biomass is required to produce biofuel. The availability of biomass fuel sources is not consistent, as reliance on the forest and agriculture residual sources is quite uncertain (Karthick, 2010).

TABLE 5.9
Biodiesel Physical Characteristics

Specific gravity	0.87 to 0.89
Kinematic viscosity at 40°C	3.7 to 5.8
Cetane number	46 to 70
Higher heating value (Btu/lb)	16,928 to 17,996
Sulfur (wt%)	0.0 to 0.0024
Cloud point (°C)	–11 to 16
Pour point (°C)	–15 to 13
Iodine number	60 to 135
Lower heating value (lb/lb)	15,700 to 16,735

- *Acid esterification*—Oil feedstocks containing more than 4% free fatty acids go through an acid esterification process to increase the yield of biodiesel. These feedstocks are filtered and preprocessed to remove water and contaminants and are then fed to the acid esterification process. The catalyst, sulfuric acid, is dissolved in methanol and then mixed with the pretreated oil. The mixture is heated and stirred, and the free fatty acids are converted to biodiesel. Once the reaction is complete, it is dewatered and then fed to the transesterification process.
- *Transesterification*—Oil feedstocks containing less than 4% free fatty acids are filtered and preprocessed to remove water and contaminants and then fed directly to the transesterification process along with any products of the acid esterification process. The catalyst, potassium hydroxide, is dissolved in methanol and then mixed with the pretreated oil. If an acid esterification process is used, then extra base catalyst must be added to neutralize the acid added in that step. Once the reaction is complete, the major co-products, biodiesel and glycerin, are separated into two layers.
- *Methanol recovery*—The methanol is typically removed after the biodiesel and glycerin have been separated to prevent the reaction from reversing itself. The methanol is cleaned and recycled back to the beginning of the process.
- *Biodiesel refining*—Once separated from the glycerin, the biodiesel goes through a clean-up or purification process to remove excess alcohol, residual catalyst, and soaps. This consists of one or more washings with clear water. It is then dried and sent to storage. Sometimes the biodiesel goes through an additional distillation step to produce a colorless, odorless, zero-sulfur biodiesel.
- *Glycerin refining*—The glycerin byproduct contains unreacted catalyst and soaps that are neutralized with an acid. Water and alcohol are removed to produce 50 to 80% crude glycerin. The remaining contaminants include unreacted fats and oils. In large biodiesel plants, the glycerin can be further purified, to 99% or higher purity, for sale to the pharmaceutical and cosmetic industries.

The most popular biodiesel production process is *transesterification* (production of the ester) of vegetable oils or animal fats, using alcohol in the presence of a chemical catalyst. About 3.4 kg of oil/fat are required for each gallon of biodiesel produced (Baize, 2006). The transesterification of degummed soybean oil produces ester and glycerin. The reaction requires heat and a strong base catalyst such as sodium hydroxide or potassium hydroxide. The simplified transesterification reaction is shown below:

$$\text{Triglycerides} + \text{Free fatty acids} (<4\%) + \text{Alcohol} \rightarrow \text{Alkyl esters} + \text{Glycerin}$$

Some feedstocks must be pretreated before they can go through the transesterification process. Feedstocks with less than 4% free fatty acids, which include vegetable oils and some food-grade animal fats, do not require pretreatment. Feedstocks with more than 4% free fatty acids, which include inedible animal fats and recycled greases, must be pretreated in an acid esterification process. In this step, the feedstock is reacted with an alcohol (such as methanol) in the presence of a strong acid catalyst (sulfuric acid), converting the free fatty acids into biodiesel. The remaining triglycerides are converted to biodiesel in the transesterification reaction:

$$\text{Triglycerides} + \text{Free fatty acids} (>4\%) + \text{Alcohol} \rightarrow \text{Alkyl esters} + \text{Triglycerides}$$

Figure 5.7 illustrates the basic technology for processing vegetable oils (such as soybeans) and recycled greases (used cooking oil and animal fat). When the feedstock is vegetable oil, the extracted oil is processed to remove all traces of water, dirt, and other contaminants. Free fatty acids are also removed. A combination of methyl alcohol and a catalyst, usually sodium hydroxide or potassium hydroxide, breaks the oil molecules apart in the esterification process. The resulting esters are then refined into usable biodiesel.

When the feedstock is used-up cooking oil and animal fats refined to produce biodiesel, the process is similar to the way biodiesel is derived from vegetable oil, except there is an additional step involved (Figure 5.7). Methyl alcohol and sulfur are used in a process called *dilute acid esterification* to obtain a substance resembling fresh vegetable oil, which is then processed in the same way as vegetable oil to obtain the final product.

Algae to Biodiesel

The focus of our discussion of biofuels to this point has been on terrestrial sources of biomass fuels. This section is concerned with photosynthetic organisms that grow in aquatic environments—namely, macroalgae, microalgae, and emergents. Macroalgae, more commonly known as seaweed, are fast-growing marine and freshwater plants that can grow to considerable size (up to 60 m in length). Emergents are plants that grow partially submerged in bogs and marshes. Microalgae are, as the name suggests, microscopic photosynthetic organisms. With regard to the mass production of oil for alternative renewable energy purposes, the focus of this discussion is mainly on microalgae—organisms capable of photosynthesis that are less than

DID YOU KNOW?

Biodiesel is routinely blended with petroleum diesel. The percentage of biodiesel in the blend is written after an uppercase letter B to denote the proportion. For example, a mixture of 20% biodiesel and 80% petroleum diesel is called B20, a mixture of equal parts biodiesel and petroleum diesel is B50, and neat (or pure) biodiesel is B100. Most conventional diesel engines can burn blends from pure petroleum diesel up to B20 without modification. With minor modification, most diesel engines built since 1994 can use blends from B20 to B100. The diesel vehicle owner's manual and vehicle warranty should be checked before using any alternative fuel.

0.4 mm in diameter, including the diatoms and cyanobacteria—as opposed to macroalgae (seaweed). Microalgae are the preferred choice because they are less complex in structure, have a fast growth rate, and typically (for some species) contain a high concentration of oil. However, it is important to point out that recent research efforts also are focusing on using seaweeds for algae fuel (biofuels), probably due to their high availability (Lewis, 2005).

The following algal species are currently being studied for their suitability as a mass oil-producing crop across various locations worldwide (Anon., 2008):

Ulva
Botryococcus braunii
Chlorella
Dunaliella tertiolecta
Gracilaria
Pleurochrysis carterae
Sargassum (has 10 times the output volume of *Gracilaria*)

The algae-to-biodiesel alternative renewable fuel source program got its start during the Carter Administration in response to the 1970s Arab fuel embargo. At the same time, the Carter Administration consolidated all federal energy activities under the auspice of the newly established U.S. Department of Energy (USDOE). Among its various programs established to develop all forms of alternative energy (related to solar energy), the USDOE initiated research on the use of plant life as a source of transportation fuels (today known as the Biofuels Program).

DID YOU KNOW?

Algae fuel, also called algal fuel, algaeoleum, or second-generation biofuel, is a biofuel derived from algae; that is, natural oils are used in the production of biodiesel.

DID YOU KNOW?

In the 1980s, the USDOE gradually shifted its focus to technologies that could have large-scale impacts on national consumption of fossil energy. Much of the USDOE's publications from this period reflect a philosophy of energy research that might, somewhat pejoratively, be called "the quads mentality." A quad is a short-hand name for the unit of energy often used by the USDOE to describe the amounts of energy that a given technology might be able to displace. Quad is short for "quadrillion Btus"—a unit of energy representing 10^{15} (1,000,000,000,000,000) Btus of energy. This perspective led the USDOE to focus on the concept of immense algae farms.

Before discussing the algae-to-biofuels process in detail, it is important for the reader to be well grounded in basic algal concepts. In many ways, the study of microalgae is a relatively limited field of study. Algae are not nearly as well understood as other organisms that have found a role in today's biotechnology industry. The study of microalgae represents an area of high risk and high gains; it also presents an opportunity for the curious and ambitious to break new ground in science by conducting research in this growing area of interest.

Algae can be both a nuisance and an ally; we might say they possess Jekyll and Hyde-like (good vs. bad) characteristics. Many ponds, lakes, rivers, streams, and bays (e.g., Chesapeake Bay) in the United States and elsewhere are undergoing *eutrophication*, which is basically the killing off (although in many cases very slowly) of calm water environments, especially ponds, marshes, and lakes, due to enrichment of an environment with inorganic substances (phosphorous and nitrogen). When eutrophication occurs, when filamentous algae such as *Caldophora* break loose in a pond, lake, stream, or river and wash ashore, algae makes it stinking, noxious presence known. More important than the offensive odor that dying algae give off is the fact that their deaths begin a biodegradation process whereby instead of adding oxygen to their watery environment they begin to use it up. Algae have a good side, too. For example, algae are allies in many wastewater treatment operations. In addition, they can be valuable in long-term oxidation ponds where they aid in the purification process by producing oxygen. Before discussing the specifics and different types of algae, it is important to be familiar with terminology associated with algae.

- *Algae*—Large and diverse assemblages of eukaryotic organisms that lack roots, stems, and leaves but have chlorophyll and other pigments for carrying out oxygen-producing photosynthesis.
- *Algology* or *phycology*—The study of algae.
- *Antheridium*—Special male reproductive structures where sperm are produced.
- *Aplanospore*—Nonmotile spores produced by sporangia.
- *Benthic*—Algae attached and living on the bottom of a body of water.
- *Binary fission*—Nuclear division followed by division of the cytoplasm.
- *Chloroplasts*—Packets that contain chlorophyll *a* and other pigments.

- *Chrysolaminarin*—The carbohydrate reserve in organisms of division Chrysophyta.
- *Diatoms*—Photosynthetic, circular or oblong chrysophyte cells.
- *Dinoflagellates*—Unicellular, photosynthetic protistan algae.
- *Dry mass factor*—The percentage of dry biomass in relation to the fresh biomass; for example, if the dry mass factor is 5%, one would need 20 kg of wet algae (algae in the media) to get 1 kg of dry algae cells.
- *Epitheca*—The larger part of the frustule (diatoms).
- *Euglenoids*—Contain chlorophylls *a* and *b* in their chloroplasts; representative genus is *Euglena*.
- *Fragmentation*—A type of asexual algal reproduction in which the thallus breaks up and each fragmented part grows to form a new thallus.
- *Frustule*—The distinctive two-piece wall of silica in diatoms.
- *Hypotheca*—The small part of the frustule (diatoms).
- *Lipid content*—The percentage of oil in relation to the dry biomass needed to get it; for example, if the algae lipid content is 40%, one would need 2.5 kg of dry algae to get 1 kg of oil.
- *Neustonic*—Algae that live at the water–atmosphere interface.
- *Oogonia*—Vegetative cells that function as female sexual structures in the algal reproductive system.
- *Pellicle*—A *Euglena* structure that allows for turning and flexing of the cell.
- *Phytoplankton*—Made up of algae and small plants.
- *Plankton*—Free-floating, mostly microscopic aquatic organisms.
- *Planktonic*—Algae suspended in water as opposed to attached and living on the bottom (benthic).
- *Protothecosis*—A disease in humans and animals caused by the green algae, *Prototheca moriformis*.
- *Thallus*—The vegetative body of algae.

Algae are autotrophic, contain the green pigment chlorophyll, and are a form of aquatic plant. Algae differ from bacteria and fungi in their ability to carry out photosynthesis—the biochemical process requiring sunlight, carbon dioxide, and raw mineral nutrients. Photosynthesis takes place in the chloroplasts. The chloroplasts are usually distinct and visible. They vary in size, shape, distribution, and numbers. In some algal types, the chloroplast may occupy most of the cell space. They usually grow near the surface of water because light cannot penetrate very far through water. Although when they are *en masse* (multicellular forms such as marine kelp) the unaided eye easily sees them, many of them are microscopic. Algal cells may be nonmotile or motile by one or more flagella, or they may exhibit gliding *motility* as in diatoms. They occur most commonly in water (fresh and polluted water, as well as in saltwater), in which they may be suspended (planktonic) or attached and living on the bottom (benthic); a few algae live at the water–atmosphere interface (neustonic). Within the freshwater and saltwater environments, they are important primary producers, which means they are at the beginning of the food chain for other organisms. During their growth phase, they are important oxygen-generating organisms and constitute a significant portion of the plankton in water.

Algae belong to seven divisions, or phylums, distributed between two different kingdoms (Plantae and Protista) in the standard biological five-kingdom system. Only five divisions are discussed in this text:

- Chlorophyta—Green algae
- Euglenophyta—Euglenids
- Chrysophyta—Golden-brown algae, diatoms
- Phaeophyta—Brown algae
- Pyrrophyta—Dinoflagellates

The primary classification of algae is based on cellular properties. Several characteristics are used to classify algae, including: (1) cellular organization and cell wall structure; (2) the nature of chlorophyll(s) present; (3) the type of motility, if any; (4) the carbon polymers that are produced and stored; and (5) the reproductive structures and methods. Table 5.10 summarizes the properties of the five divisions discussed in this text.

Algae show considerable diversity in the chemistry and structure of their cells. Some algal cell walls are thin, rigid structures usually composed of cellulose modified by the addition of other polysaccharides. In other algae, the cell wall is strengthened by the deposition of calcium carbonate. Other forms have chitin present in the cell wall. Complicating the classification of algal organisms are the euglenids, which lack cell walls. In diatoms, the cell wall is composed of silica. The frustules (shells) of diatoms have extreme resistance to decay and remain intact for long periods of time, as the fossil records indicate.

The principal feature used to distinguish algae from other microorganisms (e.g., fungi) is the presence of chlorophyll and other photosynthetic pigments in algae. All algae contain chlorophyll *a*. Some, however, contain other types of chlorophylls. The presence of these additional chlorophylls is characteristic of a particular algal group. In addition to chlorophyll, other pigments encountered in algae include fucoxanthin (brown), xanthophylls (yellow), carotenes (orange), phycocyanin (blue), and phycoerythrin (red). Many algae have flagella (a threadlike appendage). The flagella are locomotor organelles that may be either single polar or multiple polar. The *Euglena* have a simple flagellate form with a single polar flagellum. Chlorophyta have either two or four polar flagella. Dinoflagellates have two flagella of different lengths. In some cases, algae are nonmotile until they form motile gametes (a haploid cell or nucleus) during sexual reproduction. Diatoms do not have flagella but have gliding motility.

Algae can be either autotrophic or heterotrophic. Most are photoautotrophic; they require only carbon dioxide and light as their principal source of energy and carbon. In the presence of light, algae carry out oxygen-evolving photosynthesis; in the absence of light, algae use oxygen. Chlorophyll and other pigments are used to absorb light energy for photosynthetic cell maintenance and reproduction. One of the key characteristics used in the classification of algal groups is the nature of the reserve polymer synthesized as a result of utilizing carbon dioxide present in water.

Algae may reproduce either asexually or sexually. Three types of asexual reproduction occur: binary fission, spores, and fragmentation. In some unicellular algae, binary fission occurs where the division of the cytoplasm forms new individuals

TABLE 5.10
Comparative Summary of Algal Characteristics

Algal Group	Common Name	Structure	Pigments	Carbon Reserve	Motility	Reproduction
Chlorophyta	Green algae	Unicellular to multicellular	Chlorophylls *a* and *b*, carotenes, xanthophylls	Starch, oils	Most are nonmotile	Asexual and sexual
Euglenophyta	Euglenoids	Unicellular	Chlorophylls *a* and *b*, carotenes, xanthophylls	Fats	Motile	Asexual
Chrysophyta	Golden-brown algae, diatoms	Multicellular	Chlorophylls *a* and *b*, special carotenoids, xanthophylls	Oils	Gliding by diatoms; others by flagella	Asexual and sexual
Phaeophyta	Brown algae	Unicellular	Chlorophylls *a* and *b*, carotenoids, xanthophylls	Fats	Motile	Asexual and sexual
Pyrrophyta	Dinoflagellated	Unicellular	Chlorophylls *a* and *b*, carotenes, xanthophylls	Starch	Motile	Asexual; sexual rare

like the parent cell following nuclear division. Some algae reproduce through spores. These spores are unicellular and germinate without fusing with other cells. In fragmentation, the thallus breaks up and each fragment grows to form a new thallus. Sexual reproduction can involve the union of cells where eggs are formed within vegetative cells called *oogonia* (which function as female structures) and sperm are produced in male reproductive organs called *antheridia*. Algal reproduction can also occur through a reduction of chromosome number or the union of nuclei.

Characteristics of Algal Divisions

Chlorophyta (Green Algae)

The majority of algae found in ponds belong to this group; they also can be found in saltwater and soil. Several thousand species of green algae are known today. Many are unicellular; others are multicellular filaments or aggregated colonies. The green algae have chlorophylls *a* and *b*, along with specific carotenoids, and they store carbohydrates at starch. Few green algae are found at depths greater than 7 to 10 m, largely because sunlight does not penetrate to that depth. Some species have a holdfast structure that anchors them to the bottom of the pond and to other submerged inanimate objects. Green algae reproduce by both sexual and asexual means. Multicellular green algae have some division of labor, producing various reproductive cells and structures.

Euglenophyta (Euglenoids)

The Euglenophyta are a small group of unicellular microorganisms that have a combination of animal and plant properties. Euglenoids lack a cell wall, possess a gullet, have the ability to ingest food, have the ability to assimilate organic substances, and, in some species, are absent of chloroplasts. They occur in fresh, brackish, and salt waters, and on moist soils. A typical *Euglena* cell is elongated and bound by a plasma membrane; the absence of a cell wall makes them very flexible in movement. Inside the plasma membrane is a structure called the pellicle that gives the organisms a definite form and allows the cell to turn and flex. Euglenoids are photosynthetic and contain chlorophylls *a* and *b*, and they always have a red eyespot (*stigma*) that is sensitive to light (photoreceptive). Some euglenoids move about by means of flagellum; others move about by means of contracting and expanding motions. The characteristic food supply for euglenoids is a lipopolysaccharide. Reproduction in euglenoids is by simple cell division.

> ***Note:*** Some autotrophic species of *Euglena* become heterotrophic when light levels are low.

Chrysophyta (Golden-Brown Algae)

The Chrysophyta phylum is quite large, having several thousand diversified members. They differ from green algae and euglenoids in that (1) chlorophylls *a* and *c* are present; (2) fucoxanthin, a brownish pigment, is present; and (3) they store food in the form of oils and leucosin, a polysaccharide. The combination of yellow pigments, fucoxanthin, and chlorophylls causes most of these algae to appear golden brown. The

Chrysophycophyta division is also diversified in cell wall chemistry and flagellation. The division is divided into three major classes: golden-brown algae (Chrysophyceae), yellow–green algae (Xanthophycae), and diatoms (Bacillariophyceae). Some Chrysophyta lack cell walls; others have intricately patterned coverings external to the plasma membrane, such as walls, plates, and scales. The diatoms are the only group that has a hard cell wall, called a *frustule*, which is composed of pectin, cellulose, or silicon and consists of two valves: the epitheca and the hypotheca. Two anteriorly attached flagella are common among Chrysophyta; others have no flagella. Most Chrysophyta are unicellular or colonial. Asexual cell division is the usual method of reproduction in diatoms, but other forms of Chrysophyta can reproduce sexually. Diatoms have direct significance for humans. Because they make up most of the phytoplankton of the cooler ocean parts, they are the ultimate source of food for fish. Water and wastewater operators understand the importance of their ability to function as indicators of industrial water pollution. As water quality indicators, their specific tolerances to environmental parameters such as pH, nutrients, nitrogen, concentration of salts, and temperature have been determined.

> ***Note:*** Diatoms secrete a silicon dioxide shell (frustule) that forms the fossil deposits known as diatomaceous earth, which is used in filters and as abrasives in polishing compounds.

Phaeophyta (Brown Algae)

With the exception of a few freshwater species, all algal species of this division exist in marine environments as seaweed. They are a highly specialized group, consisting of multicellular organisms that are sessile (attached and not free-moving). These algae contain essentially the same pigments seen in the golden-brown algae, but they appear brown because of the predominance of and the masking effect of a greater amount of fucoxanthin. Brown algal cells store food as the carbohydrate laminarin and some lipids. Brown algae reproduce asexually. Brown algae are used in foods, animal feeds, and fertilizers and as a source for alginate, a chemical emulsifier added to ice cream, salad dressing, and candy.

Pyrrophyta (Dinoflagellates)

The principal members of this division are the dinoflagellates. The dinoflagellates comprise a diverse group of biflagellated and nonflagellated unicellular eukaryotic organisms. The dinoflagellates occupy a variety of aquatic environments, with the majority living in marine habitats. Most of these organisms have a heavy cell wall composed of cellulose-containing plates. They store food as starch, fats, and oils.

DID YOU KNOW?

Cell division in dinoflagellates differs from most protistans, with chromosomes attaching to the nuclear envelope and being pulled apart as the nuclear envelope stretches. During cell division in most other eukaryotes, the nuclear envelope dissolves.

These algae have chlorophylls *a* and *c* and several xanthophylls. The most common form of reproduction in dinoflagellates is by cell division, but sexual reproduction has also been observed.

Algal Biomass

Algal biomass contains three main components:

- Carbohydrates
- Protein
- Natural oils

Biodiesel production applies exclusively to the natural oil fraction, the main product of interest to us in this section. The bulk of natural oil made by oilseed crops is in the form of triacylglycerols (TAGs), which consist of three long chains of fatty acids attached to a glycerol backbone. The algae species of concern can produce up to 60% of their body weight in the form of TAGs. (Recall that the species of concern, the oil producers, are *Ulva*, *Botryococcus braunii*, *Chlorella*, *Dunaliella tertiolecta*, *Gracilaria*, *Pleurochrysis carterae*, and *Sargassum*.) Thus, algae represent an alternative source of biodiesel, one that does not compete with the exiting oilseed market.

Algae can produce up to 300 times more oil per acre than conventional crops, such as rapeseed, palms, soybean, or *Jatropha* (Christi, 2007). Moreover, algae has a harvesting cycle of 1 to 10 days, permitting several harvests in a very short time frame, a strategy quite different from that for yearly crops. Algae can also be grown on land that is not suitable for other established crops, such as arid land, land with excessively saline soil, and drought-stricken land. This minimizes the issue of taking away pieces of land from the cultivation of food crops (Schenk et al., 2008). Algae can grow 20 to 30 times faster than food crops (McDill, 2009).

Algae can be produced and harvested for biofuel using various technologies. These include photobioreactors (plastic tubes full of nutrients exposed to sunlight), closed-loop (not exposed to open air) systems, and open ponds. For the purposes of illustration (even though there are many objectors and dissenters to open-pond systems), the open-pond configuration of algae farms is discussed here, because the open-pond raceway system is a relatively low-cost system and is an easily understood process.

Open-Pond Algae Farms

Algae farms consist of open, shallow ponds in which some source of waste carbon dioxide (CO_2) can be bubbled into the ponds and captured by the algae. As shown in Figure 5.8, the ponds in an algae farm are "raceway" designs, in which the algae, water, and nutrients circulate around a racetrack. Paddlewheels provide the flow. The algae are thus kept suspended in water. Algae are circulated back up to the surface on a regular frequency. The ponds are kept shallow because of the need to keep the algae exposed to sunlight and the limited depth to which sunlight can penetrate the pond water. The ponds operate continuously; that is, water and nutrients are constantly fed to the pond while algae-containing water is removed at the other end. Some kind of harvesting system is required to recover the algae, which contains substantial amounts of natural oil.

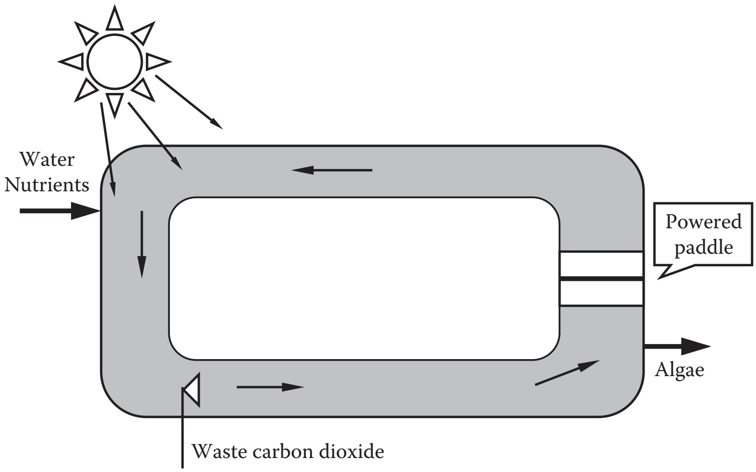

FIGURE 5.8 Raceway design algae pool.

Figure 5.9 illustrates the concept of an algae farm. The size of these ponds is measured in terms of surface area (as opposed to volume), because surface area is so critical to capturing sunlight. Their productivity is measured in terms of biomass produced per day per unit of available surface area. Even at levels of productivity

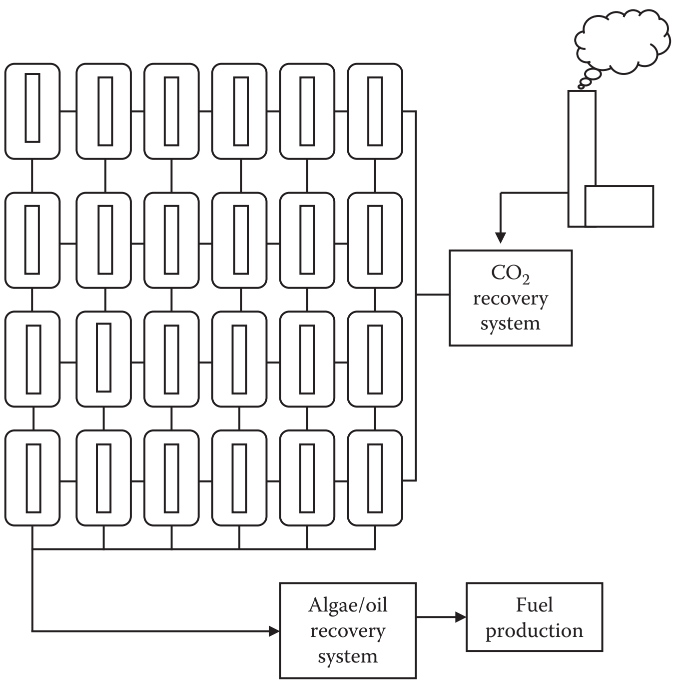

FIGURE 5.9 Algae farm.

DID YOU KNOW?

The availability of biomass fuel sources is not consistent, as reliance on the forest and agricultural residual sources is quite uncertain (Karthick, 2010).

that would stretch the limits of an aggressive research and development program, such systems will require acres of land. At such large sizes, it is more appropriate to think of these operations on the scale of a farm. Waste carbon dioxide is readily available from a number of sources. Every operation that involves combustion of fuel for energy is a potential source. Generally, coal and other fossil fuel-fired power plants are targeted as the main sources of carbon dioxide, as typical coal-fired power plants emit flue gas from their stacks containing up to 13% carbon dioxide. This high concentration of carbon dioxide enhances the transfer and uptake of carbon dioxide in the ponds. The concept of coupling a coal-fired power plant with an algae farm provides a win–win approach for recycling the carbon dioxide from coal combustion into a usable liquid fuel.

Jatropha to Biodiesel

The uninformed or misinformed might flinch when they discover that a byproduct of the plant *Jatropha curcas*—yes, the same plant known in some places as "black vomit nut" and in others as "bellyache bush" or "tuba-tub"—is being used as a product that has some credible value. *Jatropha* shrubs are inedible plants that grow mostly in countries such as the Philippines. *Jatropha* is resistant to drought and can easily be planted or propagated through seeds or cuttings. It starts producing seeds within 14 months, but reaches its maximum productivity level after 4 to 5 years. The *Jatropha* plant can produce an oil content of 30 to 58%, depending on the quality of the soil where it is planted. The seeds yield an annual equivalent of 0.75 to 2 tons or 1892 liters of biodiesel per hectare. The plant remains useful for around 30 to 40 years and can be planted in harsh climates where it would not compete for resources needed to grow food. Along with having the advantage of being a renewable fuel source, the *Jatropha* plant also reduces greenhouse gas emissions and our dependence on oil imports.

Pros and Cons of Biodiesel

The greatest advantage of biodiesel over conventional petroleum diesel is that biodiesel comes from renewable resources. The supply can be grown, over and over again. Biodiesel combustion also produces fewer emissions (except for nitrous oxides) than combustion of an equal amount of petroleum diesel. The widespread use of biodiesel can also reduce the dependency on imported oil. From a safety standpoint, biodiesel is safer than petroleum diesel because it is less combustible. From an environmental standpoint, when accidentally spilled, biodiesel is not persistent within environmental media (air, water, soil) because it is biodegradable. Biodiesel can also be produced from waste products such as cooking oils and grease.

Probably the most pressing disadvantages or shortcomings of biodiesel, at least at the present time, are its lack of availability or accessibility and high cost relative to petroleum diesel. This trend in non-availability and non-accessibility is bound to change as the less expensive, more accessible petroleum diesel becomes more expensive and difficult to find. Additional disadvantages to consider are that biodiesel requires special handling, storage and transportation management as compared to petroleum diesel. With regard to environmental considerations, biodiesel produces more nitrous oxide emissions when combusted than an equal amount of petroleum diesel. Another potential problem with the production of biodiesel is its dependence on soybeans as its primary feedstock; there is some concern that the widespread use of biodiesel as fuel will contribute to higher food prices and indirectly to world hunger. There is a slight reduction in performance and mileage per gallon with biodiesel as compared to petroleum diesel. Biodiesel can also act as a solvent in some diesel engines, causing loosened deposits that may clog filters.

BIOGAS (METHANE)

Primarily known as a fuel for interior heating systems, methane or biogas can also be used as a replacement for natural gas—a fossil fuel for electricity generation and for cooking and heating—and as an alternative fuel to gasoline. Methane is a natural gas produced by the breakdown of organic material in the absence of oxygen in termite mounds and wetlands and by some animals. Humans are also responsible for the release of methane through biomass burning, rice production, cattle raising, and releases from gas exploration. Methane can also be obtained directly from the earth; however, other methods of production have been developed, most notably the fermentation or composting of plant and animal waste. The reasons for considering biogas (methane) as a possible biofuel include the following:

- It is viable because of its potential use as an alternative fuel source.
- It is a viable alternative fuel to use to improve air quality.
- It can be produced locally, reducing the need to use imported natural gas.

Methane is produced under anaerobic conditions where organic material is biodegraded or broken down by a group of microorganisms. The three main sources of feedstock material for anaerobic digestion are given in Figure 5.10 and are described in the following.

Anaerobic Digestion

Anaerobic digestion is the traditional method of managing waste, sludge stabilization, and releasing energy. It involves using bacteria that thrive in the absence of oxygen and is slower than aerobic digestion, but it has the advantage that only a small portion of the wastes is converted into new bacterial cells. Instead, most of the organics are converted into carbon dioxide and methane gas.

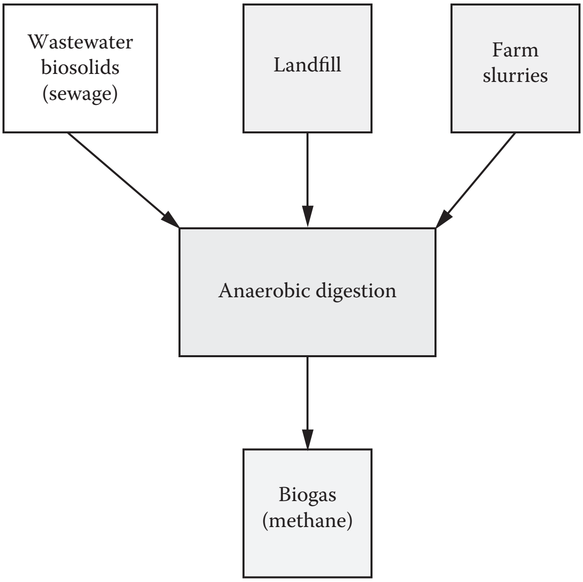

FIGURE 5.10 Production of biogas (methane, CH_4).

> ***Cautionary Note:*** Allowing air to enter an anaerobic digester should be prevented because the mixture of air and gas produced in the digester can be explosive.

Stages of Anaerobic Digestion

Anaerobic digestion (see Figure 5.11) has four key biological and chemical stages (Spellman, 2009; USEPA, 1979, 2006):

1. *Hydrolysis*—Proteins, cellulose, lipids, and other complex organics are broken down into smaller molecules and become soluble by utilizing water to split the chemical bonds of the substances.
2. *Acidogenesis*—The products of hydrolysis are converted into organic acids (where monomers are converted to fatty acids).
3. *Acetogenesis*—The fatty acids are converted to acetic acid, carbon dioxide, and hydrogen.
4. *Methanogenesis*—Organic acids produced during the fermentation step are converted to methane and carbon dioxide.

The efficiency of each phase is influenced by the temperature and the amount of time the process is allowed to react. For example, the organisms that perform hydrolysis and volatile acid fermentation (often called *acidogenic bacteria*) are fast-growing microorganisms that prefer a slightly acidic environment and higher temperatures than the organisms that perform the methane formation step (*methanogenic bacteria*).

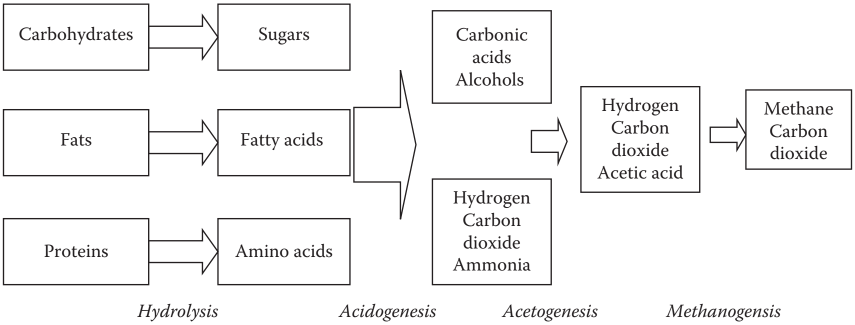

FIGURE 5.11 Key stages of anaerobic digestion.

A simplified generic chemical equation for the overall processes outlined above is as follows:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

Biogas is the ultimate waste product of the bacteria feeding off the input biodegradable feedstock and is composed primarily of methane and carbon dioxide, with a small amount of hydrogen and trace hydrogen sulfide (see Table 5.11). Keep in mind that the ultimate output from a wastewater digester is water; biogas (methane) is more of an off-gas that can be used as an energy source. Wastewater digestion and the production of biogas are discussed in the next section.

Anaerobic Digestion of Sewage Biosolids (Sludge)

Equipment used in anaerobic digestion typically includes a sealed digestion tank with either a fixed or a floating cover or an inflatable gas bubble, heating and mixing equipment, gas storage tanks, solids and supernatant withdrawal equipment, and safety equipment (e.g., vacuum relief, pressure relief, flame traps, explosion-proof electrical equipment).

> ***Caution:*** Biosolids are inherently dangerous as possible sources of explosive gases, and biosolids sites should never be entered without following OSHA's confined-space entry permit requirements. Only fully trained personnel should enter permit-required confined spaces.

TABLE 5.11
Typical Contents of Biogas

Matter	Percentage (%)
Methane (CH_4)	50–75
Carbon dioxide (CO_2)	25–50
Nitrogen (N_2)	0–10
Hydrogen (H_2)	0–1
Hydrogen sulfide (H_2S)	0–3
Oxygen (O_2)	0–2

DID YOU KNOW?

The primary purpose of a secondary digester is to allow for solids separation.

In operation, process residual (thickened or unthickened biosolids/sludge) is pumped into the sealed digester. The organic matter digests anaerobically by a two-stage process. Sugars, starches, and carbohydrates are converted to volatile acids, carbon dioxide, and hydrogen sulfide. The volatile acids are then converted to methane gas. This operation can occur in a single tank (one stage) or in two tanks (two stages). In a single-stage system, supernatant and digested solids must be removed whenever flow is added. In a two-stage operation, solids and liquids from the first stage flow into the second stage each time fresh solids are added. Supernatant is withdrawn from the second stage to provide additional treatment space. Periodically, solids are withdrawn for dewatering or disposal. The methane gas produced in the process may be used for many plant activities.

Various performance factors affect the operation of the anaerobic digester. The percent volatile matter in raw sludge, digester temperature, mixing, volatile acids-to-alkalinity ratio, feed rate, percent solids in raw biosolids, and pH are all important operational parameters that the operator must monitor (see Table 5.12). Along with being able to recognize normal and abnormal anaerobic digester performance parameters, digester operators must also know and understand normal operating procedures. Normal operating procedures include biosolids additions, supernatant withdrawal, sludge withdrawal, pH control, temperature control, mixing, and safety requirements.

Caution: Keep in mind that in fixed-cover operations additions must be balanced by withdrawals. If not, structural damage occurs.

Sludge must be pumped (in small amounts) several times each day to achieve the desired organic loading and optimum performance, and supernatant withdrawal must be controlled for maximum sludge retention time. All drawoff points are sampled, and the level with the best quality is selected. Digested sludge is withdrawn only when necessary; at least 25% seed remains. A pH of 6.8 to 7.2 is maintained by

TABLE 5.12
Sludge Parameters for Anaerobic Digesters

Raw Biosolids (Sludge) Solids	Impact
<4% solids	Loss of alkalinity
	Decreased sludge retention time
	Increased heating requirements
	Decreased volatile acids-to-alkalinity ratio
4–8% solids	Normal operation
>8% solids	Poor mixing
	Organic overloading
	Decreased volatile acids-to-alkalinity ratio

TABLE 5.13
Anaerobic Digester: Normal Operating Ranges

Parameter	Normal Range
Sludge retention time	
Heated	30–60 days
Unheated	180+ days
Volatile solids loading	0.04–0.1 lb/day/ft^3
Operating temperature	
Heated	90–95°F
Unheated	Varies with season
Mixing	
Heated—primary	Yes
Unheated—secondary	No
Methane in gas	60–72%
Carbon dioxide in gas	28–40%
pH	6.8–7.2
Volatile acids-to-alkalinity ratio	≤0.1
Volatile solids reduction	40–60%
Moisture reduction	40–60%

adjusting the feed rate, sludge withdrawal, or alkalinity additions. Anaerobic digesters must be continuously monitored and tested to ensure proper operation. Testing is performed to determine supernatant pH, volatile acids, alkalinity, biochemical oxygen demand (BOD) or chemical oxygen demand (COD), total solids, and temperature. Sludge (in and out) is routinely tested for percent solids and percent volatile matter. Normal operating parameters are listed in Table 5.13.

Note: The buffer capacity of an anaerobic digester is indicated by the volatile acids/alkalinity relationship. Decreases in alkalinity cause a corresponding increase in ratio.

If the digester is heated, the temperature must be controlled to a normal temperature range of 90 to 95°F. The temperature is never adjusted by more than 1°F per day. In digesters equipped with mixers, the mixing process ensures that organisms are exposed to food materials. Again, anaerobic digesters are inherently dangerous—several catastrophic failures have occurred. To prevent such failures, safety equipment, such as pressure relief and vacuum relief valves, flame traps, condensate traps, and gas collection safety devices, is installed. It is important that these critical safety devices be checked and maintained for proper operation.

Note: Because of the inherent danger involved with working inside anaerobic digesters, they are automatically classified as permit-required confined spaces. All operations involving internal entry must be made in accordance with OSHA's confined-space entry standard. Questions concerning safe entry into confined spaces of any type should be addressed by a Certified Safety Professional (CSP), Certified Industrial Hygienist (CIH), or Professional Engineer (PE).

Process control calculations involved with anaerobic digester operation include determining the required seed volume, volatile acids-to-alkalinity ratio, sludge retention time, estimated gas production, volatile matter reduction, and percent moisture reduction in digester sludge. Examples on how to make these calculations are provided in the following sections.

Required Seed Volume in Gallons

$$\text{Seed volume (gal)} = \text{Digester volume} \times \%\text{Seed} \tag{5.1}$$

■ Example 5.1

Problem: A new digester requires a 25% seed to achieve normal operation within the allotted time. If the digester volume is 266,000 gal, how many gallons of seed material will be required?

Solution:

$$\text{Seed volume} = 266{,}000 \times 0.25 = 66{,}500 \text{ gal}$$

Volatile Acids-to-Alkalinity Ratio

The volatile acids-to-alkalinity ratio can be used to control operation of an anaerobic digester:

$$\text{Ratio} = \frac{\text{Volatile acids concentration}}{\text{Alkalinity concentration}} \tag{5.2}$$

■ Example 5.2

Problem: The digester contains 240 mg/L volatile acids and 1860 mg/L alkalinity. What is the volatile acids-to-alkalinity ratio?

Solution:

$$\text{Ratio} = \frac{\text{Volatile acids concentration}}{\text{Alkalinity concentration}} = \frac{240 \text{ mg/L}}{186 \text{ mg/L}} = 0.13$$

Note: Increases in the ratio normally indicate a potential change in the operation condition of the digester, as shown in Table 5.14.

TABLE 5.14
Volatile Acid-to-Alkalinity Ratios

Operating Condition	Volatile Acids-to-Alkalinity Ratio
Optimum	≤0.1
Acceptable range	0.1–0.3
Increase in % carbon dioxide in gas	≥0.5
Decrease in pH	≥0.8

Sludge Retention Time

Sludge retention time (SRT) is the length of time the sludge remains in the digester:

$$\text{SRT (days)} = \frac{\text{Digester volume (gal)}}{\text{Sludge volume added per day (gpd)}} \tag{5.3}$$

■ Example 5.3

Problem: Sludge is added to a 525,000-gal digester at the rate of 12,250 gal per day. What is the sludge retention time?

Solution:

$$\text{SRT} = \frac{\text{Digester volume}}{\text{Sludge volume added per day}} = \frac{525{,}000 \text{ gal}}{12{,}250 \text{ gpd}} = 42.9 \text{ days}$$

Estimated Gas Production in Cubic Feet/Day

The rate of gas production is normally expressed as the volume of gas (ft^3) produced per pound of volatile matter destroyed. The total cubic feet of gas that a digester will produce per day can be calculated by

$$\text{Gas production} = \text{VM}_{\text{in}} \text{ (lb/day)} \times \text{\%VM reduction} \times \text{Production rate (ft}^3\text{/lb)} \tag{5.4}$$

■ Example 5.4

Problem: The digester receives 11,450 lb of volatile matter per day. Currently, the volatile matter reduction achieved by the digester is 52%. The rate of gas production is 11.2 ft^3 of gas per pound of volatile matter destroyed.

Solution:

$$\text{Gas production} = 11{,}450 \text{ lb/day} \times 0.52 \times 11.2 \text{ ft}^3\text{/lb} = 66{,}685 \text{ ft}^3\text{/day}$$

Percent Volatile Matter Reduction

Because of the changes occurring during sludge digestion, the calculation used to determine percent volatile matter reduction is more complicated:

$$\text{\%VM reduction} = \frac{(\text{\%VM}_{\text{in}} - \text{\%VM}_{\text{out}}) \times 100}{[\text{\%VM}_{\text{in}} - (\text{\%VM}_{\text{in}} \times \text{\%VM}_{\text{out}})]} \tag{5.5}$$

■ Example 5.5

Problem: Using the data provided below, determine the percent volatile matter reduction for the digester:

Raw sludge volatile matter = 74%
Digested sludge volatile matter = 55%

Solution:

$$\%\text{VM reduction} = \frac{(0.74 - 0.55) \times 100}{\left[0.74 - (0.74 \times 0.55)\right]} = 57\%$$

Percent Moisture Reduction in Digested Sludge

$$\%\text{Moisture reduction} = \frac{\left(\%\text{Moisture}_{\text{in}} - \%\text{Moisture}_{\text{out}}\right) \times 100}{\left[\%\text{Moisture}_{\text{in}} - \left(\%\text{Moisture}_{\text{in}} \times \%\text{Moisture}_{\text{out}}\right)\right]}$$

■ Example 5.6

Problem: Using the digester data provide below, determine the percent moisture reduction and percent volatile matter reduction for the digester.

Raw sludge percent solids = 6%
Digested sludge percent solids = 14%

Solution:

Note: Percent moisture = 100% – Percent solids.

$$\%\text{Moisture reduction} = \frac{(0.94 - 0.86) \times 100}{\left[0.94 - (0.94 \times 0.86)\right]} = 61\%$$

Anaerobic Digestion of Agricultural Wastes

Animal waste accounts for 10% of methane emissions in the United States. Ruminant animals, particularly cows and sheep, contain bacteria in their gastrointestinal systems that help to break down plant material. Some of these microorganisms use the acetate from the plant material to produce methane, and, because these bacteria live in the stomachs and intestines of ruminants, whenever the animal burps or defecates it emits methane as well (Spellman and Whiting, 2007). When not correctly managed, farm waste slurries can also seriously pollute local watercourses. Small anaerobic digesters have been installed on farms to treat excess animal slurries that cannot be placed on the land. The biogas formed is normally used for heat but can also be used to fuel engines and other onsite energy needs such as electricity and heating. Onsite biogas production and management also reduce offensive odors from overloaded or improperly managed manure storage facilities. These odors impair air quality and may be a nuisance to nearby communities. Anaerobic digestion of animal waste reduces these offensive odors because the volatile organic acids, the odor-causing compounds, are consumed by biogas-producing bacteria. In addition to biogas, another important byproduct of anaerobic digestion is ammonium, which is the major constituent of commercial fertilizer, which is readily available and utilized by crops. The bottom line on the production of biogas on the farm: Biogas recovery can improve profitability while improving environmental quality.

DID YOU KNOW?

Of the estimated U.S. biomass resource of 590 million net tons, only 14 million dry tons, or enough to supply about 3000 MW of capacity, are currently available (USDOE, 2014b).

Landfill Biogas

Landfills can be a source of energy. Some wastewater treatment plants with anaerobic digesters located close to landfills harness the methane from the landfill and combine it with methane from their anaerobic digesters to provide additional power for their plant site. Landfills produce methane as organic waste decomposes in the same anaerobic digestion process used to convert wastewater and farm waste slurries into biogas. Most landfill gas results from the degradation of cellulose contained in municipal and industrial solid waste. Unlike animal manure digesters, which control the anaerobic digestion process, the digestion occurring in landfills is an uncontrolled process of biomass decay. To be technically feasible, a landfill must be at least 40 feet deep and have at least a million tons of waste in place for landfill gas collection.

The efficiency of the process depends on the waste composition and moisture content of the landfill, cover material, temperature, and other factors. The biogas released from landfills, commonly called *landfill gas*, is typically 50% methane, 45% carbon dioxide, and 5% other gases. The energy content of landfill gas is 400 to 550 Btu per cubic foot.

Figure 5.12 shows a landfill energy system. Such a system consists of a series of wells drilled into the landfill. A piping system connects the wells and collects the gas. Dryers remove moisture from the gas and filters remove impurities. The gas typically fuels an engine–generator set or gas turbine to produce electricity. The gas can also fuel a boiler to produce heat or steam. Because waste-generated biogas is considered to be a dirty gas, as compared to natural gas, further gas cleanup is required to improve biogas to pipeline quality, the equivalent of natural gas. Reforming the gas to hydrogen would make possible the production of electricity using fuel cell technology.

IMPACTS OF BIOMASS CONSTRUCTION, PRODUCTION, AND OPERATION

The combination of constructing biomass facilities (and associated ancillaries), producing biomass feedstock, and operating biomass energy facilities may have environmental impacts. For example, construction activities that could have an environmental impact include ground clearing, grading, excavation, blasting, trenching, drilling, facility construction, and vehicular and pedestrian traffic. Additionally, potential environmental impacts could result from biomass feedstock production activities such as the collection of waste materials and growth and harvesting of woody and agricultural crops or algae, preprocessing, and transportation activities. Finally, operations activities that may have an environmental impact include

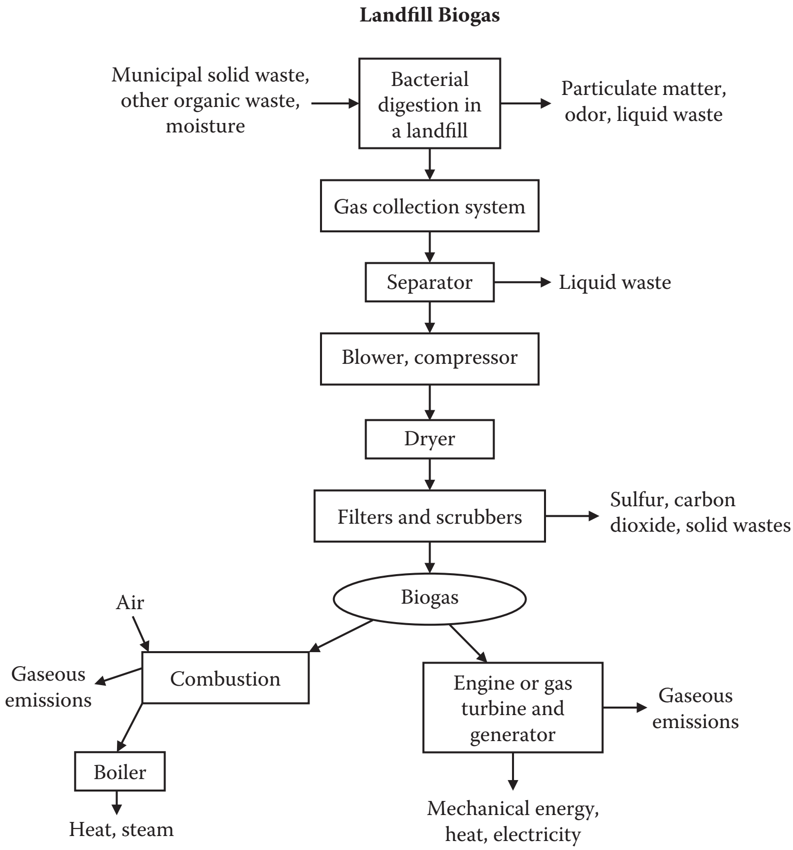

FIGURE 5.12 Landfill biogas system flow diagram.

operation of the biomass energy facility, power generation, biofuel production, and associated maintenance activities. Many of the environmental impacts resulting from these activities are discussed in the following text.

Biomass Energy Construction Impacts*

During the biomass energy facility construction phase, typical construction activities include ground clearing (removal of vegetative cover), grading, excavation, blasting, trenching, drilling, vehicular and pedestrian traffic, and construction and installation of facilities. Biomass power plants and some biogas plants that produce more electricity than required to operate the facility need transformers and transmission lines to deliver electricity to the power grid. Landfill gas production would require the drilling of wells for extraction of the gas and might require pipeline construction

* Adapted from Tribal Energy and Environmental Information Clearinghouse, http://teeic.anl.gov/er/biomass/impact/construct/index.cfm.

to deliver the gas to the user. Activities conducted in locations other than the facility site might include excavation and blasting for construction materials (e.g., sand, gravel) and access road construction. Potential impacts from these activities are presented below, by the type of affected resources.

Air Quality

Emissions generated during the construction phase include vehicle emissions; diesel emissions from large construction equipment and generators; release of volatile organic compounds (VOCs) from the storage and transfer of vehicle/equipment fuels; small amounts of carbon monoxide, nitrogen oxides, and particulates from blasting activities; and fugitive dust from any sources such as disturbing and removing soils (clearing, grading, excavating, trenching, backfilling, dumping, and truck and equipment traffic), mixing concrete, storage of unvegetated soil piles, and drilling and pile driving. Note that a permit is needed from the state or local air agency to control or mitigate these emissions; therefore, these emissions would not likely cause an exceedance of air quality standards nor have an impact on climate change. Moreover, a construction permit under the mandated prevention of significant deterioration (PSD) or air quality regulations might be required.

Cultural Resources

Direct impacts on cultural resources could result from construction activities, and indirect impacts might be caused by soil erosion and increased accessibility to possible site locations. Potential impacts include the following:

- Complete destruction of resources in areas undergoing surface disturbance or excavation
- Degradation or destruction of near-surface cultural resources on- and off-site resulting from topographic or hydrological pattern changes or from soil movement (removal, erosion, and sedimentation), although the accumulation of sediment could protect some localities by increasing the amount of protective cover
- Unauthorized removal of artifacts or vandalism to the site as a result of increases in human access to previously inaccessible areas, if significant cultural resources are present

DID YOU KNOW?

Biomass power plants emit nitrogen oxides and a small amount of sulfur dioxide. The amounts emitted depend on the type of biomass that is burned and the type of generator used. Although the burning of biomass also produces carbon dioxide, the primary greenhouse gas, it is considered to be part of the natural carbon cycle of the Earth. The plants take up carbon dioxide from the air while they are growing and then return it to the air when they are burned, thereby causing no net increase.

- Visual impacts resulting from vegetation clearing, increases in dust, and the presence of large-scale equipment, machinery, and vehicles if the affected cultural resources have an associated landscape or other visual component that contributes to their significance, such as Native American sacred landscape or a historic trail

Ecological Resources

Ecological resources that could be affected include vegetation, fish, and wildlife, as well as their habitats. Vegetation and topsoil would be removed for the construction of the biomass energy facility, associated access roads, transmission lines, pipelines, and other ancillary facilities. This would lead to a loss of wildlife habitat, reduction in plant diversity, potential for increased erosion, and potential for the introduction of invasive or noxious weeds. The recovery of vegetation following interim and final reclamation would vary by the type of plant community desired. Dust settling on vegetation may alter or limit plants' abilities to photosynthesize or reproduce. Although the potential for an increase in the spread of invasive and noxious weeds would occur during the construction phase due to increasing traffic and human activity, the potential impacts could be reduced by interim reclamation and implementation of mitigation measures. Adverse impacts on wildlife could occur during construction from

- Erosion and runoff
- Fugitive dust
- Noise
- Introduction and spread of invasive vegetation
- Modification, fragmentation, and reduction of habitat
- Mortality of biota (i.e., death of plants and animals)
- Exposure to contaminants
- Interference with behavioral activities

Wildlife would be most affected by habitat reduction within the project site, access roads, and gas and water pipeline rights-of-way. Wildlife within surrounding habitats might also be affected if the construction activity (and associated noise) disturbs normal behaviors, such as feeding and reproduction. Depletion of surface waters from perennial streams could result in a reduction of water flow, which could lead to habitat loss or degradation of aquatic species.

Water Resources

With regard to water resources (surface water and groundwater), water would be used for dust control when clearing vegetation and grading and for road traffic; for making concrete for foundations and ancillary structures; and for consumptive use by the construction crew. Water is likely to be obtained from nearby surface water bodies or aquifers, depending on availability, but could be trucked in from offsite. The bottom line on water for potable use always comes down to the Q and Q factors: quantity and quality. The quantity of water used would be small relative to water availability. Water quality could be affected by

- Activities that cause soil erosion
- Weathering of newly exposed soils that could cause leaching and oxidation, thereby releasing chemicals into the water
- Discharges of waste or sanitary water
- Untreated groundwater used to control dust could deposit dissolved salts on the surface, allowing the salts to enter surface water systems
- Chemical spills
- Pesticide applications

Surface water and groundwater flow systems could be affected by withdrawals made for water use, wastewater and stormwater discharges, and the diversion of surface water flow for access road construction or stormwater control systems. A stormwater discharge permit might be required. Excavation activities and the extraction of geological materials could affect surface and groundwater flow. The interaction between surface water and groundwater could also be affected if the surface water and groundwater were hydrologically connected, potentially resulting in unwanted dewatering or recharging of water resources.

Land Use

Impacts on land use could occur during construction if there were conflicts with existing land use plans and community goals; conflicts with existing recreational, educational, religious, scientific, or other use areas; or conversion of the existing commercial land use for the area (e.g., agriculture, grazing, mineral extraction). Existing land use during construction would be affected by intrusive impacts such as ground clearing, increased traffic, noise, dust, and human activity, as well as by changes in the visual landscape. In particular, these impacts could affect recreationists seeking solitude or recreation opportunities in a relatively pristine landscape. Ranchers or farmers could be affected by the loss of available grazing or crop lands, the potential for the introduction of invasive plants that could affect livestock forage availability, and possible increases in livestock/vehicle collisions. An expanded access road system could increase the numbers of off-highway vehicle users, hunters, and other recreationists in the surround area.

Impacts on aviation could be possible if the project is located within 20,000 feet (6100 meters) or less of an existing public or military airport, or if proposed construction involves objects greater than 200 feet (61 meters) in height. The Federal Aviation Administration (FAA) must be notified if either of these two conditions occurs, and the FAA would be responsible for determining if the project would adversely affect commercial, military, or personal air navigation safety. Similarly, impacts on military operations could occur if a project was located near a military facility, if that facility conducts low-altitude military testing and training activities.

Soils and Geologic Resources

Sands, gravels, and quarry stone for construction access roads, making concrete for foundations and ancillary structures, and improving ground surface for laydown areas and crane staging areas would either be brought in from offsite sources or would be excavated on site. Depending upon the extend of excavation and blasting

required to install access roads and support facilities, there is a limited risk of triggering geological hazards (e.g., landslides). Altering drainage patterns could also accelerate erosion and create slope instability. Disturbed soil surfaces (crusts) now cover vast areas in the western United States as a result of ever-increasing recreational and commercial uses of these semi-arid and arid areas. Based on the findings of several studies (Belnap and Gillette, 1997; McKenna-Neumann et al., 1996; Williams et al., 1995), the tremendous land area currently affected by human activity may lead to significant increases in regional global wind erosion rates. Surface disturbance, heavy equipment traffic, and changes to surface runoff patterns resulting from biomass energy construction activities could cause soil erosion and impacts on special soils (e.g., cryptobiotic soil crusts; discussed below). Impacts of soil erosion could include soil nutrient loss and reduced water quality in nearby surface water bodies.

Cryptobiotic Soils Crust

With regard to disturbance of cryptobiotic soil crusts, this is an important but often overlooked and not fully appreciated or understood soil disturbance problem, especially within the western and southwestern United States. Whether the renewable energy source is solar, wind, hydro, or biomass, the western and southwestern states are key players in harnessing and processing these energy sources. Cryptobiotic soil crusts, consisting of soil cyanobacteria, lichens, and mosses, play an important ecological role in the arid Southwest. In the cold deserts of the Colorado Plateau region (parts of Utah, Arizona, Colorado, and New Mexico), these crusts are extraordinarily well developed, often representing over 70% of the living ground cover. Cryptobiotic crusts increase the stability of otherwise easily eroded soils, increase water infiltration in regions that receive little precipitation, and increase fertility in soils often limited in essential nutrients such as nitrogen and carbon (Belnap, 1994; Belnap and Gardener, 1993; Harper and Marble, 1988; Johansen, 1993; Metting, 1991; Williams et al., 1995).

Cyanobacteria occur as single cells or as filaments. The most common type found in desert soils is the filamentous type. The cells or filaments are surrounded by sheaths that are extremely persistent in these soils. When moistened, the cyanobacterial filaments become active, moving through the soils and leaving a trail of the sticky, mucilaginous sheath material behind. This sheath material sticks to surfaces such as rock or soil particles, forming an intricate webbing of fibers in the soil. In this way, loose soil particles are joined together, and otherwise unstable and highly erosion-prone surfaces become resistant to both wind and water erosion. The soil-binding action is not dependent on the presence of living filaments. Layers of abandoned sheaths, built up over long periods of time, can still be found clinging tenaciously to soil particles at depths greater than 15 cm in sandy soils. This provides cohesion and stability in these loose sandy soils even at depth.

Cyanobacteria and cyanolichen components of these soil crusts are important contributors of fixed nitrogen (Mayland and McIntosh, 1966; Rychert and Skujins, 1974). These crusts appear to be the dominant source of nitrogen in cold-desert pinyon–juniper and grassland ecosystems over much of the Colorado Plateau (Evans

and Belnap, unpub. data; Evans and Ehleringer, 1993). Biological soil crusts are also important sources of fixed carbon on sparsely vegetated areas common throughout the arid West (Beymer and Klopatek, 1991). Plants growing on crusted soil often show higher concentrations and/or greater total accumulation of various essential nutrients when compared to plants growing in adjacent, uncrusted soils (Belnap and Harper, 1995; Harper and Pendleton, 1993).

Cryptobiotic soil crusts are highly susceptible to soil-surface disturbance such as trampling by hooves or feet, or driving of off-road vehicles, especially in soils with low aggregate stability such as areas of sand dunes and sheets in the southwest, in particular over much of the Colorado Plateau (Belnap and Gardner, 1993; Gillette et al., 1980; Webb and Wilshire, 1983). When crusts in sandy areas are broken in dry periods, previously stable areas can become moving sand dunes in a matter of only a few years.

Cyanobacterial filaments, lichens, and mosses are brittle when dry, and crush easily when subjected to compressional or shear forces by activities such as trampling or vehicular traffic. Many soils in these areas are thin and are easily removed without crust protection. As most crustal biomass is concentrated in the top 3 mm of the soil, even very little erosion can have profound consequences for ecosystem dynamics. Because crustal organism are only metabolically active when wet, re-establishment time is slow in arid systems. Although cyanobacteria are mobile and can often move up through disturbed sediments to reach needed light levels for photosynthesis, lichens and mosses are incapable of such movement and often die as a result. On newly disturbed surfaces, mosses and lichens often have extremely slow colonization and growth rates. Assuming adjoining soils are stable and rainfall is average, recovery rates for lichen cover in southern Utah have been most recently estimated at a minimum of 45 years, while recovery of moss cover was estimated at 250 years (Belnap, 1993).

Because of such slow recolonization of soil surfaces by the different crustal components, underlying soils are left vulnerable to both wind and water erosion for at least 20 years after disturbance (Belnap and Gillette, 1997). Because soils take 5000 to 10,000 years to form in arid areas such as in southern Utah (Webb, 1983), accelerated soil loss may be considered an irreversible loss. Loss of soil also means loss of site fertility through loss of organic matter, fine soil particles, nutrients, and microbial populations in soils (Harper and Marble, 1988; Schimel et al., 1985). Moving sediments further destabilize adjoining areas by burying adjacent crusts, leading to their death, or by providing material for “sandblasting” nearby surfaces, thus increasing wind erosion rates (Belnap, 1995; McKenna-Neumann et al., 1996).

Soil erosion in arid lands is a global problem. Beasley et al. (1984) estimated that in the rangelands of the United States alone, 3.6 million hectares have undergone some degree of accelerated wind erosion. Relatively undisturbed biological soil crusts can contribute a great deal of stability to otherwise high erodible soils. Unlike vascular plant cover, crustal cover is not reduced in drought, and unlike rain crusts, these organic crusts are present year-round; consequently, they offer stability over time and under adverse conditions that is often lacking in other soil surface protectors.

Paleontological Resources

Impacts on paleontological resources could occur directly from the construction activities or indirectly from soil erosion and increased accessibility to fossil locations. Potential impacts include the following:

- Complete destruction of resources in areas undergoing surface disturbance or excavation
- Degradation or destruction of near-surface fossil resources on- and offsite caused by changes in topography, changes in hydrological patterns, and soil movement (removal, erosion, and sedimentation), although the accumulation of sediment could serve to protect some locations by increasing the amount of protective cover
- Unauthorized removal of fossil resources or vandalism to the site as a result of increased human access to previously inaccessible areas, if significant paleontological resources are present

Transportation

Short-term increases in the use of local roadways would occur during the construction period. Heavy equipment likely would remain at the site. Shipments of materials are unlikely to affect primary or secondary road networks significantly, but this would depend on the location of the project site relative to material source. Oversized loads could cause temporary transportation disruptions and could require some modifications to roads or bridges (such as fortifying bridges to accommodate the size or weight). Shipment weight might also affect the design of access roads for grade determinations and turning clearance requirements.

Visual Resources

The magnitude of visual impacts of construction of a biomass facility is dependent upon the distance of the construction activities from the viewer, the view duration, and the scenic quality of the landscape. Possible sources of visual impacts during construction include the following:

- Ground disturbance and vegetation removal could result in visual impacts that produce contrasts of color, form, texture, and line. Excavation for foundations and ancillary structures, trenching to bury pipelines, grading and surfacing roads, cleaning and leveling staging areas, and stockpiling soil might be visible to viewers in the vicinity of the site. Soil scars and exposed slope faces would result from excavation, leveling, and equipment movement.
- Road development (new roads or expansion of existing roads) and parking areas could introduce strong visual contrasts in the landscape, depending on the route relative to surface contours, and the width, length, and surface treatment of the roads.
- Conspicuous and frequent small-vehicle traffic for worker access and frequent large-equipment (trucks, graders, excavators, and cranes) traffic for road construction, site preparation, and biomass facility construction could

produce visible activity and dust in dry soils. Suspension and visibility of dust would be influenced by vehicle speeds and road surface materials.

- There would be a temporary presence of large equipment producing emissions while in operation and creating visible exhaust plumes. Support facilities and fencing associated with the construction work would also be visible.
- Night lighting would change the nature of the visual environment in the vicinity.

Socioeconomics

Direct impacts would include the creation of new jobs for construction workers and the associated income and taxes generated by the biomass facility. Indirect impacts would occur as a result of the new economic development and would include new jobs at businesses that support the expanded workforce or provide project materials, and associated income and taxes. Proximity to biomass facilities could potentially affect property values, either positively from increased employment effects or negatively from proximity to residences or local businesses and any associated or perceived environmental effect (noise, visual, etc.). Adverse impacts could occur if a large in-migrant workforce, culturally different for the local indigenous group, is brought in during construction. This influx of migrant workers could strain the existing community infrastructure and social services.

Environmental Justice

If significant impacts occurred in any resource areas, and these impacts disproportionately affected minority or low-income populations, then there could be an environmental justice impact. Issues of potential concern during construction are noise, dust, and visual impacts from the construction site and possible impacts associated with the construction of new access roads. Additional impacts include limitations on access to the area for recreation, subsistence, and traditional activities.

Biomass Feedstock Production Impacts

The impacts of biomass production are essentially the same as those of farming and forestry. The biomass production phase can be broken down into feedstock production and feedstock logistics. Feedstock production is the cultivation of crops such as corn, soybeans, or grasses and the collection of crop residues and wood residues from forests. These can be further categorized as primary, secondary, and tertiary resources:

- Primary feedstock includes grain and oilseed crops, such as corn or soybeans, that are grown specifically to make biofuels; crop residues such as corn stover and straw; perennial grasses and woody crops; algae; logging residue; and excess biomass from forests.
- Secondary feedstock consists of manure from farm animals, food residue, wood processing mill residue, and pulping liquors.
- Tertiary feedstock includes municipal solid waste, municipal sanitary waste sludge, landfill gases, urban wood waste, construction and demolition debris, and packaging waste.

Feedstock logistics consist of harvesting or collecting the feedstock from the production area, processing it for use in a biomass facility, storing it to provide for a steady supply, and delivering it to the plant. The following potential impacts may result from biomass energy production activities.

Air Quality

Emissions generated during the feedstock production phase include vehicle emissions, diesel emissions from large equipment, emissions from storage and dispensing of fuels, and fugitive dust from many sources. The level of emissions would vary with the scale of operations and may be greater for agriculture operations than forestry operations. For feedstocks that do not require annual replanting (e.g., switchgrass, hybrid poplars) and cultivation (e.g., mill residues) or for algae, which is grown in enclosed aquaculture facilities, potential air emissions would be greatly reduced. If all vehicles and equipment have emission control devices and dust control measures are implemented, air emissions are unlikely to cause an exceedance of air quality standards. The removal of biomass from forests can reduce the potential for major forest fires and limit the need for prescribed burns, thereby eliminating some air pollution sources. However, from a climate change perspective, large reductions in forest mass (clear cutting) can remove biomass that served to capture carbon dioxide. Carbon dioxide, a greenhouse gas, is considered a major contributor to climate change. Mechanisms that can capture or contain carbon dioxide, such as forests, are considered to be a viable mitigation measure against climate change.

Cultural Resources

Any cultural material present on the surface or buried below the surface of existing agricultural areas has already been disturbed, some for many decades. The conversion of uncultivated land to agricultural use to produce feedstock for biomass facilities would disturb previously undisturbed land and could affect cultural resources on or buried below the surface. Harvesting and collecting biomass from the forests could also affect cultural resources on or buried below the surface associated with the harvesting. If new access roads were required, this construction could also affect cultural resources. These agricultural and forestry activities could affect areas of interest to Native Americans depending on their physical placement and level of visual intrusion. Surveys conducted prior to the commencement of farming uncultivated land or harvesting in the forest to evaluate the presence and significance of cultural resources in the area would assist developers in properly managing cultural resources so they can plan their project to avoid or minimize impacts on these resources.

Ecological Resources

Vegetation and wildlife, including threatened, endangered, and sensitive species and their critical habitats, have been displaced from years of crop production. Converting uncultivated or fallow land to agriculture crops would result in additional displacement of native vegetation and wildlife. Forest stand thinning improves the growth of the remaining trees and reduces fire hazards; however, some native wildlife populations may decline as a result of habitat loss, fragmentation, and disturbance due to forest openings resulting from road construction and biomass collection. The

presence of workers could increase human disturbance to wildlife. Limiting work activities in the vicinity of any known active nesting sites would help protect wildlife. Habitat alteration, including canopy cover and soil compaction, can degrade habitat for native plant populations and provide for the establishment of invasive plant species. After clearing a given area of biomass, additional seeding of highly disturbed soils with native grasses and taking steps to prevent the spread of noxious weeds could minimize impacts. However, a lower abundance of birds is sometimes found in reforested areas compared with natural forest or grassland.

Water Resources

Agricultural land use can degrade water quality where it results in runoff or the migration of nutrients, pesticides, and other chemicals into surface water and groundwater. Conversion of idle land to agriculture use would add to the degradation. Converting annual crops to perennial crops reduces the requirement for pesticides and fertilizers. If the conversion of idle land requires irrigation, then water would have to be withdrawn from surface water or groundwater sources. Large withdrawals could affect the water availability for other uses. Sedimentation from road construction and other ground-disturbing activities in forested regions could increase sedimentation levels in streams.

Land Use

Demand for increasing amounts of agricultural biomass feedstock would convert the land and cropland pasture to cultivation of perennial crops such as grass and wood crops. No change in land use in forests would occur as a result of clearing and thinning to remove biomass.

Soils and Geologic Resources

Crop residue left in the field and tree residue left in the forest help to maintain soil moisture, soil organic matter content, and soil carbon levels and to limit wind erosion. Removing too much residue would be detrimental to the soil. Soil compaction in agricultural operations would result from multiple passes of equipment for crop residue collection. These impacts can be partially mitigated by converting land from annual crop to perennial biomass crop production. This would increase the organic matter content of the soils and maximize the potential benefits listed above. The application of pesticides affects soil quality by adding toxic chemicals to the soil. Converting annual crops to perennial crops reduces the requirement for pesticides and fertilizers. Proper management of the type and quantities of pesticides can reduce the impact. Soil compaction, erosion, and topsoil loss result from logging operations. Biomass removal would utilize the same footprint as commercial harvesting activities and would not add to the amount of compacted or disturbed soil.

Paleontological Resources

Any paleontological resources present on the surface or buried below the surface of existing agricultural areas have already been disturbed. The conversion of uncultivated land to agricultural use to produce feedstock for biomass facilities would disturb previously undisturbed land and affect paleontological resources on or buried below the

surface. Harvesting and collecting biomass from the forests could also affect paleontological resources on or buried below the surface associated with the harvesting. If new access roads were required, this construction could also affect these resources. Surveys conducted prior to the commencement of farming uncultivated land or harvesting in the forest to evaluate the presence and/or significance of paleontological resources in the area would assist developers in properly managing paleontological resources so they can plan their project to avoid or minimize impacts on these resources.

Transportation

Increased road congestion from agricultural vehicles, logging trucks, and workers would occur for the duration of the activities in a given area. Transportation of collected biomass from the point of generation to storage facilities or to biomass energy production facilities could also result in impacts on the transportation system.

Visual Resources

Converting idle land to agricultural use would change the visual aspect of an area and probably would be noticeable by any nearby residents or travelers that are familiar with the area. Major timber harvests change the look and character of hillsides and the views that local residents and tourists have of the forest. Collection of the residue biomass would not add to the visual degradation. Changes in the character of the forest resulting from the collection of biomass in forest thinning projects would most likely not be observed from a distance.

Socioeconomics

Direct impacts would include the creation of new jobs for farmworkers and the associated income and taxes generated by increased production of crops and grasses and new markets for crop residue. Increased biomass collection in forested regions would also create new jobs. Indirect impacts would include new jobs at businesses that support the expanded workforce or provide farm and logging equipment materials, and associated income taxes.

Environmental Justice

If significant impacts occurred in any resource areas, and these impacts disproportionately affect minority or low-income populations, then there could be an environmental justice impact. Issues of potential concern are noise, dust, and visual impacts from biomass production and harvesting and potential construction of new access roads. Additional impacts include limitations on access to the area for recreation, subsistence, and traditional activities.

Biomass Energy Operations Impacts

Operations activities that may cause environmental impacts include operation of the biomass energy facility, power generation, biofuel production, and associated maintenance activities. Typical activities during biomass facility operation include power generation or production of biofuels and associated maintenance activities that would require vehicular access and heavy equipment operation when components are being

replaced. Biomass power plants require pollution control devices to reduce emissions from combustion and large cooling systems. Water requirements vary greatly among the various biomass facilities. Potential impacts for these activities are presented below, by the type of affected resource.

Air Quality

Operation of biomass facilities results in emissions of criteria air pollutants and hazardous air pollutants (HAPs). Criteria air pollutants include particulate matter, carbon monoxide, sulfur oxides, nitrogen oxides, lead, and volatile organic compounds (VOCs). HAPs are 189 toxic chemicals, known or suspected be carcinogens, which are regulated by the U.S. Environmental Protection Agency as directed by the 1990 Clean Air Act. If the facility is in an area designated as "attainment" for all state and national ambient air quality standards (NAAQS), then emissions from operation, when added to the natural background levels, must not cause or contribute to ambient pollution levels that exceed the ambient air quality standards.

In particular, combustion of municipal solid wastes could result in trace quantities of mercury, other heavy metals, and dioxins in the air emissions. The use of best available control technology (BACT) would minimize the potential for adverse air quality impacts from biomass facilities. A gas-fired regenerative thermal oxidizer would reduce VOCs by 95%. Baghouses, which are a type of dust collector using fabric filters, control particulate matter. Enclosing the processing equipment in a slight negative pressure envelope in addition to the use of baghouses could minimize fugitive dust emissions from milling operations.

The use of cultivated biomass fuel (i.e., fuel specifically grown for energy production) in place of possible fuels such as coal, oil, and natural gas can result in a reduction in the amount of carbon dioxide that accumulates in the atmosphere only if the carbon released by combustion of biomass fuels is effectively recaptured by the next generation of feedstock plants. If the biomass source is not replaced by growing more plants, the carbon released in biomass combustion is not recaptured; therefore, these forms of biomass energy can only be considered to be carbon free if the energy production cycle includes replacing the feedstock. Using perennial or fast-growing biomass plants, such as switchgrass or poplar hybrids, can increase the rate of carbon recapture. Although the combustion of biomass fuels under these conditions can be considered to be carbon free, in practice any gains in terms of reduced carbon dioxide emissions are offset by carbon dioxide emissions associated with the use of fossil fuels in the cultivation, harvesting, and transportation of the biomass feedstock. Certain agricultural practices (e.g., no-till agriculture, use of perennial feedstock crops) produce fewer carbon dioxide emissions than conventional practices. Biomass energy derived from waste product fuels (e.g., residues from forestry operations, construction wastes, municipal wastes) is not considered to be carbon free, as the energy production cycle does not involve any cultivation of new biomass.

Cultural Resources

Impacts during the operations phase would be limited to unauthorized collection of artifacts and visual impacts. The threat of unauthorized collection would be present once the access roads are constructed in the construction phase, making remote

lands accessible to the public. Visual impacts resulting from the presence of a biomass facility and transmission lines could affect some cultural resources, such as sacred landscapes or historic trails.

Ecological Resources

During operation, adverse ecological effects could occur from (1) disturbance of wildlife by equipment noise and human activity, (2) exposure of biota to chemical spills and other contaminants, and (3) mortality of wildlife due to increased vehicular traffic and collisions with or electrocution by transmission lines. Disturbed wildlife would be expected to eventually acclimatize to facility operations. Deposition of water and salts from the operation of mechanical-draft cooling towers has the potential to impact vegetation. Water intake structures (see Figure 5.13) for withdrawal of water from lakes or rivers would result in impingement and entrainment of aquatic species. Proper design of these structures can minimize these impacts. Discharge of heated cooling water into water bodies could be beneficial or adverse, depending upon the design of the discharge structure and the temperature of the effluent.

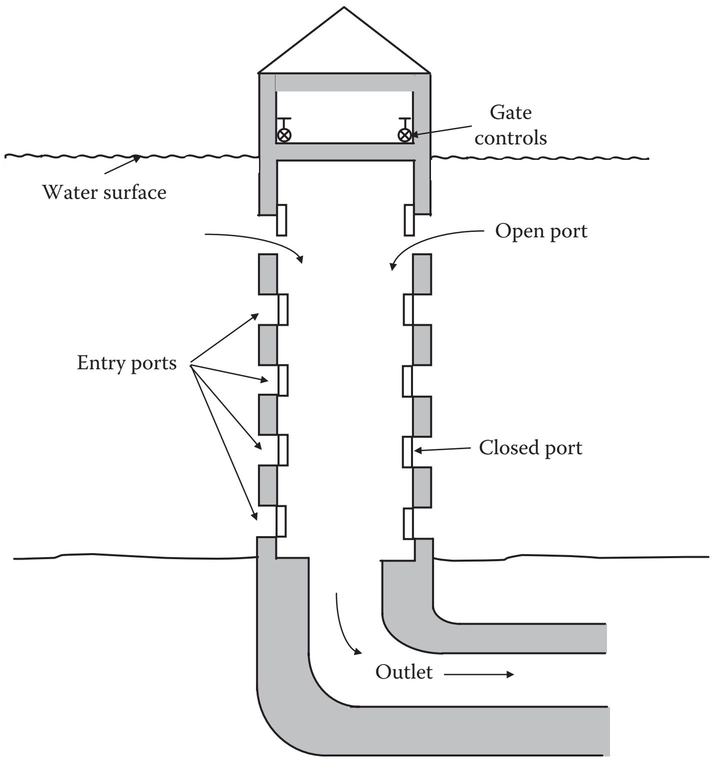

FIGURE 5.13 Tower water intake for a reservoir or lake water supply (larger than scale).

Water Resources

Withdrawals of surface water and/or groundwater are expected to continue during the operations phase of both biomass power plants and biofuel production and refinery facilities. The amount of water needed depends on the type of facility. In a typical biomass power plant, the primary consumptive use of water will be to support the cooling system used to condense spent steam for reuse. Once-through cooling systems require large quantities of water to be withdrawn from and returned to a surface body of water. Wet recirculating cooling systems recycle cooling water through cooling towers where some portion of water is allowed to evaporate and must be continuously replenished. Wet recirculating cooling systems also periodically discharge small volumes of water as blowdown and replace that amount with freshwater to control chemical and biological contaminants to acceptable levels. A third type of cooling system, the dry cooling system, condenses and cools steam using only ambient air and requires no water to operate; however, some dry cooling systems can also be hybridized into wet/dry systems that use minimal amounts of water, which is allowed to evaporate to improve performance. Other consumptive uses of water at a biomass power plant include the initial filling and maintenance of the steam cycle, sanitary applications to support the workforce, and a wide variety of incidental maintenance-related industrial applications.

Most uses of water at a biomass power plant will ultimately result in the generation of some wastewater. Blowdown from both the steam cycle and the wet recirculating cooling system will represent the largest wastewater stream and, because water in both the steam cycle and the cooling system undergoes some chemical treatment, the discharge will contain chemical residuals. Its temperature will also be elevated. Water discharged from once-through systems does not undergo chemical treatment, but the temperature of the discharge will be elevated. All wastewater discharges from biomass power plants can be directed to a holding pond for evaporation, cooling, and further treatment but are likely to be eventually discharged to surface waters. The Clean Water Act requires any facility that discharges from a point source into water of the United States to obtain a National Pollutant Discharge Elimination System (NPDES) permit. The NPDES permit ensures that the state's water quality standards are being met.

Water is used in a wide variety of applications for biofuel production and refining facilities and can be consumed at rates as high as 400 gallons per minute (gpm). Some water used in production and refining activities can be recovered and recycled to reduce the demand on the water source. Algae production ponds can be large but are very shallow (about 12 inches). Only a small volume of water would need to be added to replace any evaporation. Bioreactors for algae production are closed systems and require very little additional water. As much as 100 gpm of wastewater can be discharged from a biofuel production and refining plant. The effluent discharge temperature would be at or slightly above ambient temperature and would often contain small amounts of chemicals. As with wastewaters from biomass power plants, such discharges can be directed to lined holding ponds for further treatment or discharged directly to a surface water body under the authority of an USEPA-issued NPDES permit.

Land Use

Any land use impacts would occur during construction, and no further impacts would be expected to result from biomass facility operation.

Soils and Geologic Resources

During operation, the soil and geologic conditions would stabilize with time. Soil erosion and soil compaction are both likely to continue to occur along access roads. Within the project footprint, soil erosion, surface runoff, and sedimentation of nearby water bodies will continue to occur during operation, but to a lesser degree than during the construction phase.

Paleontological Resources

Impacts during the operations phase would be limited to unauthorized collection of fossils. This threat is present once the access roads are constructed in the construction phase, making remote lands accessible to the public.

Transportation

Increases in the use of local roadways and rail lines would occur during operations. Biomass fuels for boilers and power plants would arrive daily by truck or rail. Feedstock for biofuels facilities, such as corn, soybeans, wood products, manure, and sludge, would also arrive by truck or rail, and ethanol and biodiesel produced would most likely be trucked to the end user, who would blend or sell the product. Depending upon the size and function of the facility, truck traffic could be on the order of 250 trucks per day. Biogas facilities would either combust the gas at the production plant or send it by pipeline to the user. Landfill gas would either be used to produce electricity near the point of collection or be sent by pipeline to the user.

Visual Resources

The magnitude of visual impacts from operation of a biomass facility is dependent on the distance of the facility from the viewer, the view duration, and the scenic quality of the landscape. Facility lighting would adversely affect the view of the night sky in the immediate vicinity of the facility. Plumes from stacks of cooling towers might be visible, particularly on cold days. Additional visual impacts would occur from the increase in vehicular traffic.

Socioeconomics

Direct impacts would include the creation of new jobs for operation and maintenance workers and the associated income and taxes paid. Indirect impacts are those impacts that would occur as a result of the new economic development and would include new jobs at businesses that support the workforce or that provide project materials, and associated income and taxes. The number of project personnel required during the operation and maintenance phase would be fewer than during construction; therefore, socioeconomic impacts related directly to jobs would be smaller than during construction.

Environmental Justice

Possible environmental justice impacts during operation include the alteration of scenic quality in areas of traditional or cultural significance to minority or low-income populations and disruption of access to those areas. Noise impacts, health and safety impacts, and water consumption are also possible sources of disproportionate effect.

IMPACTS ON HUMAN HEALTH AND SAFETY*

As demand for low-carbon-impact, domestically sourced fuels has increased, biofuels have become a fast-growing part of the energy sector. Biofuels are produced from renewable resources, such as grains, plants biomass, vegetable oils, and treated municipal and industrial wastes. They are flammable or combustible, and their manufacture can involve potentially dangerous chemical reactions. Employers must protect workers from the hazards of these fuels and their production processes. There are currently two major types of biofuels being produced in the United States:

- *Ethanol* is a flammable liquid that is readily ignited at ordinary temperatures. Renewable ethanol is produced by the fermentation of grains, or, using advanced technologies, from cellulosic material such as waste paper, wood chips, and agricultural wastes. The production process can involve other hazardous materials, such as acids, bases, and gasoline (to denature the alcohol or for blending). Up to 10% ethanol is blended with gasoline in most automotive fuel currently sold in the United States. Higher ethanol blends, up to E85 (85% ethanol blended with gasoline), are also available in some parts of the country.
- *Biodiesel* is a combustible liquid that burns readily when heated; blending it with petroleum-based diesel fuel or contamination by materials used in manufacturing can increase its flammability. Biodiesel is produced by reacting organic materials such as vegetable oils with an alcohol, typically methanol, using a strong base, such as a caustic, as a catalyst. Glycerin, a combustible liquid, is produced as a byproduct. The caustic is neutralized with acid, typically sulfuric acid. All of these materials may require careful management to protect workers. Biodiesel blended with petroleum-based diesel is widely available.

Biofuel Hazards

Potential hazards in biofuels production and handling include the following:

- Fire/explosion hazards
- Chemical reactivity hazards
- Toxicity hazards

* Adapted from OSHA's *Green Job Hazards: Biofuels*, https://www.osha.gov/dep/greenjobs/biofuels.html.

Fire and Explosion Hazards*

Employers producing biofuels may expose workers to potential fire and explosion hazards, and they must protect them from these hazards by preventing releases, avoiding ignition of spills, and having appropriate fire protection systems and emergency response procedures in place. Engineering controls that should be used include the following:

- Good facility layout
- Proper design of vessels and piping systems
- Proper selection of electrical equipment for use in hazardous (classified) areas
- Adequate instrumentation with alarms, interlocks, and shutdowns

Administration controls that should be used include the following:

- Operating procedures
- Good maintenance practices
- Safe work practices/procedures

Facilities processing more than 10,000 pounds of flammable liquids or flammable mixtures may be covered by 29 CFR 1910.119 (Process Safety Management of Highly Hazardous Chemicals).

Chemical Reactivity Hazards†

Biofuels manufacturing processes can present reactive hazards. Although ethanol production by fermentation involves biological reactions that do not present an explosive "run-away reaction" hazard, some processes for making ethanol from materials such as waste paper and wood chips use concentrated acids and bases that can react vigorously with many materials. Also, the gases produced during ethanol fermentation need to be properly vented to avoid overpressuring equipment and piping. Biodiesel is produced by the chemical reaction of organic oils with an alcohol, typically using a strong base as a catalyst. The glycerin that is co-produced with the biodiesel is then often treated with acid. These reactions need to be carefully controlled. Failure to control potentially dangerous chemical reactions can lead to the rupture of equipment and piping, explosions, fires, and exposures to hazardous chemicals. Employers need to protect their workers from these hazards. Engineering and administrative controls to keep the process within safe limits include controlling the rate and order of chemical addition, providing robust cooling, segregating incompatible materials to prevent inadvertent mixing, and the use of detailed operating procedures. Several OSHA standards address potential reactive hazards:

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* Adapted from OSHA's *Green Job Hazards: Biofuels—Fire and Explosion Hazards of Biofuels*, https://www.osha.gov/dep/greenjobs/bio_fireexplosion.html.

† Adapted from OSHA's *Green Job Hazards: Biofuels—Chemical Reactivity Hazards in Biofuel Manufacturing*, https://www.osha.gov/dep/greenjobs/bio_chemical.html.

DID YOU KNOW?

Hazards, including toxic hazards that are not addressed by specific OSHA standards, still need to be controlled. Under Section 5(a)(1) of the OSHA Act, the "General Duty Clause," employers are required to provide workers with a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious physical harm to employees.

- 29 CFR 1910.119, Process Safety Management of Highly Hazardous Chemicals
- 29 CFR 1910.1200, Hazard Communication
- 29 CFR 1910.147, The Control of Hazardous Energy (Lockout/Tagout)

Toxicity Hazards*

Biofuels and the chemicals used in their manufacture present toxic exposure hazards that need to be carefully controlled to protect workers. Material Safety Data Sheets (MSDSs) should be consulted to determine the potential for toxic exposures to feedstocks, products, and other chemicals used in biofuel processes, including, but not limited to, methanol, caustic, sulfuric acid, ethanol, and biodiesel, as well as hydrocarbons used for blending and alcohol denaturing. Engineering and administrative controls should be used to control hazards, including, but not limited to, good engineering, design, fabrication, and maintenance practices to prevent releases, ventilation and drainage to reduce exposures, and appropriate use of personal protective equipment, when needed. A number of OSHA standards address these potential hazards:

- 29 CFR 1910.119, Process Safety Management of Highly Hazardous Chemicals
- 29 CFR 1910.1200, Hazard Communication
- 29 CFR 1910, Subpart I, Personal Protective Equipment
- 29 CFR 1910.134, Respiratory Protection
- 29 CFR 1910.146, Permit-Required Confined Spaces
- 29 CFR 1910.147, The Control of Hazardous Energy (Lockout/Tagout)

FATALITIES AND INCIDENTS

Ethanol

- Two employees were burned when ethanol vapors escaped from an adsorption column. No procedure was used to ensure that the column was safe to start up.
- Two workers were burned when grain alcohol leaking from the process was ignited by sparks from a hotwork operation in the area.

* Adapted from OSHA's *Green Job Hazards: Biofuels—Toxicity Hazards in Biofuel Manufacturing*, https://www.osha.gov/dep/greenjobs/bio_toxicity.html.

Biodiesel

- An employee was killed while using an oxyacetylene torch on a storage tank containing residual glycerin and methanol vapors in a biodiesel facility.
- An employee was killed when his power tool ignited methanol vapors in an impure glycerin tank in a biodiesel facility.

BIOFUELS: THE BOTTOM LINE

With near record oil prices, the future of biofuel—made from plant material (biomass)—is of keen interest worldwide. Using biofuels to power industry, private vehicles, and personal appliances offers several benefits over the use of conventional fuels. For example, environmental benefits include the use of biomass energy to greatly reduce greenhouse gas emissions. Burning biomass releases about the same amount of carbon dioxide as burning fossil fuels. However, fossil fuels release carbon dioxide captured by photosynthesis millions of years ago—an essentially "new" greenhouse gas. Biomass, on the other hand, releases carbon dioxide that is largely balanced by the carbon dioxide captured in its own growth (depending on how much energy was used to grow, harvest, and process the fuel).

Another benefit of biomass use for fuel is that it can reduce dependence on foreign oil because biofuels are the only renewable liquid transportation fuels available. Moreover, biomass energy supports U.S. agricultural and forest-product industries. The main biomass feedstocks for power are paper mill residue, lumber mill scrap, and municipal waste. For biomass fuels, the feedstocks are corn (for ethanol) and soybeans (for biodiesel), both surplus crops. In the near future—and with developed technology—agricultural residues such as corn stover (the stalks, leaves, and husks of the plant) and wheat straw will also be used. Long-term plans include growing and using dedicated energy crops, such as fast-growing trees and grasses that can grow sustainably on land that will not support intensive food crops.

The preceding lists many of the benefits of using biomass fuel; that is all well and good, but the reality is that the future role of biofuels depends on profitability and new technologies. Technological advances and efficiency gains—higher biomass yields per acre and more gallons of biofuel per ton of biomass—could steadily reduce the economic cost and environmental impact of biofuel production. Biofuel production will likely be most profitable and environmentally benign in tropical areas where growing seasons are longer, per-acre biofuel yields are higher, and fuel and other input costs are lower. For example, Brazil uses *bagasse*, which is a byproduct from sugar production, to power ethanol distilleries, whereas the United States uses natural gas or coal.

Biofuels will most likely be part of a portfolio of solutions to high oil prices, including conservation and the use of other alternative fuels. The role of biofuels in global fuel supplies is likely to remain modest because of their land intensity. In the United States, replacing all current gasoline consumption with ethanol would require more land in corn production than is currently used for all agricultural production. Technology will be central to boosting the role of biofuels. If the energy of widely available, cellulose materials could be economically harnessed around the world, biofuel yields per acre could more than double, reducing land requirements significantly (USDA, 2012).

THOUGHT-PROVOKING QUESTIONS

5.1 Do you agree with Kurt Anderson's assertion that the current generation is the Grasshopper Generation? Explain.
5.2. Can you think of any other biomass feedstocks that might be considered for biofuel production?
5.3 Why does the author characterize algae as Jekyll and Hyde-like organisms?
5.4 Do you think using food corn as a feedstock for ethanol production is a good practice? Explain.
5.5 Is the production of biomass carbon neutral? Explain.
5.6 Is deforestation worth the production of biofuel? Explain.

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6 Geothermal Energy

> The U.S. Geological Survey has calculated that the heat energy in the upper 10 kilometers of the Earth's crust in the U.S. is equal to over 600,000 times the country's annual non-transportation energy consumption. Probably no more than a tiny fraction of this energy could ever be extracted economically. However, just one hundredth of 1% of the total is equal to half the country's current non-transportation energy needs for more than a century, with only a fraction of the pollution from fossil-fueled energy sources.
>
> **McLarty et al. (2000)**

> Geothermal heat is the only renewable energy source created naturally by the Earth itself.
>
> **—Kimberly K. Smith, Carlton College**

> If we utilize waste biomass, solar (passive and thermal), wind (on shore), photovoltaic, geothermal, and other renewable resources available to us in the United States, we would exceed the demand (what we need) by at least five times as much energy as we need, all from clean, renewable sources.
>
> **—Frank R. Spellman**

On May 30, 2009, at 5:00 p.m., a worker of Terra-Gen Operating Company LLC was seriously injured with second- and third-degree burns to his body while at the company's remote worksite near Inyokem, California, performing his regular assigned duties as an operation supervisor at the geothermal electric power generation facility. The worker observed a leak of 150 to 160°F geothermal water coming from a temporary diesel engine-powered pump and piping system at a collection pond. He shut off the diesel engine of one of the five temporary pumps at the site, then turned around to walk away. After rotating his body he fell into a pool of heated water. The pressurized water from the leak gouged out an approximately 2-foot-deep depression in the sand and gravelly desert soil. He radioed a coworker and alerted him of the incident. The company's emergency action plan was implemented. The worker was airlifted to Fresno Regional Medical Center to receive treatment. An inspection was initiated by the OSH Fresno District Office.

INTRODUCTION*

Approximately 4000 miles below the Earth's surface is the core, where temperatures can reach 9000°F. This heat—geothermal energy (*geo* meaning "earth" and *thermos* meaning "heat")—flows outward from the core, heating the surrounding area, which can form underground reservoirs of hot water and steam (Figure 6.1). These

* Adapted from USDOE, *Renewable Energy: An Overview*, U.S. Department of Energy, Washington, DC, 2001 (http://www.nrel.gov/docs/fy01osti/27955.pdf).

FIGURE 6.1 Drilled geothermal energy source in New Mexico. (From NREL, *Image Gallery*, National Renewable Energy Laboratory, Washington, DC, 2014, http://images.nrel.gov/.)

reservoirs can be tapped for a variety of uses, such as to generate electricity or to heat buildings. The geothermal energy potential in the uppermost 6 miles of the Earth's crust amounts to 50,000 times the energy of all oil and gas resources in the world. In the United States, most geothermal reservoirs are located in the western states, Alaska, and Hawaii; however, geothermal heat pumps (GHPs), which take advantage of the shallow ground's stable temperature for heating and cooling buildings, can be used almost anywhere.

DID YOU KNOW?

Scientists estimate that geothermal potential could be as large as 100 million kilowatts.

It is important to emphasize that there is nothing new about renewable energy. From solar power to burning biomass (wood) in caves and elsewhere, humans have taken advantage of renewable resources from time immemorial. Hot springs have been used for bathing since Paleolithic times or earlier (USDOE, 2010), and the early Romans used hot springs to supply public baths and for underfloor heating systems. The world's oldest geothermal district heating system has been operating in France since the 14th century (Lund, 2007). The history of geothermal energy use in the United States is interesting and lengthy; following is a brief chronology of major geothermal events in this country (EERE, 2014a).

Geothermal Timeline*

8000 B.C. (and Earlier)

Paleo-Indians used hot springs for cooking and for refuge and respite. Hot springs were neutral zones where members of warring nations would bathe together in peace. Native Americans have a history with every major hot spring in the United States.

1807

As European settlers moved westward across the continent, they gravitated toward these springs of warmth and vitality. In 1807, the first European visited the Yellowstone area; John Colter (*c.* 1774–1813), widely considered to be the first mountain man, probably encountered hot springs, leading to the designation "Colter's Hell." Also that year, settlers founded the city of Hot Springs in Arkansas, where, in 1830, Asa Thompson charged $1 a person for the use of three spring-fed baths in a wooden tub—the first known commercial use of geothermal energy.

1847

William Bell Elliot, a member of John C. Fremont's survey party, stumbled upon a steaming valley just north of what is now San Francisco, California. Elliot called the area *The Geysers*—a misnomer—and thought he had found the gates of Hell.

1852

The Geysers was developed into a spa called The Geysers Resort Hotel. Guests included J. Pierpont Morgan, Ulysses S. Grant, Theodore Roosevelt, and Mark Twain.

1862

At springs located southeast of The Geysers, businessman Sam Brannan poured an estimated half million dollars into an extravagant development dubbed "Calistoga," replete with hotel, bathhouse, skating pavilion, and racetrack. Brannan's was one of many spas reminiscent of those of Europe.

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* Adapted from EERE, *A History of Geothermal Energy in the United States*, Energy Efficiency & Renewable Energy, U.S. Department of Energy, Washington, DC, 2014 (http://www1.eere.energy.gov/geothermal/history.html)

1864

Homes and dwellings had been built near springs through the millennia to take advantage of their natural heat, but the construction of the Hot Lake Hotel near La Grande, Oregon, marked the first time that the energy from hot springs was used on a large scale.

1892

Boise, Idaho, provided the world's first district heating system as water was piped from hot springs to town buildings. Within a few years, the system was serving 200 homes and 40 downtown businesses. Today, there are four district heating systems in Boise that provide heat to over 5 million square feet of residential, business, and governmental space. The United States has 17 district heating systems, and dozens more can be found around the world.

1900

Hot springs water was piped to homes in Klamath Falls, Oregon.

1921

John D. Grant drilled a well at The Geysers with the intention of generating electricity. This effort was unsuccessful, but a year later Grant met with success across the valley at another site, and the United States' first geothermal power plant went into operation. Grant used steam from the first well to build a second well, and several wells later the operation was producing 250 kilowatts, enough electricity to light the buildings and streets at the resort. The plant, however, was not competitive with other sources of power, and it soon fell into disuse.

1927

Pioneer Development Company drilled the first exploratory well at Imperial Valley, California.

1930

The first commercial greenhouse use of geothermal energy was undertaken in Boise, Idaho. The operation used a 1000-foot well drilled in 1926. In Klamath Falls, Charlie Lieb developed the first downhole heat exchanger (DHE) to heat his house. Today, more than 500 DHEs are in use around the country.

1940

The first residential space heating in Nevada became available in the Moan area in Reno.

1948

Geothermal technology moved east when Carl Nielsen developed the first ground-source heat pump for use at his residence. J.D. Krocker, an engineer in Portland, Oregon, pioneered the first commercial building use of a groundwater heat pump.

1960

The country's first large-scale geothermal electricity-generating plant began operation. Pacific Gas and Electric operated the plant located at The Geysers. The first turbine produced 11 megawatts (MW) of net power and operated successfully for more than 30 years. Today, 69 generating facilities are in operation at 18 resource sites around the country.

1978

Geothermal Food Processors, Inc., opened the first geothermal food-processing (crop-drying) plant in Brady Hot Springs, Nevada. The Loan Guaranty Program provided \$3.5 million for the facility.

1979

The first electrical development of a water-dominated geothermal resource occurred at the east Mesa field in the Imperial Valley in California. The plant was named for B.C. McCabe, the geothermal pioneer who, with his Magma Power Company, did field development work at several sites, including The Geysers.

1980

TAD's Enterprises of Nevada pioneered the use of geothermal energy for the cooking, distilling, and drying processes associated with alcohol fuel production. UNOCAL built the country's first flash plant, generating 10 MW at Brawley, California.

1982

Economical electrical generation began at California's Salton Sea geothermal field through the use of crystallizer-clarifier technology. The technology resulted from a government/industry effort to manage the high-salinity brines at the site.

1984

A 20-MW plant began generating power at Utah's Roosevelt Hot Springs. Nevada's first geothermal electricity was generated when a 1.3-MW binary power plant went into operation.

1987

Geothermal fluids were used in the first geothermal-enhanced heap leaching project for gold recovery near Round Mountain, Nevada.

1989

The world's first hybrid (organic Rankine/gas engine) geopressure–geothermal power plant began operation at Pleasant Bayou, Texas, using both the heat and the methane of a geopressured resource.

1992

Electrical generation began at the 25-MW geothermal plant in the Puna field of Hawaii.

1993

A 23-MW binary power plant was completed at Steamboat Springs, Nevada.

1995

In Empire, Nevada, Integrated Ingredients dedicated a food-dehydration facility capable of processing 15 million pounds of dried onions and garlic per year. A DOE low-temperature resource assessment of 10 western states identified nearly 9000 thermal wells and springs and 271 communities collocated with a geothermal resource greater than 50.

2002

Organized by GeoPowering the West, geothermal development working groups were active in five states—Nevada, Idaho, New Mexico, Oregon, and Washington. Group members represented all stakeholder organizations. The working groups began identifying barriers to geothermal development in their states and bringing together all interested parties to arrive at mutually beneficial solutions.

2003

The Utah Geothermal Working Group was formed.

Geothermal Energy as a Renewable Energy Source

Table 6.1 shows geothermal energy's ranking as a renewable energy source. The 0.360 geothermal quadrillion Btu figure is expected to steadily increase, which should be reflected in later figures when they are released.

TABLE 6.1
U.S. Energy Consumption by Energy Source (2008)

Energy Source	Energy Consumption (quadrillion Btu)
Total	99.438
Renewable	7.367
Biomass (total)	3.852
Biofuels	1.372
Waste	0.436
Wood and wood-derived fuels	2.044
Geothermal energy	**0.360**
Hydroelectric conventional	2.512
Solar thermal/PV energy	0.097
Wind energy	0.546

Source: EIA, *U.S. Energy Consumption by Energy Source*, Environmental Investigation Agency, Washington, DC, 2007 (http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/table1.html).

GEOTHERMAL ENERGY: THE BASICS

Geothermal energy processes utilize the natural heat of the Earth for beneficial purposes when the heat is collected and transported to the surface. To gain a proper understanding of geothermal energy as it is used at present, it is important to define *enthalpy*, the heat content of a substance per unit mass. Temperature alone is not sufficient to define the useful energy content of a steam/water mixture. A mass of steam at a given temperature and pressure can provide much more energy than the same mass of water under the same conditions. Enthalpy is a function of

$$\text{Pressure} + \text{Volume} + \text{Temperature} = \text{Enthalpy}$$

Geothermal practitioners usually classify geothermal resources as high enthalpy (water and steam at temperatures above about 180 to 200°C), medium enthalpy (about 100 to 180°C), and low enthalpy (<100°C). For the purpose of this text, though, it is sufficient to think of temperature and enthalpy as the same.

Earth's Layers

Earth is made up of three main compositional layers: crust, mantle, and core (see Figure 6.2). The crust has variable thickness and composition; the continental crust is 10 to 50 km thick, and the oceanic crust is 8 to 10 km thick. The elements silicon, oxygen, and aluminum, among others, make up the Earth's crust. Like the shell of an egg, the Earth's crust is brittle and can break. Based on seismic (earthquake) waves that pass through the Earth, we know that below the crust is the mantle, a dense, hot layer of semisolid rock approximately 2900 km thick. The mantle might be thought of as the white of a boiled egg. It contains silicon, oxygen, aluminum, and more iron, magnesium, and calcium than the crust. The mantle is hotter and more dense than

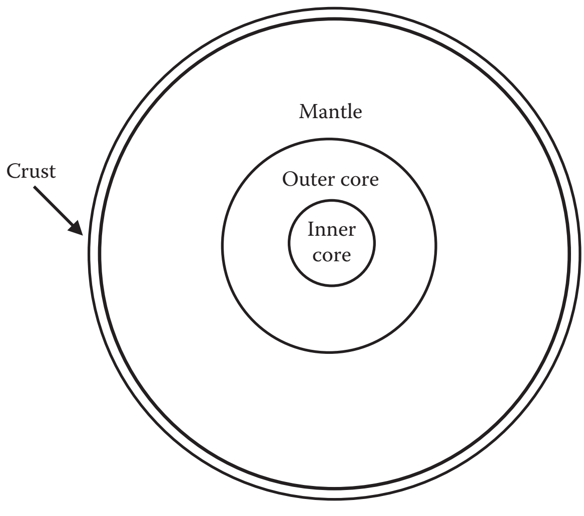

FIGURE 6.2 Layers of the Earth.

the crust because temperature and pressure inside the Earth increase with depth. The temperature at the top of the mantle is 870°C; the temperature at the bottom is 2200°C. The 30-km-thick transitional layer between the mantle and crust is called the Moho layer.

At the center of the Earth lies the core, which is nearly twice as dense as the mantle because its composition is metallic (comprised of iron–nickel alloy) rather than stony. Unlike the yolk of an egg, however, the Earth's core is actually made up of two distinct parts: a 2200-km-thick liquid outer core and a 1250-km-thick solid inner core. As the Earth rotates, the liquid outer core spins, creating the Earth's magnetic field. Several important points related to Earth's structure and geothermal properties include the following:

- Heat flows outward from the center as a result of radioactive decay.
- The crust insulates us from the interior heat.
- The temperature at the base of crust is about 1000°C and increases slowly deeper into the core.
- Hot spots are located 2 to 3 km from the surface.

Crustal Plates

Geologists have developed the theory of *plate tectonics* (from the Greek word for "builder"). The theory of plate tectonics deals with the formation, destruction, and large-scale motions of great segments of the Earth's surface (crust), called *plates*. This theory relies heavily on the older concept of continental drift (developed during the first half of the 20th century) and newer understanding of seafloor spreading, both of which help to explain earthquakes and volcanic eruptions, as well as the origin of fold mountain systems. Large quantities of heat (that are economically extractable) tend to be concentrated in places where hot or even molten (magma) rock exists at relatively shallow depths in the Earth's outmost layer (the crust). Such hot zones generally are near the boundaries of the dozen or so slabs of rigid rock (or plates) that form the Earth's lithosphere. These crustal plates are composed of great slabs of rock (lithosphere) about 100 km thick and cover many thousands of square miles (they are thin in comparison to their length and width). Geologists recognize at least seven main plates:

- African Plate (covering Africa)
- Antarctic Plate (covering Australia)
- Eurasian Plate (covering Asia and Europe)
- Indo-Australian Plate (covering Indian subcontinent, part of the Indian Ocean, and Australia)
- North American Plate (covering North America and northeast Siberia)
- Pacific Plate (covering the Pacific Ocean)
- South American Plate (covering South America)

as well as several minor plates:

- Arabian Plate
- Caribbean Plate
- Cocos Plate
- Juan de Fuca Plate
- Nazea Plate
- Philippine Plate
- Scotia Plate

The plates literally ride on the *asthenosphere*, which is the ductile, soft, plastic-like zone in the upper mantle. Crustal plates move in relation to one another at one of three types of plate boundaries: convergent (collision) boundaries, divergent (spreading) boundaries, and transform boundaries. These boundaries between plates are typically associated with deep-sea trenches, large faults, fold mountain ranges, and mid-oceanic ridges.

Convergent Boundaries

Convergent boundaries (or active margins) develop where two plates slide toward each other, commonly forming either a subduction zone (if one plate subducts or moves underneath the other) or a continental collision (if the two plates contain continental crust). To relieve the stress created by the colliding plates, one plate deforms and slips below the other.

Divergent Boundaries

Divergent boundaries occur where two plates slide apart from each other. Oceanic ridges, which are examples of divergent boundaries, occur where new oceanic, melted lithosphere materials well up, resulting in basaltic magmas, which intrude and erupt at the oceanic ridge, in turn creating new oceanic lithosphere and crust (new ocean floor). Along with volcanic activity, the mid-oceanic ridges are also areas of seismic activity.

Transform Boundaries

Transform boundaries do not separate or collide; rather, they slide past each other in a horizontal manner with a shearing motion. Most transform boundaries occur where oceanic ridges are offset on the sea floor. The San Andreas Fault in California is an example of a transform fault.

DID YOU KNOW?

Plates are in constant motion (several centimeters per year). When collision or grinding occurs, it can create mountains, volcanoes, geysers, and earthquakes. Near the junction of these plates is where heat travels rapidly from the interior of the planet.

ENERGY CONVERSION

The conversion of heat to electricity is common to most power plants. This is the case whether the energy source is coal, gas, nuclear power, wind power, solar power, water power, or geothermal power. Powering the nontransportation section of our economy is important, of course, so converting any fuel source to electrical power for industrial use is a prime objective in our constant and insatiable appetite for energy. It is tempting to think that we should focus solely on the production of electricity to power not only our industries and homes but also everything else—one genie in one bottle to accomplish everything. Liquid fuels are the fuels of choice right now because they are accessible, available, and relatively inexpensive. Thus, although our ongoing research for other energy sources persists, we still do not have that absolute pressing need to come up with a liquid fuel replacement—at least not yet. Anyway, when our energy-needs focus shifts due to necessity, absolute or otherwise, geothermal energy will be available, and we need to continue our research in this important area. Energy conversion occurs routinely today, with a variety of types of energy, and geothermal conversion is nothing new; only the procedures and methodology differ.

Geothermal energy conversion refers to the power-plant technology that converts the hot geothermal fluids into electric power. Even though geothermal power plants have much in common with traditional power-generating stations—turbines, generators, heat exchangers, and other standard power-generating equipment—there are important differences between geothermal and other power-generating technologies. Each geothermal site, for example, has its own unique set of characteristics and operating conditions that must be taken into account. The fluid produced from a geothermal well can be steam, brine, or a mixture or the two, and the temperature and pressure of the resource can vary substantially from site to site. The chemical composition of the resource can contain dissolved minerals, gases, and other substances that are difficult to manage. Because these site-specific conditions can have a profound affect on efficiency, productivity, and economic viability, engineers strive to fine tune geothermal conversion technology, precisely matching plant design to the site-specific conditions.

GEOTHERMAL POWER PLANT TECHNOLOGIES

Geothermal power plants fall into one of three conversion categories: *dry steam*, *flash*, or *binary cycle*. The type of conversion used depends on the state of the fluid (whether steam or water) and its temperature. The first geothermal power generation plant built was a dry steam power plant; this type of plant uses the steam from the geothermal reservoir as it comes from wells and routes it directly through turbine/generator units to produce electricity. Flash steam plants, the most common type of geothermal power generation plants in operation today, pump water at temperatures greater than 360°F (182°C) and under high pressure to generation equipment at the surface. Binary cycle geothermal power generation plants differ from dry steam and flash steam systems in that the water or steam from the geothermal reservoir never comes in contact with the turbine/generator units.

DID YOU KNOW?

The temperature of the Earth increases, on average, by about 28°C for every kilometer (80°F for every mile) of depth below the surface for the first several kilometers down.

Dry Steam Power Plants

Location-specific dry steam power plants take advantage of subterranean rocks that are so hot that the water vaporizes on its way up through the production well (see Figure 6.3). This type of geothermal power plant is able to use steam directly from the ground to drive the turbine. This is the oldest type of geothermal power plant. It was first used in Italy in 1904 and is still very effective. These geothermal plants emit only excess steam and very minor amount of gases (EERE, 2010a).

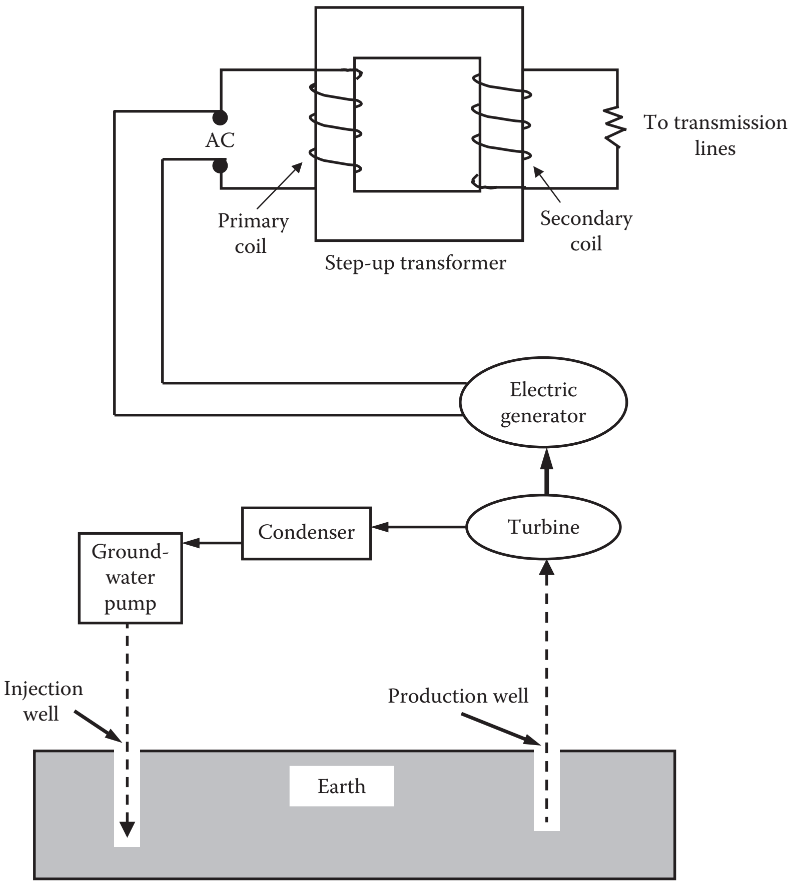

FIGURE 6.3 Simplified functional diagram of a dry steam geothermal power plant.

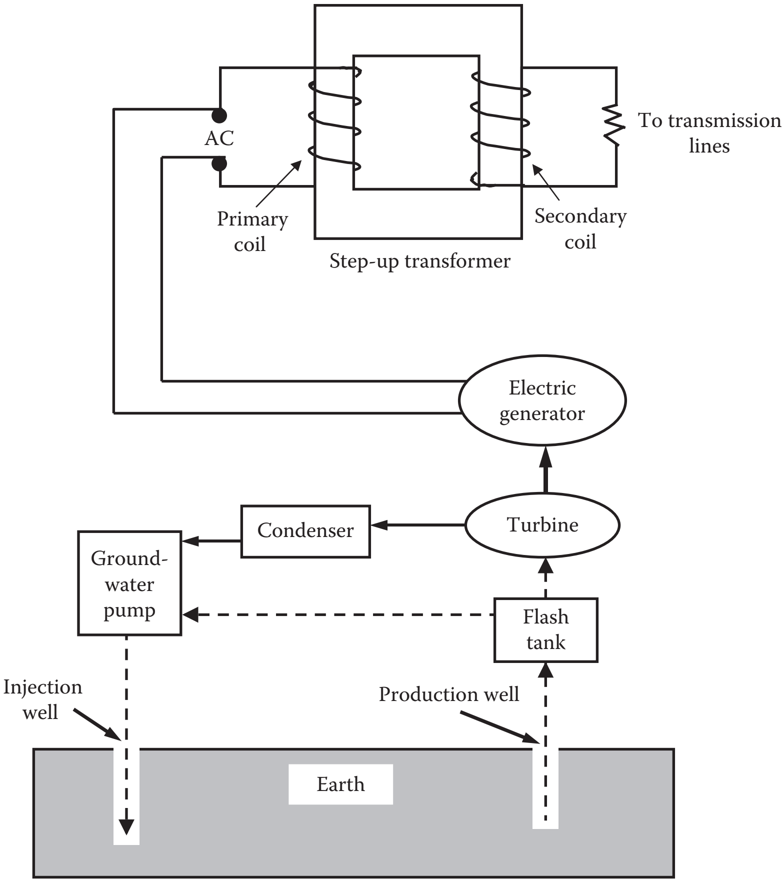

FIGURE 6.4 Simplified functional diagram of a flash steam geothermal power plant.

Flash Steam Power Plants

Figure 6.4 illustrates a flash steam geothermal power plant. Fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or "flash." The vapor then drives a turbine, which drives a generator. If any liquid remains in the tank, it is returned to the groundwater pump to be forced down into the Earth again so it can be flashed again to extract more energy.

Binary Cycle Power Plants

In a binary cycle geothermal power plant (see Figure 6.5), water is pumped into the Earth and comes back up hot, just as it does in the flash steam system. Instead of going into a flash tank, however, the hot water enters a *heat exchanger* (see Figure 6.5), where most of its energy is transferred to another fluid, the binary liquid. This fluid can be water, but more often it is a volatile liquid resembling refrigerant that boils easily into vapor at a lower temperature than the water. The liquid-to-vapor

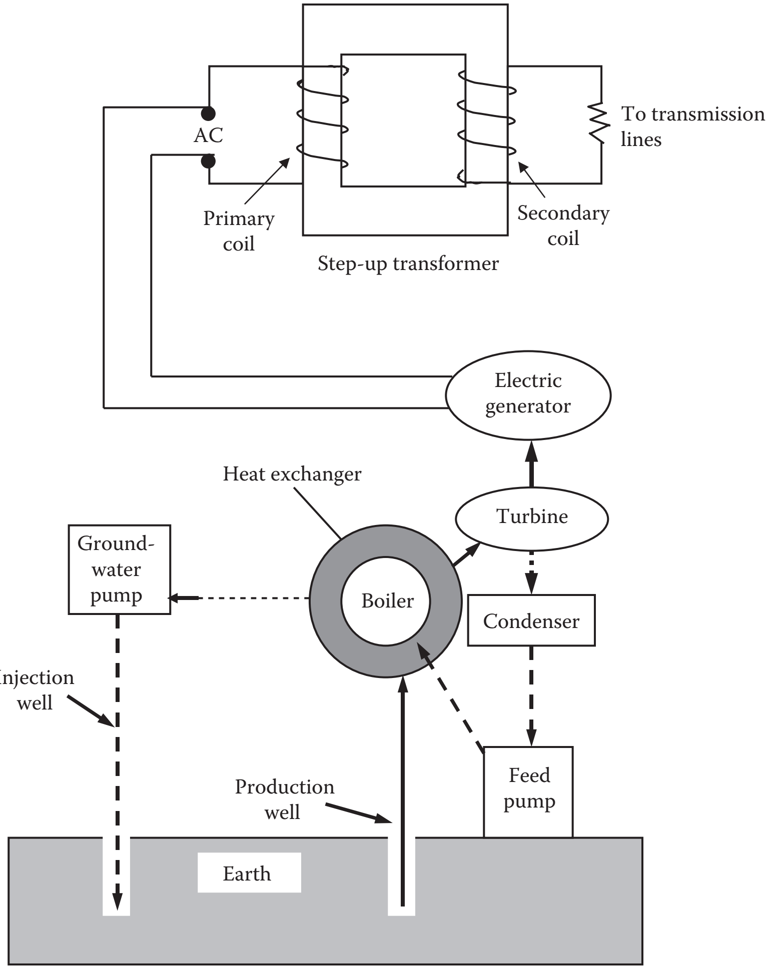

FIGURE 6.5 Simplified functional diagram of a binary cycle geothermal power plant.

conversion occurs in a special low-temperature boiler. Then the vapor leaves the turbine, is cooled back into liquid by a condenser, and is recirculated to the boiler. Because this is a closed-loop system, virtually nothing is emitted to the atmosphere. Moderate temperature water is by far the more common geothermal resource, and most geothermal power plants in the future will be binary cycle plants.

ENHANCED GEOTHERMAL SYSTEMS

The great potential for dramatically expanding the use of geothermal energy can be realized by using enhanced geothermal systems (EGSs), also sometimes called *engineered geothermal systems*. Current geothermal power generation comes from hydrothermal reservoirs and is somewhat limited in geographic application to specific ideal places in the western United States. This represents the "lower hanging

fruit" of geothermal energy potential (EERE, 2012). Enhanced geothermal systems offer the ability to extend the use of geothermal resources to large areas of the western United States, as well as into new geographic areas of the entire country. More than 100,000 MWe (megawatt electrical) of economically viable capacity may be available in the continental United States, representing a 40-fold increase over current geothermal power generating capacity. This potential is about 10% of the overall U.S. electrical capacity today, and such systems represent a domestic energy source that is clean, reliable, and proven.

The EGS concept is to extract heat by creating a subsurface fracture system, a reservoir, to which water can be added from injection wells, which are drilled into hot basement rock that has limited permeability and fluid content. This type of geothermal resource is sometimes referred to as "hot, dry rock" and represents an enormous potential energy resource. Creating an enhanced, or engineered, geothermal system requires improving the natural permeability of rock. Rocks are permeable due to minute fractures and pore spaces between mineral grains. Water is injected at sufficient pressure to ensure fracturing; the water is heated by contact with the rock and returns to the surface through production wells, as in naturally occurring hydrothermal systems. Additional production wells are drilled to extract heat from large volumes of rock mass to meet power generation requirements. A previously unused but large energy resource is now available for clean, geothermal power generation.

GEOTHERMAL HEAT PUMPS

Geothermal heat pumps (GHPs), sometimes referred to as geoexchange, earth-coupled, ground-source, or water-source heat pumps, have been in use since the later 1940s. Geothermal heat pumps use the constant temperature of the Earth as the exchange medium instead of the outside air temperature. This allows the system to reach fairly high efficiencies (300 to 600%) on the coldest of winter nights, compared to 175 to 250% for air-source heat pumps on cool days. Geothermal heat pumps are used for space heating and cooling, as well as water heating. Their great advantage is that they work by concentrating naturally existing heat, rather than by producing heat through the combustion of fossil fuels. The system includes three principal components (see Figure 6.6):

- *Geothermal Earth connection subsystems*—Using the Earth as a heat source (sink), a series of pipes, commonly called a *loop*, is buried in the ground near the building to be conditioned. The loop can be buried either vertically or horizontally. It circulates a fluid (water, or a mixture of water and antifreeze) that absorbs heat from, or relinquishes heat to, the surrounding soil, depending on whether the ambient air is colder or warmer than the soil.
- *Geothermal heat pump subsystem*—For heating, a geothermal heat pump removes the heat from the fluid in the Earth connection, concentrates it, and then transfers it to the building. For cooling, the process is reversed.
- *Geothermal heat distribution subsystem*—Conventional ductwork is generally used to distribute heated or cooled air from the geothermal heat pump throughout the building.

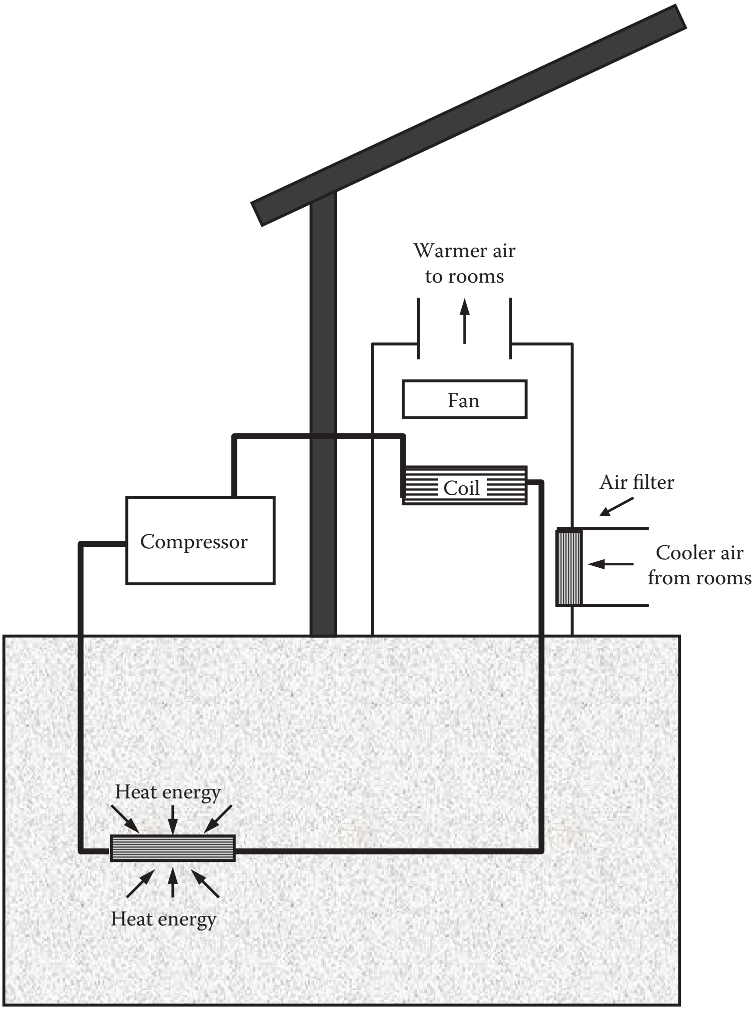

FIGURE 6.6 Geothermal heat pump system. (Adapted from Gibilisco, S., *Alternative Energy Demystified*, McGraw-Hill, New York, 2007, p. 54.)

In addition to space conditioning, geothermal heat pumps can be used to provide domestic hot water while the system is operating. Many residential systems are now equipped with *desuperheaters*, which transfer excess heat from the compressor of the geothermal heat pump compressor to the hot water tank. A desuperheater provides no hot water during the spring and fall when the geothermal heat pump system is not operating; however, because the geothermal heat pump is so much more efficient than other means of water heating, manufacturers are beginning to offer "full demand" systems that use a separate heat exchanger to meet all of a household's hot water needs. These units cost-effectively provide hot water as quickly as any competing system (EERE, 2014b).

Types of Geothermal Heat Pumps

There are four basic types of ground-loop geothermal heat pump systems. Three of these—horizontal, vertical, and pond/lake—are closed-loop systems. The fourth type of system is an open-loop option. Which one of these is best depends on the climate, soil conditions, available land, and local installation costs at the site. All of these approaches can be used for residential and commercial building applications (EERE, 2014b).

Closed-Loop Systems

- *Horizontal*—This type of installation is generally most cost effective for residential installations, particularly for new construction where sufficient land is available. It requires trenches at least 4 feet deep. The most common layouts use either two pipes, one buried at 6 feet and the other at 4 feet, or two pipes placed side-by-side 5 feet in the ground in a 2-foot-wide trench. The Slinky™ method of looping pipe allows more pipe in a short trench, which cuts down on installation costs and makes horizontal installation possible in areas where conventional horizontal applications would not be possible.
- *Vertical*—Large commercial buildings and schools use vertical systems when the land area required for horizontal loops would be prohibitive. Vertical loops are also used where the soil is too shallow for trenching, and they minimize the disturbance to existing landscaping. For a vertical system, holes (approximately 4 inches in diameter) are drilled about 20 feet apart and 100 to 400 feet deep. Into these holes go two pipes that are connected at the bottom with a U-bend to form a loop. The vertical loops are connected with horizontal pipe (i.e., manifold), placed in trenches, and connected to the heat pump in the building.
- *Pond/lake*—If the site has an adequate water body, this may be the lowest cost option. A supply line pipe is run underground from the building to the water and coiled into circles at least 8 feet under the surface to prevent freezing. The coils should only be placed in a water source that meets minimum volume, depth, and quality criteria.

DID YOU KNOW?

Geothermal system life is estimated at 25 years for the inside components and 50+ years for the ground loop. Approximately 50,000 geothermal heat pumps are installed in the United States each year. Even with the large number of annual installations, it is important to keep in mind that heat pumps are relatively expensive to install new. This is especially true of the deep-ground source type. It may take a long time for a new system to pay for itself.

Open-Loop System

This type of system uses well or surface body water as the heat-exchange fluid that circulates directly through the GHP system. Once it has circulated through the system, the water returns to the ground through the well, a recharge well, or surface discharge. This option is obviously practical only where there is an adequate supply of relatively clean water and all local codes and regulations regarding groundwater discharge are met.

ENVIRONMENTAL IMPACTS OF GEOTHERMAL POWER DEVELOPMENT*

There are several potential environmental impacts from any geothermal power development:

- *Gaseous emissions*—Gaseous emissions result from the discharge of noncondensable gases (NCGs) that are carried in the source stream to the power plant. For hydrothermal installations, the most common NCGs are carbon dioxide (CO_2) and hydrogen sulfide (H_2S), although species such as methane, hydrogen, sulfur dioxide, and ammonia are often encountered in lower concentrations.
- *Water pollution*—Liquid streams from well drilling, stimulation, and production may contain a variety of dissolved minerals, especially for high-temperature reservoirs (>230°C). The amount of dissolved solids increases significantly with temperature. Some of these dissolved minerals (e.g., boron and arsenic) could poison surface or ground waters and also harm local vegetation. Liquid streams may enter the environment through surface runoff or through breaks in the well casing.
- *Solids emissions*—There is practically no chance for contamination of surface facilities or the surrounding area by the discharge of solids *per se* from the geofluid. The only conceivable situation would be an accident associated with a fluid treatment or minerals recovery system that somehow failed in a catastrophic manner and spewed removed solids onto the area.
- *Noise pollution*—Noise pollution from geothermal operations is typical of many industrial activities (DiPippo, 1991). The highest noise levels are usually produced during the well drilling, stimulation, and testing phases when noise levels ranging from about 80 to 115 decibels A-weighted (dBA) may occur at the plant fence boundary. During normal operations of a geothermal power plant, noise levels are in the range of 71 to 83 decibels at a distance of 900 m (DiPippo, 2005).

* Adapted from MIT, *The Future of Geothermal Energy*, Massachusetts Institute of Technology, Cambridge, MA, 2006 (https://www1.eere.energy.gov/geothermal/pdfs/egs_chapter_8.pdf); Tribal Energy and Environmental Information Clearinghouse, http://teeic.anl.gov/er/biomass/impact/construct/index.cfm.

- *Land use*—Land footprints for hydrothermal power plants vary considerably by site because the properties of the geothermal reservoir fluid and the best options for wastestream discharge (usually reinjection) are highly site-specific. Typically, the power plant is built at or near the geothermal reservoir because long transmission lines degrade the pressure and temperature of the geofluid. Although well fields can cover a considerable area, typically 5 to 10 km^2 or more, the well pads themselves will only cover about 2% of the area.
- *Land subsidence*—If geothermal fluid production rates are much greater than recharge rates, the formation may experience consolidation, which will manifest itself as a lowering of the surface elevation (i.e., surface subsidence). This was observed early in the history of geothermal power at the Wairakei field in New Zealand where reinjection was not used. Subsidence rates in one part of the field were as high as 0.45 m per year (Allis, 1990). Wairakei used shallow wells in a sedimentary basin. Subsidence in this case is very similar to mining activities at shallow depths where raw minerals are extracted, leaving a void that can manifest itself as subsidence on the surface.
- *Induced seismicity*—In normal hydrothermal settings, induced seismicity has not been a problem because the injection of waste fluids does not require very high pressures. However, the situation in the case of many EGS reservoirs will be different and requires serious attention. Induced seismicity continues to be under active review and evaluation by researchers worldwide.
- *Induced landslides*—There have been instances of landslides at geothermal fields. The cause of the landslide is often unclear. Many geothermal fields are in rugged terrain that is prone to natural landslides, and some fields actually have been developed atop ancient landslides.
- *Water resources*—Geothermal projects, in general, require access to water during several stages of development and operation.
- *Disturbance of natural hydrothermal manifestations*—Although numerous cases can be cited of the compromising or total destruction of natural hydrothermal manifestations, such as geysers, hot springs, or mud pots, by geothermal developments (Jones, 2006; Keam et al., 2005), EGS projects will generally be located in non-hydrothermal areas and will not have the opportunity to interfere with such manifestations.
- *Disturbance of wildlife habitat, vegetation, and scenic vistas*—It is undeniable that any power generation facility constructed where none previously existed will alter the view of the landscape.
- *Catastrophic events*—Accidents can occur during various phases of geothermal activity, including well blowouts, ruptured steam pipes, turbine failures, fires, etc.
- *Thermal pollution*—Although thermal pollution is currently not a specially regulated quantity, it does represent an environmental impact for all power plants that rely on a heat source for their motive force.

Specific environmental impacts related to geothermal energy exploration, drilling, construction, operation, and maintenance activities are discussed in the following sections.

Geothermal Energy Exploration and Drilling Impacts

Activities during the resource exploration and drilling phase are temporary and are conducted at a smaller scale than those during the construction, operations, and maintenance phases. The impacts described for each resource would occur from typical exploration and drilling activities, such as localized ground clearing, vehicular traffic, seismic testing, positioning of equipment, and drilling. Most impacts during the resource exploration and drilling phase would be associated with the development (improving or constructing) of access roads and exploratory and flow testing wells. Many of these impacts would be reduced by implementing good industry practices and restoring disturbed areas once drilling activities have been completed.

Air Quality

Emissions generated during the exploration and drilling phase include exhaust from vehicular traffic and drilling rigs, fugitive dust from traffic on paved and unpaved roads, and the release of geothermal fluid vapors (especially hydrogen sulfide, carbon dioxide, mercury, arsenic, and boron, if present in the reservoir). Initial exploration activities such as surveying and sampling would have minimal air quality impacts. Activities such as site clearing and grading, road construction, well pad development, sump pit construction, and the drilling of production and injection wells would have more intense exhaust-related emissions over a period of 1 to 5 years. Impacts would depend upon the amount, duration, location, and characteristics of the emissions and the meteorological conditions (e.g., wind speed and direction, precipitation, relative humidity). Emissions during this phase would not have a measurable impact on climate change. State and local regulators may require permits and air monitoring programs.

Cultural Resources

Cultural resources could be impacted if additional roads or routes are developed across or within the historic landscape of a cultural resource. Additional roads could lead to increased surface and subsurface disturbances that could increase illegal collection and vandalism. The magnitude and extent of impacts would depend on the current state of the resource and their eligibility for the National Register of Historic Places. Drilling activities could result in long-term impacts on archeological artifacts and historic buildings or structures, if present. Surveys conducted during this phase to evaluate the presence and/or significance of cultural resources in the area would assist developers in locating sensitive resources and siting project facilities in such a way as to avoid or minimize impacts on these resources.

Ecological Resources

Most impacts on ecological resources (vegetation, wildlife, aquatic biota, special status species, and their habitats) would be low to moderate and localized during exploration and drilling (although impacts due to noise could be high). Activities such as site clearing and grading, road construction, well drilling, ancillary facility construction, and vehicle traffic have the potential to affect ecological resources by disturbing habitat, increasing erosion and runoff, and creating noise at the project site. Impacts on vegetation include the loss of native species and species diversity, increased risk of invasive species, increased risk of topsoil erosion and seed bank depletion, increased risk of fire, and alteration of water and seed dispersal. Exploration and drilling activities have the potential to destroy or injure wildlife (especially species with limited mobility); disrupt the breeding, migration, and foraging behavior of wildlife; reduce habitat quality and species diversity; disturb habitat (e.g., causing loss of cover or food source); and reduce the reproductive success of some species (e.g., amphibians). Accidental spills could be toxic to fish and wildlife. The noise from seismic surveys and drilling has a high potential to disturb wildlife and affect breeding, foraging, and migrating behavior. If not fenced or covered in netting, sump pits containing high concentrations of minerals and chemicals from drilling fluids could adversely impact animals (e.g., birds, wild horses and burrows, grazing livestock). Surveys conducted during this phase to evaluate the presence and significance of ecological resources in the area would assist developers in locating sensitive resources and siting project facilities in such a way as to avoid or minimize impact to these resources.

Water Resources

Impacts on water resources during the exploration and drilling phase would range from low to high. Survey activities would have little or no impact on surface water or groundwater. Exploration drilling would involve some ground-disturbing activities that could lead to increased erosions and surface runoff. Drilling into the reservoir can create pathways for geothermal fluids (which are under high pressure) to rise and mix with shallower groundwater. Impacts of these pathways may include alteration of the natural circulation of geothermal fluids and the usefulness of the resource. Geothermal fluids may also degrade the quality of shallow aquifers. Best management practices based on stormwater pollution prevention requirements and other industry guidelines would ensure that soil erosion and surface runoff are controlled. Proper drilling practices and closure and capping of wells can reduce the potential for drilling-related impacts.

Temporary impacts on surface water may also occur as a result of the release of geothermal fluids during any testing, if they are not contained. Geothermal fluids are hot and highly mineralized and, if released to surface water, could cause thermal changes and changes in water quality. Accidental spills of geothermal fluids could occur due to well blowouts during drilling, leaks in piping or well heads, or overflow from sump pits. Proper well casing and drilling techniques would minimize these risks.

Extracting geothermal fluids could also cause drawdowns in connected shallower aquifers, potentially affecting connected springs or streams. The potential for these types of adverse effects is moderate to high, but may be reduced through extensive

aquifer testing and selection combined with compliance with the state and federal regulations that protect water quality and the limitations of water rights as issued. During the exploration and drilling phase, water would be required for dust control, making concrete, consumptive use by the construction crew, and drilling of wells. Depending on availability, it may be trucked in from offsite or obtained from local groundwater wells of nearby municipal supplies.

Land Use

Temporary and localized impacts on land use would result from exploration and drilling activities. These activities could create a temporary disturbance in the immediate vicinity of a surveying or drilling site (e.g., recreational activities, livestock grazing). The magnitude and extent of impacts from constructing additional roads would depend on the current land use in the area; however, long-term impacts on land use would be minimized by reclaiming all roads and routes that are not needed once exploration and drilling activities are completed. All other land uses on land under well pads would be precluded as long as they are in operation. Exploration activities are unlikely to affect mining and energy development activities, military operations, livestock grazing, or aviation on surrounding lands. Activities affecting resources and values identified for protection areas would likely be prohibited.

Soils and Geologic Resources

Impacts on soils and geologic resources would be proportional to the amount of disturbance. The amount of surface disturbance and use of geologic materials during exploration would be minimal. Surface effects from vehicular traffic could occur in areas that contain special soils. The loss of biological or desert crusts can substantially increase water and wind erosion. Also, soil compaction due to development activities at the exploratory well pads and along access roads would reduce aeration, permeability, and the water-holding capacity of the soils and cause an increase in surface runoff, potentially causing increased sheet, rill, and gully erosion. The excavation and reapplication of surface soils could cause the mixing of shallow soil horizons, resulting in a blending of soil characteristics and types. This blending would modify the physical characteristics of the soils, including structure, texture, and rock content, that could lead to reduced permeability and increased runoff from these areas. Soil compaction and blending could also impact the viability of future vegetation. Any geologic resources within the areas of disturbance would not be accessible during the life of the development. Possible geological hazards (earthquakes, landslides, and subsidence) could be activated by drilling and blasting. Altering drainage patterns could also accelerate erosion and create slope instability.

Paleontological Resources

Paleontological resources are nonrenewable resources. Disturbance to such resources, whether through mechanical surface disturbance, erosion, or paleontological excavation, irrevocably alters or destroys them. The potential for impacts on paleontological resources is high where grading for access roads and drilling sites intercept geologic units with important fossil resources. Seismic surveys, ground clearing, and vehicular traffic have the potential to impact the fossil resources at the

surface. The disturbance caused by all these activities could increase illegal collection and vandalism. Surveys conducted during this phase to evaluate the presence and significance of paleontological resources in the area would assist developers in locating significant resources so they can be studied and collected or so that project facilities can be sited in other areas.

Transportation

No impacts on transportation are anticipated during the exploration and drilling phase. Transportation activities would be temporary and intermittent and limited to a low volume of light utility trucks and personal vehicles.

Visual Resources

Impacts on visual resources would be considered adverse if the landscape were substantially degraded or modified. Exploration and drilling activities would have only temporary and minor visual effects, resulting from the presence of drill rigs, workers, vehicles, and other equipment (including lighting for safety), as well as from vegetation damage, scarring of the terrain, and altering landforms or contours. Reclamation following exploration and drilling to restore visual resources to predisturbance conditions would lessen these impacts.

Socioeconomics

As the activities conducted during the exploration and drilling phase are temporary and limited in scope, they would not result in significant socioeconomic impacts on equipment, local services, or property values.

Environmental Justice

Exploration activities are limited and would not result in significant long-term impacts in any resource area; therefore, environmental justice is not expected to be an issue during this phase.

Geothermal Energy Construction Impacts

Activities that may cause environmental impacts during construction include site preparation (e.g., clearing and grading), facility construction (e.g., geothermal power plant, pipelines, transmissions lines), and vehicular and pedestrian traffic. The construction of the geothermal power plant would disturb about 15 to 25 acres of land. Transmission line construction would disturb about 1 acre of land per mile of line. Impacts would be similar to but more extensive than those addressed for the exploration and drilling phase; however, many of these impacts would be reduced by implementing good industry practices and restoring disturbed areas once construction activities have been completed.

Air Quality

Emissions generated during the construction phase include exhaust from vehicular traffic and construction equipment, fugitive dust from traffic on paved and unpaved roads, and the release of geothermal fluid vapors (especially hydrogen sulfide, carbon

dioxide, mercury, arsenic, and boron, if present in the reservoir). Activities such as site clearing and grading, power plant and pipeline system construction, and transmission line construction would have more intense exhaust-related emissions over a period of 2 to 10 years. Impacts would depend on the amount, duration, location, and characteristics of the emissions and the meteorological conditions (e.g., wind speed and direction, precipitation, relative humidity). Emissions during this phase would not have a measurable impact on climate change. State and local regulators may require permits and air monitoring programs.

Cultural Resources

Potential impacts on cultural resources during the construction phase could occur due to land disturbance related to the construction of the power plant and transmission lines. Impacts include destruction of cultural resources in areas undergoing surface disturbance and unauthorized removal of artifacts or vandalism as a result of human access to previously inaccessible areas (resulting in lost opportunities to expand scientific study and education and interpretive uses of these resources). In addition, for cultural resources that have an associated landscape component that contributes to their significance (e.g., sacred landscapes, historic trails), visual impacts could result from large areas of exposed surface, increases in dust, and the presence of large-scale equipment, machinery, and vehicles. Although the potential for encountering buried sites is relatively low, the possibility that buried sites would be disturbed during construction does exist. Unless the buried site is detected early in the surface-disturbing activities, the impact to the site can be considerable. Disturbance that uncovers cultural resources of significant importance that would otherwise have remained buried and unavailable could be viewed as a beneficial impact, provided the discovery results in study, curation, or recording of the resource. Vibration, resulting from increased traffic and drilling/development activities may also have effects on rock art and other associated sites (e.g., sites with standing architecture).

Ecological Resources

Most impacts on ecological resources (vegetation, wildlife, aquatic biota, special status species, and their habitats) would be low to moderate and localized during the construction phase (although impacts due to noise could be high). Activities such as site clearing and grading, road construction, power plant construction, ancillary facility construction, and vehicle traffic have the potential to affect ecological resources by disturbing habitat, increasing erosion and runoff, and creating noise at the project site. Impacts on vegetation include loss of native species and species diversity, increased risk of invasive species, increased risk of topsoil erosion and seed bank depletion, increased risk of fire, and alteration of water and seed dispersal. Construction activities have the potential to destroy or injure wildlife (especially species with limited mobility); disrupt the breeding, migration, and foraging behavior of wildlife; reduce habitat quality and species diversity; disturb habitat (e.g., causing loss of cover or food source); and reduce the reproductive success of some species (e.g., amphibians). Accidental spills could be toxic to fish and wildlife. The noise from construction and vehicle traffic has a high potential to disturb wildlife and affect breeding, foraging, and migrating behavior. Wild horses, burros, and

grazing livestock could be adversely affected by the loss of forage, reduced forage palatability (due to dust settlement on vegetation), and restricted movement around the development area.

Water Resources

Impacts on water resources during the construction phase would be moderate because of ground-disturbing activities (related to road, well pad, and power plant construction) that could lead to an increase in soil erosion and surface runoff. Impacts on surface water would be moderate but temporary and could be reduced by implementing best management practices based on stormwater pollution-preventing requirements and other industry guidelines. During the construction phase, water would be required for dust control, making concrete, and consumptive use by the construction crew. Depending on availability, it may be trucked in from offsite or obtained from local groundwater wells or nearby municipal supplies.

Land Use

Temporary and localized impacts on land use would result from construction activities. These activities could create a temporary disturbance in the immediate vicinity of a construction site (e.g., to recreational activities or livestock grazing). The magnitude and extent of impacts from constructing power plants and pipeline systems would depend on the current land use in the area; however, long-term impacts on land use would be minimized by reclaiming all roads and routes that are not needed once construction is completed. All other land uses on land under well pads, buildings, and structures would be precluded as long as they are in operation. Construction activities are unlikely to affect mining and energy development activities, military operation, livestock grazing, or aviation on surrounding lands. Activities affecting resources and values identified for protection areas would likely be prohibited.

Soils and Geologic Resources

Impacts on soils and geologic resources would be greater during the construction phase than for other phases of development because of the increased footprint and would be particularly significant if biological or desert crusts are disturbed. Construction of additional roads, well pads, the geothermal power plant, and structures related to the power plant (e.g., pipeline system, transmission lines) would occur during this phase. Construction of well pads, the geothermal power plant, and structures related to the power plant, pipeline system, access roads, and other project facilities could cause topographic changes. These changes would be minor but long term. Soil compaction due to construction activities would reduce aeration, permeability, and water-holding capacity of the soils and cause an increase in surface runoff, potentially causing increased sheet, rill, and gully erosion. The excavation and reapplication of surface soils could cause the mixing of shallow soil horizons, resulting in a blending of soil characteristics and types. This blending would modify the physical characteristics of the soils, including structure, texture, and rock content, which could lead to reduced permeability and increased runoff from these areas. Soil compaction and blending could also impact the viability of future vegetation. Any geologic resources within the areas of disturbance would not be accessible

during the life of the development. It is unlikely that construction activities would activate geologic hazards; however, altering drainage patterns or building on steep slopes could accelerate erosion and create slope instability. It is unlikely that construction activities would activate geologic hazards; however, altering drainage patterns or building on steep slopes could accelerate erosion and create slope instability.

Paleontological Resources

The potential for impacts on paleontological resources is high where grading and excavation intercept geologic units with important fossil resources. Ground clearing and vehicular traffic have the potential to impact the fossil resources at the surface. The disturbance caused by all these activities could increase illegal collection and vandalism. Disturbance that uncovers paleontological resources of significant importance that would otherwise have remained buried and unavailable could be viewed as a beneficial impact, provided the discovery results in study, collection, or recording of the resource.

Transportation

Geothermal development would result in the need to construct or improve access roads and would result in an increase in industrial traffic. Overweight and oversized loads could cause temporary disruptions and could require extensive modifications to roads or bridges (e.g., widening roads or fortifying bridges to accommodate the size or weight of truck loads). An overall increase in heavy truck traffic would accelerate the deterioration of pavement, requiring local government agencies to schedule pavement repair or replacement more frequently than under the existing traffic conditions. Increased traffic would also result in a potential for increased accidents within the project area. The locations at which accidents are most likely to occur are intersections used by project-related vehicles to turn onto or off of highways from access roads. Conflicts between industrial traffic and other traffic are likely to occur, especially on weekends, holidays, and seasons of high use by recreationists. Increased recreational use of the area could contribute to a gradual increase in traffic on the access roads.

Visual Resources

Impacts on visual resources would be considered adverse if the landscape were substantially degraded or modified. Construction activities would have only temporary and minor visual effects, resulting from the presence of workers, vehicles, and construction equipment (including lighting for safety) and from vegetation damage, dust generation, scarring of the terrain, and altering landforms or contours. Reclamation following construction to restore visual resources to pre-disturbance conditions would lessen these impacts.

Socioeconomics

Construction phase activities would contribute to the local economy by providing employment opportunities, monies to local contractors, and recycled revenues through the local economy. The magnitude of these benefits would vary depending on the resource potential. Construction of a typical 50-megawatt (MW) power plant

and related transmission lines would require an estimated 387 jobs and $22.5 million in income but would vary depending on the community. Job availability would vary with different stages of construction. Expenditures for equipment, materials, fuel, lodging, food, and other needs would stimulate the local economy over the duration of construction. Economic impacts may occur if other land use activities (e.g., recreation, grazing, hunting) are altered by geothermal development. Constructing facilities will alter the landscape and could affect the nonmarket values of the immediate area. Many of these land uses may be compatible; however, it is possible that some land uses will be displaced by geothermal development.

Environmental Justice

Environmental justice impacts occur only if significant impacts in other resource areas disproportionately affect minority or low-income populations. It is anticipated that the development of geothermal energy could benefit low-income, minority, and tribal populations by creating job opportunities and stimulating local economic growth via project revenues and increased tourism. However, noise, dust, visual impacts, and habitat destruction could have an adverse effect on traditional tribal life ways and religious and cultural sites. Development of wells and ancillary facilities could affect the natural character of previously undisturbed areas and transform the landscape into a more industrialized setting. Development activities could impact the use of cultural sites for traditional tribal activities (hunting and plant-gathering activities, as well as areas in which artifacts, rock art, or other significant cultural sites are located).

Geothermal Energy Operations and Maintenance Impacts

Typical activities during the operations and maintenance phase include operation and maintenance of production and injection wells and pipeline systems, operation and maintenance of the power plant, waste management, and maintenance and replacement of facility components.

Air Quality

Emissions generated during the operations and maintenance phase include exhaust from vehicular traffic and fugitive dust from traffic on paved and unpaved roads, most of which would be generally limited to worker and maintenance vehicle traffic. In addition, emission could include the release of geothermal fluid vapors (especially hydrogen sulfide, carbon dioxide, mercury, arsenic, and boron, if present in the reservoir). Impacts would depend on the amount, duration, location, and characteristics of the emissions and the meteorological conditions (e.g., wind speed and direction, precipitation, relative humidity). Carbon dioxide emissions would be considerably less than for comparable power plants using fossil fuel. State and local regulators may require permits and air monitoring programs.

Cultural Resources

During the operations and maintenance phase, impacts on cultural resources could occur primarily from unauthorized collection of artifacts and from visual impacts. In the latter case, the presence of the aboveground structures could impact cultural

resources with an associated landscape component that contributes to their significance, such as a sacred landscape or historic trail. The potential for indirect impacts (e.g., vandalism, unauthorized collection) would be greater during the operations and maintenance phase compared to prior phases due to its longer duration.

Ecological Resources

Most impacts on ecological resources (vegetation, wildlife, aquatic biota, special status species, and their habitat) would be less during the operations and maintenance phase than for the exploration and drilling and construction phases because no new drilling or construction activities would take place. However, operations and maintenance activities have the potential to affect ecological resources mainly by reducing the acreage for foraging and migrating animals, fragmenting habitat, and creating noise at the project site during the life cycle of the project (which could last up to 50 years). Some of these impacts could be significant. Increased human activity also increases the risk of fire, especially in arid or semiarid areas. Application of herbicides to control vegetation along access roads, buildings, and power plant structures would increase the risk of wildlife exposure to contaminants.

Water Resources

Impacts on water resources during the operations and maintenance phase result mainly from the water demands associated with operating a geothermal power plant. Water resources during operations would be needed for replenishment of the geothermal reservoir through reinjection. However, because some water would be consumed by evaporation, additional water would have to be added to the system from another source. Makeup water to replace the evaporative losses and blowdown in a water-cooled power plant system would also be needed, depending on the type of power plant used (e.g., flash steam facilities can lose up to 20% of its cooling water due to evaporation, but binary plants are nonconsumptive because they use a closed-loop system). Water can also be lost due to pipeline failures or surface discharge for monitoring and testing the geothermal reservoir. The availability of water resources could be a limiting factor in siting or expanding a geothermal development at a given location. Cooling water or water from geothermal wells that is discharged to the ground or to an evaporation pond could affect the quality of shallow groundwater if allowed to percolate through the ground. However, the potential for this type of impact is considered minor or negligible because the facility would have to comply with the terms of the discharge permit required by the state.

Land Use

Impacts on land uses during the operations and maintenance phase are an extension of those that occurred during the exploration and drilling and construction phases. Although, to some extent, land use can revert to its original uses (e.g., livestock grazing), many other uses (e.g., mining, farming, hunting) would be precluded during the life span of the geothermal development. Mineral resources would remain available for recovery, and operations and maintenance activities are unlikely to affect mining and energy development activities, military operations, livestock grazing, or aviation on surrounding lands.

Soils and Geologic Resources

Impacts on soils and geologic resources would be minimal during the operations and maintenance phase. The initial areas disturbed during the construction phase would continue to be used during standard operation and maintenance activities, but no additional impacts would occur unless new construction projects or drill sites are needed. Impacts associated with new construction projects or drill sites would be similar to those described for the exploration and drilling construction phases.

Paleontological Resources

The potential for impacts on paleontological resources would be limited primarily to the unauthorized collection of fossils. This threat is present once the access roads are constructed, making remote areas more accessible to the public. Damage to locations caused by off-highway vehicle use could also occur. The potential for indirect impacts (e.g., vandalism, unauthorized collection) would be greater during the production phase compared to the drilling/development phase, due to the longer duration of the production phase.

Transportation

Daily traffic levels, particularly heavy truck traffic, would be expected to be lower during the operations and maintenance phase compared to other phases of geothermal development. For the most part, heavy truck traffic would be limited to period monitoring and maintenance activities at the well pads and power plant.

Visual Resources

Adverse impacts on visual resources would occur during the 10- to 30-year life of the geothermal development. Impacts during the operations and maintenance phase would result from the presence of facility structures and roads (where undeveloped land once stood), increased vehicular traffic to the site, and releases of steam plumes from the geothermal power plant. Periodic construction projects occurring through the life of the development would have impacts similar to those described for the construction phase.

Socioeconomics

Activities during the operations and maintenance phase would contribute to the local economy by providing employment opportunities, monies to local contractors, and recycled revenues through the local economy. The magnitude of these benefits would vary depending on the resource potential. Operation of a typical 50-MW power plant and related transmission line would provide an estimated 93 jobs and $8 million in income, but would vary depending on the community. Job availability would vary with different stages of construction. Expenditures for equipment, materials, fuel, lodging, food, and other needs would stimulate the local economy over the duration of the project, which could last up to 50 years. Economic impacts may occur if other land use activities (e.g., recreation, grazing, hunting) are altered by geothermal development. Constructing facilities will alter the landscape and could affect the nonmarket values of the immediate area during the life of the geothermal development.

Environmental Justice

Possible environmental justice impacts during the operations and maintenance phase include alteration of the scenic quality in areas of traditional or cultural significance to minority populations. Noise, water, and health and safety impacts are also potential sources of disproportionate effects to minority or low-income populations.

IMPACTS ON HUMAN HEALTH AND SAFETY*

Fatalities and Incidents

- An employee was installing geothermal piping in a trench that was 6 feet deep and 30 inches wide. The trench was not sloped, shored, or braced and it caved in. He was crushed by the dirt and died from asphyxia.
- At approximately 6:30 p.m. on April 19, 1996, Employee #1, a laborer for Acme Temporary Services, was working at a geothermal power generating facility that was being shut down for periodic cleaning. Workers had been set up in teams of two to open side hatch covers on vessels from which shale and sand were to be removed. Employee #1 was standing to the right of a coworker who was removing the retention bolts from a hatch cover when the hatch popped open and hot water sprayed out over Employee #1. He sustained severe burns on his arms, back, chest, and legs. Coworkers in the area came to his aid, removed his clothing and gloves, and placed him in a full shower. Emergency Services was called and Employee #1 was taken to the office where burn cream was applied. He was transported by paramedics to a local medical facility and later taken to a regional burn facility. Subsequent investigation revealed that the hot water had been trapped in the vessel due to a faulty drain line.
- At approximately 11:35 a.m. on August 25, 1994, Employee #1 entered an 8.4-foot-deep by 8-foot-wide geothermal vault with a 32-inch manhole entry to rebuild a pressure reducing valve. Before any chemical substance was introduced into the vault, the oxygen level was between 19.5 and 19.6%. Atmospheric testing was conducted by the EC unit and by Employee #1 using a Gastech GX-82 oxygen meter, serial #HX-13452, without an extension hose; the oxygen levels found were between 19.6 and 19.7%. After WD-40 and Graff-off were introduced into the vault, the oxygen level dropped to 18.9%. Employee #1 also noted hydrogen sulfide levels of 8 ppm. Employee #1 complained of dizziness, nausea, and difficulty in breathing. He was diagnosed as having pulmonary edema, which turned into pneumonia three weeks later. The causal factors of the accident include the employer's failure to provide workers with confined space and hazard communication training and with the Material Safety Data Sheet for the product used in the confined space. The chemical constituents of WD-40 include aliphatic petroleum distillates and A-70 hydrocarbon propellant; the chemical constituents of Graff-off include isopropyl alcohol and 40% toluene by weight.

* Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy*, http://www.osha.gov/dep/greenjobs/geothermal.html.

- On July 14, 2008, at 10:30 a.m., an employee of Trison Construction was injured. The employer reported the accident on July 17, 2008, at 10:30 a.m. The injured employee was removing a "drill stem" from a 3-inch pipe on a Driltech Marlin M5, serial #732658, truck-mounted drilling machine. He wedged a 60-inch pipe wrench near the operator's platform to break the connection. The pipe wrench broke loose, striking the employee on the right knee and fracturing it. This contractor specializes in geothermal drilling.

As indicated by the fatality and accident reports above, the construction of geothermal energy production sites and the use of geothermal energy can be a potentially dangerous undertaking or occupation. Geothermal systems use the heat from the Earth to create electricity and to heat and cool buildings. Some geothermal systems pump water underground through piping, allow it to be heated by the Earth, and then use the hot water to create electricity or heat and cool buildings. Other systems drill directly into the Earth's natural geothermal reservoirs, using the resulting hot water and steam to create electricity. Some geothermal systems use a brine or saltwater solution while others use glycol. These solutions may pose hazards of their own to workers. The hazards associated with the growing industry include some very familiar safety issues for which the Occupational Safety and Health Administration (OSHA) already has standards and information. The hazards (along with controls) that workers in the geothermal industry may face are provided below.

Hazards and Controls

- Trenching and excavations
- Silica
- Personal protective equipment
- Electrical
- Welding and cutting
- Fall protection

Each of these hazards and controls is briefly discussed below. OSHA and other regulatory requirements are contained in 29 CFR 1910 and 1926, along with detailed explanations of each standard, regulation, or requirement.

Trenching and Excavation Hazards*

A large number of trenching and excavation specialty companies (e.g., utilities, green energy industries) experience cave-ins. Attempting repair work on aboveground pipes is relatively easy as compared to making repairs on underground piping systems. When repairs are to be made on underground lines, either trenching or excavation is required. A trench is a narrow excavation that is less than 15 feet wide and is deeper than its width. An excavation, on the other hand, is a cavity or depression that is cut or dug into the Earth's surface. Whether trenching or excavating,

* Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy—Trenching and Excavation*, https://www.osha.gov/dep/greenjobs/geo_excavations.html.

DID YOU KNOW?

Here is an example of a death due to unsafe access or egress. Two employees were laying pipe in a bench 12-feet deep, when one of the employees saw the bottom face of the trench move. He jumped out of the way along the length of trench; the other employee was fatally injured as the wall caved in. The walls of the trench were not sloped, and no means of emergency egress were provided.

either operation is inherently dangerous. As a matter of fact, working around and in excavations is one of the most dangerous jobs in construction work. It is estimated, for example, that in the construction industry alone, cave-ins claim about 100 lives every year; thus, excavating piping systems presents very real hazards to geothermal workers. Post-incident investigations of trenching and excavation mishaps have shown that little heed was paid by excavators to the hazards involved with excavating and trenching. Whenever geothermal construction or maintenance is conducted on underground geothermal lines, OSHA regulations pertaining to trenching and shoring must be followed. OSHA regulations for trenching and excavation can be found in 29 CFR 1926.650–652 (Construction Standard).

An effective trenching and shoring safety program begins with knowing the hazards. Workers must know what they face during these operations. Additionally, workers must know how to protect themselves from injury through proper use of safe work practices—in trenching and excavation work there is no room for error. When a trench or excavation fails, injuries and fatalities occur fast, often in a matter of seconds. There is no room for poor judgment in performing excavation and trenching operations. Before beginning to trench or excavate, certain conditions must be checked. For example, the location of utility installations, such as telephone, fuel, electric, water lines, or any other underground installations that reasonably may be expected to be encountered during excavation work, must be determined prior to beginning an excavation.

There are other conditions that must be checked before the excavation is attempted, such as soil, weather, and climate conditions. These factors will determine the amount and degree of sloping that must be used. Moreover, the actual strength of trenching support members (bracing and shoring) is based on soil type and weather conditions.

Failure to properly support walls for a trench or excavation may cause disaster. Often, trenching and excavation jobs are driven by cost and time saving requirements. At other times the supervisor in charge of the operation might determine that the trench or excavation will only be open for a short period and decides that proper shoring is not needed. What the supervisor who takes such a short cut might end up with is a short cut to disaster.

In auditing various excavation construction sites it is not unusual to find a weak link in the program. This weak link can usually be attributed to a lack of supervisor and worker knowledge. The auditor often finds that workers are not made aware of the hazards involved and the precautions necessary to minimize the hazard. A trenching and excavation training program should provide the information necessary

to ensure that supervisors and workers know the hazards. They should know that the major hazard is cave-ins, which can crush or suffocate them. They should know that trenches and excavations can contain poisonous gases. There is also the very real possibility of uncovering a pocket of combustible vapors or gases; for example, when digging around interceptor lines it is not unusual to run into a pocket of methane, leading to the danger of fire or explosion. Supervisors and workers also need to know that OSHA requires excavations to be protected from cave-ins by an adequate protective system that is designed to resist without failure all loads that are intended or could reasonably be expected to be applied or transmitted to the system.

Trenches and excavations can be full of additional obstacles. For example, carelessly placed tools and equipment or excavated material can cause injuries due to slips, trips, or falls. After explaining the general hazards that are present with any trenching or excavation job, the person performing the training needs to inform the workers about the causes of cave-ins so the workers know what to look for. Workers need to understand that cave-ins occur when an unsupported wall is weakened or undermined by too much weight or pressure or by an unstable bottom.

One of the danger signs to look for in trenching or excavation work is surface cracking. These cracks usually occur near the edge of the trench or excavation. Overhangs and bulges are other signs of danger. An overhang at the top—or a bulge in a wall—can cause soil to slide into the trench or excavation. Whenever cracks or overhangs are discovered, work should be stopped and the problem reported immediately.

Weather and climate can have a serious impact on trenching and excavation activities. Rain, melting snow, groundwater, storm drains, nearby streams, and damaged water lines can loosen soil and increase pressure on walls. At the opposite extreme, extremely dry weather can also be dangerous because it tends to loosen soil. Frozen ground presents another problem. When the frozen ground thaws, walls of a trench or excavation can be weakened. When the excavation is a long-term job, there may be a need for extra weather and climate protection. Sides and faces of the dig should be covered with tarps to reduce danger.

Supervisors and workers also need to be trained in soil-type recognition procedures. Soils with high silt or sand content are very unstable, unless properly shored or sloped. Wet or back-filled soil is also unstable and requires wall support. Even hard rock can present a problem unless it is properly supported. Hard rock that cracks or splits through a fault can break away and fall into the excavation.

One area of danger that is often overlooked in trenching and shoring operations is the presence of vibration. Vibrations can loosen soil and cause walls to collapse unless proper shoring or sloping is used. There are several sources of vibration at the work site: vehicles, moving machinery, blasting operations, and machines that might be used nearby such as punch presses and forging hammers.

Excavated material can also pose a hazard to the excavators. Excavated material (or spoil) should always be stored at least 2 feet from the edge of a trench or excavation. Never let excavated material accumulate near wall sides. Additionally, moving excavated soil can also pose a hazard to excavators. Heavy equipment operating near the trench or excavation can exert tremendous pressure on walls.

In order to protect excavators against accidents, proper techniques and equipment must be used in the trenching and shoring operation. Trench shoring material should consist of sheeting, bracing, and jacks. Never use shoring materials that have not been certified for use by a licensed professional engineer. After installation of the correct shoring materials, these materials should be inspected daily before anyone enters the trench or excavation.

When the decision is made to use ground sloping techniques to prevent cave-ins, the sides of a trench or excavation must be sloped correctly so that soil will not slide. Determining the *angle of repose* is critical in shaping the proper slope. The angle of repose is the steepest angle at which trench or excavation walls will lie without sliding. The more unstable the soil, the flatter the angle should be; for example, the angle of repose for solid rock should be set at 90°. For average soil an angle of 45° is recommended. For loose sand, the proper angle of repose should be set at about 25°.

Several other safety considerations are necessary whenever a trenching or excavation project is undertaken. Workers must understand that it is important to provide site protection. Site protection not only protects workers from rocks or other objects kicked or thrown into the trench but also protects pedestrians who might inadvertently fall into an open trench or excavation. Safety measures such as fences, barricades, covers for manholes, flags, security guards, and warning signs may be necessary. It is important to remember that lighting may be necessary so that safety can be maintained at night.

Along with providing proper lighting so that excavators can see well enough to work in an excavation, a stairway, ladder, ramp, or other safe means of egress must be located in trench excavations that are 4 feet or more in depth so as to require no more than 25 feet of lateral travel for workers.

As with any other dangerous operation, the plant safety official should ensure that a contingency plan for emergency response is in place and is used. This contingency plan must be made clear and understandable to all trenching and excavation personnel. Emergency procedures are worthless if they are not common knowledge. Someone should always be outside the trench or excavation to help, if necessary. Emergency telephone and numbers should be readily available. As a final precaution, the trench or excavation should be backfilled as soon as possible when the work is completed.

As with many other work activities, OSHA requires that personnel involved with excavation activities be trained and that this training be documented. Moreover, OSHA also requires that the person in charge of the excavation be a *qualified* or *competent person*. When qualifying a qualified or competent person for excavation and trenching operations, it is wise to assemble an excavation crew with a potential qualified or competent person as the person in charge and to have the crew dig a 12-foot-deep hole in a practice area. Experience gained through actually performing the work can never be replicated by listening to a classroom lecture on the topic. While observing the digging and shoring procedures, note whether or not the potential qualified or competent person is conducting the dig as required.

Silica Exposure*

Silica sand is a basic component of soil, sand, and granite and can be found in many concrete and masonry products. Silica can become airborne when workers chip out, drill, or grind objects that contain crystalline silica, and the workers may be exposed to many forms of silica dust. Operations such as excavating or installing concrete for pump wells can expose workers to silica. Silicosis is the permanent damage to the lungs caused by breathing the fine particles of crystalline silica dust. Silicosis can be debilitating and can lead in death. Workers in the geothermal energy industry may be exposed to crystalline silica. OSHA has established a permissible exposure limit (PEL), which is the maximum amount of crystalline silica to which workers may be exposed during an 8-hour shift (29 CFR 1926.55, 29 CFR 1910.1000). OSHA also requires hazard communication awareness and training for workers exposed to crystalline silica (29 CFR 1910.1200) and requires utilization of a respirator program until engineering controls are implemented. Additionally, OSHA has a National Emphasis Program (NEP) for crystalline silica exposure to identify, reduce, and eliminate health hazards associated with occupational exposures.

Personal Protective Equipment†

Using personal protective equipment (PPE) is often essential, but it is generally the last line of defense after engineering controls, work practices, and administrative controls. Geothermal energy employers must assess their workplace to determine if hazards are present that require the use of protective equipment. Geothermal energy workers can be exposed to many hazards that may require the use of safety glasses, hard hats, gloves, respirators, or other personal protective equipment designed to protect against injuries and illnesses.

Electrical Safety‡

Geothermal projects can expose workers to a range of electrical hazards. Systems may require the installation, operation, and maintenance of large electrical pumps to move water through miles of underground piping. Ground is essential for this type of operation. If this energy is used to heat or cool a building, then the components of the heating and cooling system could also expose workers to electrical hazards. Geothermal systems that generate electrical power may be covered by electric power generation, transmission, and distribution standards and, therefore, may be required to implement the safe work practices and worker training requirements of OSHA's Electric Power Generation, Transmission, and Distribution standard (29 CFR 1910.269). Typically, geothermal systems that generate electrical power are covered by OSHA Subpart S standards in Part 1910, if they are not connected to

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* Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy—Silica*, https://www.osha.gov/dep/greenjobs/geo_silica.html.

† Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy—Personal Protective Equipment*, https://www.osha.gov/dep/greenjobs/geo_ppe.html.

‡ Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy—Electrical*, https://www.osha.gov/dep/greenjobs/geo_electrical.html.

DID YOU KNOW?

Caution! If the system has stainless steel pipe, a worker may be exposed to hexavalent chromium hazards.

distribution systems (i.e., a system that is supplying power to town or more buildings) or if they are only emergency or standby nature. However, if they supply power to a distribution system, then the provisions contained in 29 CFR 1910.269 (Electric Power Generation, Transmission, and Distribution) will apply.

Welding and Cutting*

Many geothermal systems will be built with metal pipe at some part of the system. This will be the same as any pipe fitting or welding project. Welding and cutting metals can be very dangerous. Workers can be burned by the hot metals and may be exposed to ultraviolet light from arc welding. Workers must be protected from these welding hazards.

Fall Protection†

Workers installing and maintaining geothermal systems can be exposed to fall hazards when working near trenches, excavations, and pits that are dug for the piping systems. Falls can also occur when workers are installing above-ground system components on roofs or other elevated locations. Falls may also be a hazard when constructing, operating, and maintaining systems used for power generation. Falls kill hundreds of construction workers each year. OSHA standards require employers to protect workers from fall hazards. In the case of trenches, guardrails and barricades may be used to keep workers away from an open trench. Construction workers who are exposed to fall distances of 6 feet or more must be protected from falls by using one of the following methods. Many times the nature and location of the work will dictate the form that fall protection takes.

Guardrail Systems

An employer that chooses to use a guardrail system must comply with the following provisions:

- The top edge height of the top rails, or equivalent guardrail system members, must be between 39 and 45 inches above the walking/working level, except when conditions warrant otherwise and all other criteria are met (e.g., when employees are using stilts, the top edge height of the top rail must be increased by an amount equal to the height of the stilts).

* Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy—Welding*, https://www.osha.gov/dep/greenjobs/geo_welding.html.

† Adapted from OSHA's *Green Job Hazards: Geo-Thermal Energy—Fall Protection*, https://www.osha.gov/dep/greenjobs/geo_falls.html.

- Midrails, screens, mesh, intermediate vertical members, or equivalent intermediate structures must be installed between the top edge and the walking/working surface when there is no wall or other structure at least 21 inches high.
- Midrails must be midway between the top edge of the guardrail system and the walking/working level.
- Screens and mesh must extend from the top rail to the walking/working level and along the entire opening between rail supports.
- Intermediate members (such as balasters) between posts must be no more than 19 inches apart.
- Other structural members (such as additional midrails or architectural panels) must be installed to leave no openings wider than 19 inches.
- Guardrail systems must be capable of withstanding at least 200 pounds of force applied within 2 inches of the top edge, in any direction and at any point along the edge, and without causing the top edge of the guardrail to deflect downward to a height less than 39 inches above the walking/working level.
- Midrails, screens, mesh, and other intermediate members must be capable of withstanding at least 150 pounds of force applied in any direction at any point along the midrail or other member.
- Guardrail systems must not have rough or jagged surfaces that would cause punctures, lacerations, or snagged clothing.
- Top rails and midrails must not cause a projection hazard by overhanging the terminal posts.

Safety Net Systems

An employer that chooses to use a safety net system must comply with the following provisions:

- Safety nets must be installed as close as practicable under the surface on which employees are working, but in no case more than 30 feet below.
- When nets are used on bridges, the potential fall area must be unobstructed.
- Safety nets must extend outward from the outermost projection of the work surface as follows:

Vertical distance from working level to horizontal plane of net	Minimum required horizontal distance of outer edge of net from the edge of the working surface
Up to 5 feet	8 feet
5 to 10 feet	10 feet
More than 10 feet	13 feet

- Safety nets must be installed with sufficient clearance to prevent contact with the surface or structures under them when subjected to an impact force equal to the drop test described below.
- Safety nets and their installations must be capable of absorbing an impact force equal to the drop test described below.

- Safety nets and safety net installations must be drop-tested at the jobsite:
  - After initial installation and before being used
  - Whenever relocated
  - After major repair
  - At 6-month intervals if left in one place
- The drop test consists of a 400-pound bag of sand, 28 to 32 inches in diameter, dropped into the net from the highest surface at which employees are exposed to fall hazards, but not from less than 42 inches about that level.
- When the employer can demonstrate that it is unreasonable to perform the drop test described above, the employer or a designated competent person shall certify that the net and net installation have sufficient clearance and impact absorption by preparing a certification record prior to the net being used as a fall protection system. The certification must include
  - Identification of the net and net installation
  - Date that it was determined that the net and net installation were in compliance
  - Signature of the person making the determination and certification
- The most recent certification records for each net and net installation must be available at the jobsite for inspection.
- Safety nets must be inspected for wear, damage, and other deterioration at least once a week and after any occurrence that could affect the integrity of the system.
- Defective nets must not be used, and defective components must be removed from service.
- Objects that have fallen into the safety net, such as scrap pieces, equipment, and tools, must be removed as soon as possible from the net and at least before the next work shift.
- Maximum mesh size must not exceed 6 inches by 6 inches. All mesh crossings must be secured to prevent enlargement of the mesh opening, which must be no longer than 6 inches, measured center-to-center.
- Each safety net, or section thereof, must have border rope for webbing with a minimum breaking strength of 5000 pounds.
- Connections between safety net panels must be as strong as integral net components and must not be spaced more 6 inches apart.

Personal Fall Arrest System

A personal fall arrest system is one option of protection that OSHA requires for workers on construction sites who are exposed to vertical drops of 6 feet or more. To use fall arrest systems safely,

- Be sure that the personal fall arrest system will, when stopping a fall,
  - Limit maximum arresting force to 1800 pounds.
  - Be rigged such that an employee can neither free fall more than 6 feet nor contact any lower level.

  - Bring an employee to a complete stop and limit maximum deceleration distance to 3.5 feet.
  - Have sufficient strength to withstand twice the potential impact energy of a worker free falling a distance of 6 feet or the free fall distance permitted by the system, whichever is less.
- Remove systems and components from service immediately if they have been subjected to fall impact until they have been inspected by a competent person and deemed undamaged and suitable for use.
- Promptly rescue employees in the event of a fall or be sure that they are able to rescue themselves.
- Inspect systems before each use for wear, damage, and other deterioration, and remove defective components from service.
- Do not attach fall arrest systems to guardrail systems or hoists.
- Rig fall arrest systems to allow movement of the worker only as far as the edge of the walking/working surface, when used in hoisting areas.

Hazardous Materials and Waste Management

Industrial wastes are generated during routine construction, operations, and maintenance activities (e.g., lubricating oils, hydraulic fluids, coolants, solvents, cleaning agents). These wastes are typically placed in containers, characterized and labeled, possibly stored briefly, and transported by a licensed hauler to an appropriate permitted offsite disposal facility as a standard practice. Impacts could result if these wastes are not properly handled and are released to the environment. Environmental contamination could occur from accidental spills of herbicides or, more significantly, oil. Chemicals in open pits used to store wastes may pose a threat to wildlife and livestock.

GEOTHERMAL ENERGY: THE BOTTOM LINE

The supply of geothermal energy is vast and can be considered renewable, as long as each site is properly engineered and operated to ensure that excessive water is not pumped into the earth in one location in too short a time. Geothermal energy can be and already is accessed by drilling water or steam wells in a process similar to drilling for oil. Geothermal energy is an enormous, underused heat and power resource that is clean (emits little or no greenhouse gases), reliable (average system availability of 95%), and home grown (making us less dependent on foreign oil). Geothermal resources range from shallow ground to hot water and rock several miles below the Earth's surface, and even farther down to the extremely hot molten rock called magma. Wells that are a mile or more deep can be drilled into underground reservoirs to tap steam and very hot water that can be brought to the surface for use in a variety of applications. In the United States, most geothermal reservoirs are located in the western states, Alaska, and Hawaii; however, before geothermal electricity can be considered a key element of the U.S. energy infrastructure, it must become more cost competitive compared with traditional forms of energy.

THOUGHT-PROVOKING QUESTIONS

6.1 Geothermal power plants can possibly cause groundwater contamination when drilling wells and extracting hot water or steam. How would you prevent this type of contamination? Explain.

6.2. Is geothermal energy a viable alternative renewable energy source that is capable of replacing fossil fuels in the United States? Explain.

6.3 Why do you think there has not been more extensive development of geothermal energy? Explain.

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7 Marine and Hydrokinetic Energy

One day King Canute told his followers to carry him and his throne to the seashore at low tide. "Set me down right there at the water's edge," he said. "And I will command the sea to stay away. I will order the tide not to rise." "Oh, wow!" said his followers as they obeyed the King. "This ought to be something to see!" King Canute sat. He shouted: "Sea, stay away! Tide, do not rise!" But slowly, slowly, the tide came in and the sea rose, over his feet, past his knees, up to his waist. The crowd of followers pulled back a little to keep their own feet dry. They were puzzled. Why did the sea not obey the King? The water rose higher and higher, up to the King's shoulders, over his chin. "Loyal [glub] subjects," he gurgled. "Now you see that [glub] there are some things no man, be he [glub] king or commoner, can [glub] do! Now pull me the [glub] out of here!"

—Based on Viking legend

Hydrokinetic energy: lay of the land or motion of the ocean.

—Alla Weinstein, President and CEO, Aqua Energy Group, Ltd.

When you get right down to it—that is, right down to the barebones or to the bone marrow of it all—hydrokinetic generators are nothing more than underwater windmills.

—Frank R. Spellman

INTRODUCTION

As King Canute reportedly discovered, the rise and fall of the seas represent a vast and relentless natural phenomenon—certainly beyond the absolute control of all earthly subjects. Broadly categorized as marine and hydrokinetic energy systems, a new generation of water power technologies offers the possibility of generating electricity from water without the need for dams and diversions. There are numerous plans, both in the United States and internationally, to develop these energy conversion technologies; however, because the concepts are new, few devices have been deployed and tested in rivers and oceans. Even fewer environmental studies of these technologies have been carried out, and thus potential environmental effects remain mostly speculative (Boehlert et al., 2008; Cada et al., 2007; Michel et al., 2007; Pelc and Fujita, 2002). The following account is based on what we currently know or what we think we know about the potential environmental impacts of hydrokinetic technologies.

The ocean can produce two types of energy: *thermal energy* from the sun's heat and *mechanical energy* from the tides and waves. Generating technologies for deriving electrical power from the ocean include tidal power, wave power, ocean thermal energy conversion, ocean currents, ocean winds, and salinity gradients. Of these,

the three most well-developed technologies are *tidal power*, *wave power*, and *ocean thermal energy conversion* (OTEC). Ocean thermal energy conversion is limited to tropical regions, such as Hawaii, and to a portion of the Atlantic coast. Ocean thermal energy can be used for many applications, including electricity generation, which utilizes either warm surface water or boiled seawater to turn a turbine, which activates a generator. Tidal power requires large tidal differences which, in the United States, occur only in Maine and Alaska. Wave energy has a more general application. The western coastline of the United States has the highest wave potential; in California, the greatest potential is along the state's northern coast.

It is important to distinguish tidal energy from hydropower. Hydropower is derived from the hydrological climate cycle, powered by solar energy, which is usually harnessed via hydroelectric dams. In contrast, tidal energy is the result of the interaction of the gravitational pull of the moon and, to a lesser extent, the sun on the seas. Processes that use tidal energy rely on the twice-daily tides and the resultant upstream flows and downstream ebbs in estuaries and lower reaches of some rivers.

The conversion of tidal and wave energy into electricity usually involves mechanical devices. A dam is typically used to convert tidal energy into electricity by forcing the water through turbines that activate a generator. The mechanical power created from these systems either directly activates a generator or transfers to a working fluid, water, or air, which then drives a turbine or generator.

Before we discuss the thermal and mechanical energy potential of the ocean, it is important to have a basic understanding of oceans and especially their margins; it is at the margins of coastal regions where most, if not all, ocean energy is harnessed using current technology. The following section provides a foundation for better understanding the ocean energy concepts presented later in this chapter.

OCEANS AND THEIR MARGINS*

Oceans are a principal component of the hydrosphere and the storehouse of Earth's water. Oceans cover about 71% of Earth's surface. The average depth of the oceans is about 3800 m, but the greatest ocean depth of 11,036 m was recorded in the Mariana Trench. The volume of all of the oceans is about 1.35 billion cubic kilometers, representing 96.5% of Earth's total water supply; however, the volume fluctuates with the growth and melting of glacial ice. The composition of ocean water has remained constant throughout geologic time, with the major constituents dissolving in ocean water from rivers and precipitation, as well as from weathering and degassing of the mantle by volcanic activity. Seawater is approximately 3.5% salt and 96.5% water, by weight. The dissolved salts include chloride (55.07%), sodium (30.62%), sulfate (7.72%), magnesium (3.68%), calcium (1.17%), potassium (1.10%), bicarbonate (0.40%), bromine (0.19%), and strontium (0.02%).

The most significant factor related to ocean water that everyone is familiar with is the salinity of the water—how salty it is. *Salinity*, a measure of the amount of dissolved ions in the water, ranges between 33 and 37 parts per thousand. The

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* Adapted from Spellman, F.R., *Geology for Nongeologists*, Government Institutes Press, Lanham, MD, 2009.

concentration is the amount (by weight) of salt in water, usually expressed as parts per million (ppm); 1 ppm is equivalent to a shot glass of water taken from an Olympic-sized swimming pool. Water is saline if it has a concentration of more than 1000 ppm of dissolved salts; ocean water contains about 35,000 ppm of salt (USGS, 2007). Chemical precipitation, absorption onto clay minerals, and plants and animals prevent seawater from having higher salinity concentrations; however, salinity does vary in the oceans because surface water evaporates, rain and stream water is added, and ice forms or thaws.

Along with salinity another important property of seawater is temperature. The temperature of surface seawater varies with latitude, from near 0°C near the poles to 29°C near the equator. Some isolated areas can have temperatures up to 37°C. Temperature decreases with ocean depth.

OCEAN FLOOR

The bottoms of the ocean basins (ocean floors) are marked by mountain ranges, plateaus, and other relief features similar to (although not as rugged as) those on the land. As shown in Figure 7.1, the floor of the ocean can be divided into four divisions: continental shelf, continental slope, continental rise, and deep-sea floor or abyssal plain:

- The *continental shelf* is the flooded, nearly flat true margins of the continents. Varying in width to about 40 miles and a depth of approximately 650 feet, continental shelves slope gently outward from the shores of the continents. Continental shelves occupy approximately 7.5% of the ocean floor.
- The *continental slope* is a relatively steep slope descending from the continental shelf; it descends rather abruptly to the deeper parts of the ocean. These slopes represent about 8.5% of the ocean floor.
- The *continental rise* is a broad gentle slope below the continental slope containing sediment that has accumulated along parts of the continental slope.
- The *abyssal plain* is a sediment-covered deep-sea plain about 12,000 to 18,000 feet below sea level. This plain accounts for about 42% of the ocean floor.

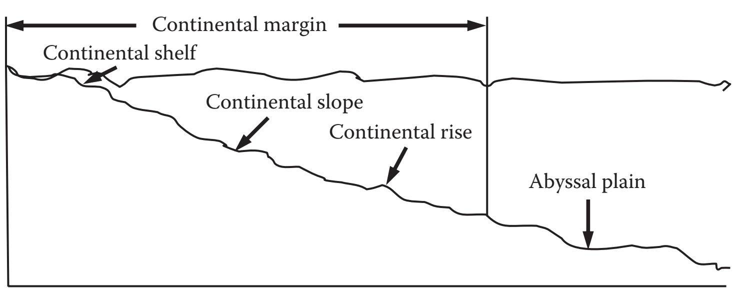

FIGURE 7.1 Cross-section of ocean floor showing major elements of topography.

The deep ocean floor does not consist exclusively of the abyssal plain. Some areas have considerable relief. Among the more important of such features are the following:

- *Seamounts* are isolated mountain-shaped elevations more than 3000 feet high.
- *Mid-oceanic ridges* are submarine mountains, extending more than 37,000 miles through the oceans, generally 10,000 feet above the abyssal plain.
- *Trenches* are deep, steep-sided troughs in an abyssal plain.
- *Guyots* are flat-topped volcanic mountains that rise from the ocean bottom and usually are covered by 3000 to 6000 feet of water.

OCEAN TIDES, CURRENTS, AND WAVES

The Earth's coastline, including sea cliffs, shores, and beaches, is primarily sculpted by water—tides, currents, and waves. The ceaseless, restless motion of the sea is an extremely effective geologic agent. Seawater in motion erodes cliffs, transports debris along shores, and dumps it on beaches. Most coasts retreat or advance over time.

Tides

Tides are the periodic rise and fall of the sea, once every 12 hours and 26 minutes. The gravitational pull of the moon and, to a lesser extent, the sun causes water on Earth to bulge toward them. It is interesting to note that a similar bulge occurs on the opposite side of the Earth due to inertial forces (further explanation is beyond the scope of this text). The effect of the tides is not too noticeable in the open sea, as the difference between high and low tide amounts to only about 2 feet. The tidal range may be considerably greater near shore, however. It may range from less than 2 feet to as much as 50 feet. The tidal range will vary according to the phase of the moon and the distance of the moon from the Earth. The type of shoreline and the physical configuration of the ocean floor will also affect the tidal range.

Currents

Ocean currents are localized movements of masses of seawater. They are the result of drift of the upper 50 to 100 m of the ocean due to drag by wind. Thus, surface ocean currents generally follow the same patterns as atmospheric circulation, with the exception that atmospheric currents continue over the land surface while ocean currents are deflected by the land. Along with wind action, currents may also be caused by tides, variations in the salinity of the water, rotation of the Earth, and concentrations of turbid or muddy water. In addition to this surface circulation, seawater also circulates vertically due to differences in temperature and salinity that affect water density.

Waves

Waves are produced by the friction of wind on open water. Wave height and power depend on wind strength and fetch, the amount of unobstructed ocean over which the wind has blown. In a wave, water travels in loops (essentially up-and-down movements), with the diameter of the loops decreasing with depth. The diameter of loops at the surface is equal to the wave height. Breakers are formed when waves come into shallow water near the shore. The lower part of the wave is retarded by the ocean bottom, and the top, having greater momentum, is hurled forward, causing the wave to break. These breaking waves may do great damage to coastal property as they race across coastal lowlands driven by high winds.

COASTAL EROSION, TRANSPORTATION, AND DEPOSITION

The geologic work of the sea consists of erosion, transportation, and deposition. The sea accomplishes its work of coastal landform sculpting largely by means of waves and wave-produced currents; their effect on the seacoast may be quite pronounced. The coast and accompanying coastal deposits and landform development represent a balance between wave energy and sediment supply.

Wave Erosion

Waves attack shorelines and erode by a combination of several processes. The resistance of the rocks composing the shoreline and the intensity of wave action to which they are subjected are factors that determine how rapidly the shore will erode. Wave erosion works chiefly by hydraulic action, corrosion, and attrition. As waves strike a sea cliff, *hydraulic action* crams air into rock crevices, putting tremendous pressure on the surrounding rock; as waves retreat, the explosively expanding air enlarges cracks and breaks off chunks of rock (known as *scree*). Chunks hurled by waves against the cliff wear off more scree in a process called *corrasion*. In a similar process known as *attrition*, rocks collide with each other in the waves and become smaller and smoother until they are reduced to pebbles and sand grains (Lambert, 2007). Several coastal features are formed by marine erosion due to various combinations of wave action, rock types, and rock beds:

- *Sea cliffs* or *wave-cut platforms* are formed by wave erosion of underlying rock followed by caving-in of the overhanging rocks. As waves eat farther back inland, they leave a wave-cut beach or platform. Such cliffs are essentially vertical and are common at certain localities along the New England and Pacific coasts of North American.
- *Wave-cut benches* are the result of wave action not having enough time to lower the coastline to sea level. Because of the resistance to erosion, a relatively flat wave-cut bench develops. If subsequent uplift of the wave-cut bench occurs, it may be preserved above sea level as a marine terrace.
- *Headlands* are finger-like projections of resistant rock extending out into the water. Indentations between headlands are termed *coves*.

- *Sea caves*, *sea arches*, and *stacks* are formed by continued wave action on a sea cliff. Wave action hollows out cavities or caves in the sea cliffs. Eventually, waves may cut completely through a headland to form a sea arch; if the roof of the arch collapses, the rock left separated from the headland is called a *stack*.

Marine Transportation

Waves and currents are important transporting agents. Rip currents and undertow carry rock particles back to the sea, and long-shore currents will pick up sediments (some of it in solution), moving them out from shore into deeper water. Materials carried in solution or suspension may drift seaward for great distances and eventually be deposited far from shore. During the transportation process sediments undergo additional erosion, becoming reduced in size.

Marine Deposition

Marine deposition takes place whenever the velocity of currents and waves is reduced. Some rocks are thrown up on the shore by wave action. Most of the sediments thus deposited consist of rock fragments derived from the mechanical weathering of the continents, and they differ considerably from terrestrial or continental deposits. Due to the input of sediments from rivers deltas may form, and due to beach drift such features as spits and hooks, bay barriers, and tombolos may form. Depositional features along coasts are discussed below:

- *Beaches* are transitory coastal deposits of debris that lie above the low-tide limit in the shore zone.
- *Barrier islands* are long, narrow accumulations of sand lying parallel to the shore and separated from the shore by a shallow lagoon.
- *Spits and hooks* are elongated, narrow embankments of sand and pebbles extending out into the water but attached by one end to the land.
- *Tombolos* are bars of sand or gravel connecting an island with the mainland or another island.
- *Wave-built terraces* are structures built up from sediments deposited in deep water beyond a wave-cut terrace.

WAVE ENERGY*

Waves are caused by the wind blowing over the surface of the ocean. In many areas of the world, the wind blows with enough consistency and force to provide continuous waves. Wave energy does not have the tremendous power of tidal fluctuations, but the regular pounding of the waves should not be underestimated because there is tremendous energy in the ocean waves. The total power of waves breaking on the

* Adapted from USDOI, *Ocean Wave Energy*, Minerals Management Service, U.S. Department of Interior, Washington, DC, 2014 (http://www.boem.gov/Renewable-Energy-Program/Renewable-Energy-Guide/Ocean-Wave-Energy.aspx).

world's coastlines is estimated at between 2 and 3 million megawatts. In optimal wave areas, more than 65 megawatts of electricity could be produced along a single mile of shoreline (EERE, 2010a). Because the wind is originally derived from the sun, we can consider the energy in ocean waves to be a stored, moderately high-density form of solar energy. According to certain estimates, wave technologies could feasibly fulfill 10% of the global electricity supply if fully developed (WEC, 2010). The west coasts of the United States and Europe and the coasts of Japan and New Zealand are good sites for harnessing wave energy.

Wave Energy: Facts, Parameters, and Equations

Three main processes create waves: (1) air flowing over the sea exerts a tangential stress on the water surface, resulting in the formation and growth of waves; (2) turbulent air flow close to the water surface creates rapidly varying shear stresses and pressure fluctuations (when these oscillations are in phase with existing waves, further wave development occurs); and (3) when waves have reached a certain size, the wind can exert a stronger force on the upwind face of the wave, resulting in additional wave growth.

Waves located within or close to the areas where they are generated are called *storm waves*; waves known as *swell waves* can develop at great distances from their point of origin. The distance over which wind energy is transferred into the ocean to form waves is called the *fetch*. Sea state is the general condition of the free surface of a large body of water, with respect to wind waves and swell, at a certain location and moment (see Table 7.1).

The shape of a typical wave is described as *sinusoidal* (i.e., it has the form of a mathematical sine function) (see Figure 7.2). The difference in height between the peaks and troughs is height H, and the distance between successive peaks (or troughs) of the wave is wavelength λ. The time in seconds required for successive

TABLE 7.1
World Meteorological Organization (WMO) Sea State Codes

WMO Sea State Code	Wave Height (meters)	Characteristics
0	0	Calm (glassy)
1	0–0.1	Calm (rippled)
2	0.1–0.5	Smooth (wavelets)
3	0.5–1.25	Slight
4	1.25–2.5	Moderate
5	2.5–4	Rough
6	4–6	Very rough
7	6–9	High
8	9–14	Very high
9	Over 14	Phenomenal

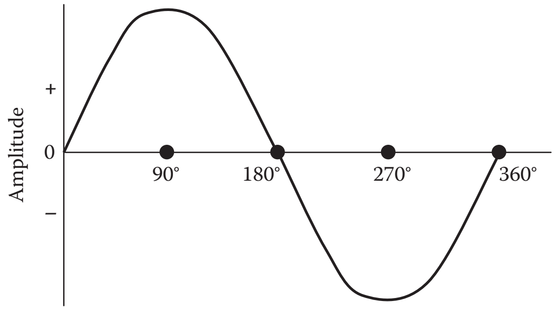

FIGURE 7.2 Sinusoidal wave showing wavelength and amplitude.

peaks (or troughs) to pass a given fixed point is period T. The *frequency* (ν) of the wave describes the number of peak-to-peak (or trough-to-trough) oscillations of the wave surface per second, as seen by a fixed observer, and is the reciprocal of the period; that is, $\nu = 1/T$.

If a wave is traveling at velocity v past a given fixed point, it will travel a distance equal to its wavelength (λ) in a time equal to the wave period T (i.e., $v = \lambda/T$). The power (P) of an idealized ocean wave is approximately equal to the square of height H multiplied by wave period T. The exact expression is

$$P = \frac{g^2 H T^2}{32}$$

where P is in units of watts per meter and g is the acceleration due to gravity (9.81 m/s^2) (Phillips, 1977).

Deep Water Waves

For deep water waves, the velocity of a long ocean wave can be shown to be proportional to the period (if the depth of water is greater than about half of wavelength λ) as follows:

$$v = \frac{gT}{2\pi}$$

The velocity in meters per second is approximately 1.5 times the wave period in seconds. It is interesting to note that in the deep ocean long waves travel faster than shorter waves. Moreover, if the above relationships hold, we can find the deep water wavelength (λ) for any given wave period:

$$\lambda = \frac{gT^2}{2^\pi}$$

Intermediate Depth Waves

As the water becomes shallower, the properties of the waves become increasingly dominated by water depth. When waves reach shallow water, their properties are completely governed by the water depth, but in intermediate depths (i.e., between $d = \lambda/2\pi$ and $d = \lambda/4\pi$), the properties of the waves will be influenced by both water depth d and wave period T (Phillips, 1977).

Shallow Water Waves

As waves approach the shore, the seabed begins to have an effect on their speed, and it can be shown that if the water depth d is less than a quarter of the wavelength then the velocity is given by

$$v = \sqrt{gd}$$

Group Velocity

As waves propagate, their energy is transported. The energy transport velocity is the group velocity. The wave energy flux, through a vertical plane of unit width perpendicular to the wave propagation direction, is equal to

$$P = E \times c_g$$

where c_g is the group velocity (m/s).

Wave Energy Conversion Technology

Development of modern wave energy dates back to 1799 (Ross, 1995), but the technology did not receive worldwide attention until the 1970s when an oil crisis occurred and Stephen Salter published a notable paper about the technology in *Nature* (Salter, 1974). In the early 1980s, after a significant drop in oil prices, technical setbacks, and a general lack of confidence, progress slowed in the development of wave energy devices as a commercial source of electrical power. In the late 1990s, awareness of the depletion of traditional energy resources and the environmental impacts of the large utilization of fossil fuels significantly increased, thereby facilitating the development of green energy resources. The development of wave energy technology grew rapidly, particularly in oceanic countries such as Ireland, Denmark, Portugal, the United

DID YOU KNOW?

Wave height increases with increases in the following factors:

- Wind speed
- Time duration of the wind blowing
- Fetch
- Water depth

Kingdom, and the United States. Quite a few pre-commercial ocean devices were deployed. For example, a U.S. company, Ocean Power Technology, deployed one of their 150-kW wave energy conversion (WEC) systems in Scotland in 2011 (Ocean Power Technologies, 2011). An Irish company, Wavebob, tested a one-quarter model in Galway Bay, Ireland, in 2006 (Wavebob, 2014). In Denmark, the half-scale 600-kW Wavestar® energy system was deployed at Hanstholm in 2009 (Wavestar, 2014), and quarter- and half-size models of the Wave Dragon were tested at Nissum Bredning in 2003 (Wave Dragon, 2014). Furthermore, international organizations, such as the International Energy Agency and the International Electrotechnical Commission (IEC), are heavily involved in the development of wave energy devices. In 2001, the International Energy Agency established an Ocean Energy System Implementation Agreement to facilitate the coordination of ocean energy studies between countries (IEA, 2014). In 2007, the IEC established an Ocean Energy Technical Committee to develop ocean energy standards (IEC, 2014).

In the early 1970s, the harnessing of wave power focused on using floating devices such as Cockerell rafts (a wave power hydraulic device), Salter's duck (curved-cam-like device that can capture 90% of waves for energy conversion), rectifiers (to convert AC to DC electricity), and the clam (a floating, rigid, doughnut-shaped device that converts wave energy to electrical energy). Wave energy converters can be classified in terms of their location: fixed to the seabed, generally in shallow water; floating offshore in deep water; or tethered in intermediate depths. These floating devices are not cost effective and significant mooring problems remain to be solved, so current practice is to move closer to shore, sacrificing some energy. Fixed devices do have several advantages, including (Tovey, 2005):

- Easier maintenance
- Easier to land on device
- No mooring problems
- Easier power transmission
- Enhanced productivity
- Better design life

Wave energy devices can be classified by means of their reaction system, but it is often more instructive to discuss how they interact with the wave field. In this context, each moving body may be labeled as either a displacer or a reactor:

- A *displacer* is a body moved by the waves. It might be a buoyant vessel or a mass of water. If buoyant, the displacer may pierce the surface of the waves or be submerged.
- A *reactor* is a body that provides reaction to the displacer. It could a body fixed to the seabed, or the seabed itself. It could also be another structure or mass that is not fixed but moves in such a way that reaction forces are created (e.g., by moving by a different amount or at different times). A degree of control over the forces acting on each body or acting between the bodies (particularly stiffness and damping characteristics) is often required to optimize the amount of energy captured.

DID YOU KNOW?

Hydrokinetic energy (KE) is the energy possessed by a body of water because of its motion ($KE = 1.2mv^2$). Hydrostatic (potential) energy (PE) is the energy possessed by a body because of its position or location at an elevation or height above a reference or datum ($PE = mgh$).

In some designs, the reactor is actually inside the displacer, while in others it is an external body. Internal reactors are not subject to wave forces, but external reactors may experience loads that cause them to move in ways similar to a displacer; thus, some devices do not have dedicated reactors at all but rather a system of displacers whose relative motion creates a reaction system (INL, 2005). The three types of well-known wave energy conversion devices are point absorbers, terminators, and attenuators (see Figure 7.3):

- A *point absorber* is a floating structure that absorbs energy in all directions by virtue of its movements at or near the water surface (see Figure 7.4). It may be designed so as to resonate—that is, move with larger amplitudes than the waves themselves. This feature is useful to maximize the amount of power that is available for capture. The power take-off system may take a number of forms, depending on the figuration of displacers/reactors.
- A *terminator* is also a floating structure that moves at or near the water surface, but it absorbs energy in only a single direction (see Figure 7.5). The device extends in the direction normal to the predominant wave direction, so that as waves arrive the device restrains them. Again, resonance may be employed and the power take-off system may take a variety of forms.

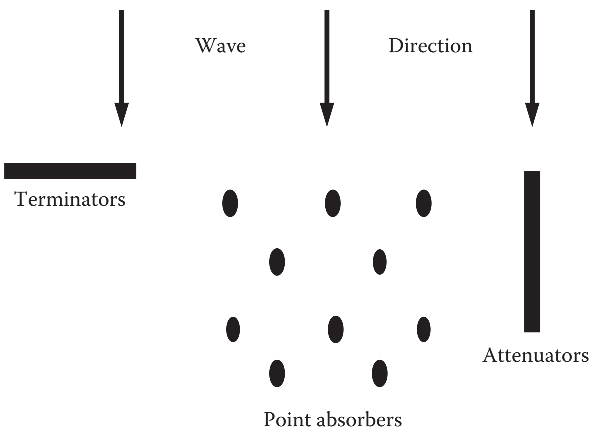

FIGURE 7.3 Wave energy converters. (Adapted from Tovey, N.K., *ENV-2E02 Energy Resources 2004–2005 Lecture*, University of East Anglia, Norwich, U.K., 2005.)

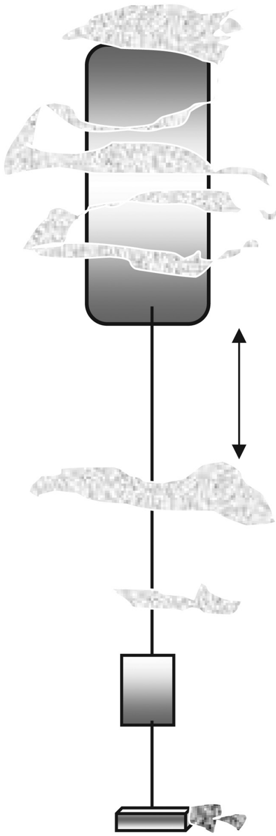

FIGURE 7.4 Point absorber.

- An *attenuator* is a long floating structure like the terminator, but it is orientated parallel to the waves rather than normal to them (see Figure 7.6). It rides the waves like a ship, and movements of the device at its bow and along its length can be restrained to extract energy. A theoretical advantage of the attenuator over the terminator is that its area normal to the waves is small so the forces it experiences are much lower.

TIDAL ENERGY

The tides rise and fall in eternal cycles. Tides are changes in the level of the oceans caused by the gravitational pull of the moon and sun and the rotation of the Earth. The relative motions of these cause several different tidal cycles, including a semidiurnal cycle (with a period of 12 hours and 25 minutes); a semimonthly cycle (spring or neap tides corresponding with the position of the moon, with the highest tides occurring in March and September); a semiannual cycle (with a period of about 178 days which is associated with the moon's orbit); and longer term cycles (e.g., a

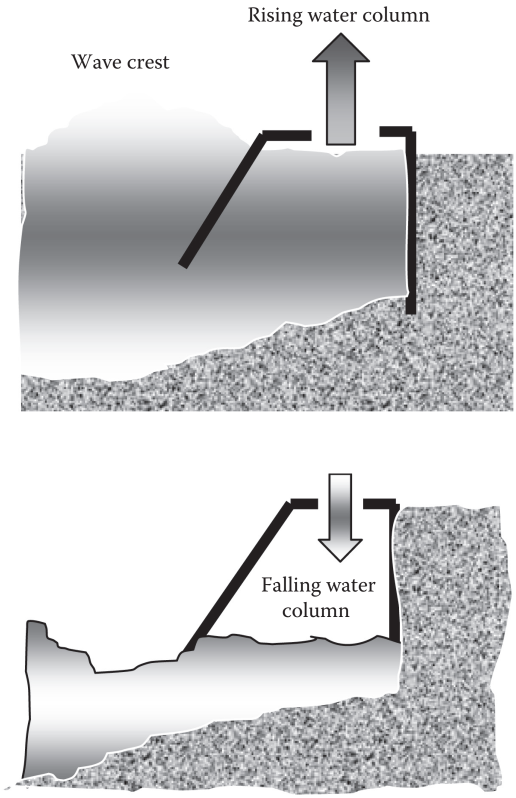

FIGURE 7.5 Terminator.

19-year moon cycle). Nearshore water levels can vary up to 40 feet, depending on the season and local factors. Only about 20 locations have good inlets and a large enough tidal range—about 10 feet—to produce energy economically (USDOI, 2010). The tide ranges have been classified as follows (Masselink and Short, 1993):

- *Micromareal*, when the tidal range is less than 2 meters
- *Mesomareal*, when the tidal range is between 2 meters and 4 meters
- *Macromareal*, when the tidal range is higher than 4 meters

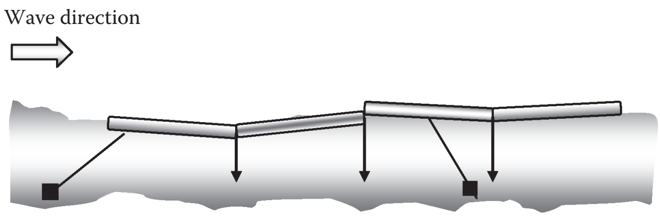

FIGURE 7.6 Attenuator.

DID YOU KNOW?

Spring tides have a range about twice that of neap tides; the other cycles can cause further variations of up to 15%. The tidal range is amplified in estuaries, and in some situations the shape of the estuary is such that near resonance occurs.

Tidal Energy Technologies

Some of the oldest ocean energy technologies use tidal power. Tidal power is more predictable than solar power and wind energy. All coastal areas consistently experience two high and two low tides over a period of slightly greater than 24 hours. For those tidal differences to be harnessed into electricity, the difference between high and low tide must be at least 5 meters, or more than 16 feet. There only about 40 sites on the Earth with tidal ranges of this magnitude. Currently, there are no tidal power plants in the United States, although conditions are good for tidal power generation in both the Pacific Northwest and the Atlantic Northeast regions of the country. Tidal energy technologies include the following:

- *Tidal barrages*—A barrage is a simple generation system for tidal plants that involves installing a dam, or barrage, across an inlet. Sluice gates (gates commonly used to control water levels and flow rates) on the barrage allow the tidal basin to fill on the incoming high tides and to empty through the turbine system on the outgoing tide, also known as the ebb tide. Two-way systems generate electricity on both the incoming and outgoing tides. A potential disadvantage of a barrage tidal power system is the effect a tidal station can have on plants and animals in estuaries. Tidal barrages can change the tidal level in the basin and increase the amount of matter in suspension in the water (turbidity). They can also affect navigation and recreation.
- *Tidal fences*—These look like giant turnstiles. A tidal fence has vertical-axis turbines mounted in a fence. All the water that passes is forced through the turbines. Some of these currents run at 5 to 8 knots (5.6 to 9 miles per hour) and generate as much energy as winds of much higher velocity. Tidal fences can be used in areas such as channels between two land masses. Tidal fences are less expensive to install than tidal barrages and have less impact on the environment tidal barrages, although they can disrupt the movement of large marine animals.
- *Tidal turbines*—These are basically wind turbines in the water that can be located anywhere with strong tidal flow; they function best where coastal currents run at between 3.6 and 4.9 knots (4 to 5.5 mph). Because water is about 800 times more dense than air, tidal turbines have to be much sturdier than wind turbines. Tidal turbines are heavier and more expensive to build but capture more energy.

OCEAN THERMAL ENERGY CONVERSION

The most plentiful renewable energy source in our planet by far is solar radiation: 170,000 TW (170,000 × 10^{12} W) falling on Earth. Because of its dilute and erratic nature, however, it is difficult to harness. To capture this energy, we must employ the use of large collecting areas and large storage capacities, requirements satisfied on Earth by only the tropical oceans. We are all taught at an early age that water covers about 71% (or two-thirds) of Earth's surface. With regard to the vast oceans covering the majority of Earth, it is fitting that Ambrose Bierce (1842–1914) referred to them as "a body of water occupying about two-thirds of the world made for man who has no gills." True, we have no gills, so those who look out upon those vast bodies of water that cover the surface might ask: "What is their purpose?" This is a good question with several possible answers. With regard to renewable energy, we could look out upon those vast seas and wonder how we might use this massive storehouse of energy for our own needs; it is so vast and deep that it absorbs much of the heat and light that come from the sun. One thing seems certain: The secret to our origin, past, present, and future lies within those massive wet confines we call oceans.

Ocean Energy Conversion Process*

The ocean is essentially a gigantic solar collector. The energy from the sun heats the surface water of the ocean. In tropical regions, the surface water can be 40 or more degrees warmer than the deep water. This temperature difference can be used to produce electricity. Ocean thermal energy conversion (OTEC) has the potential to produce more energy than tidal, wave, and wind energy combined. The OTEC systems can be open or closed. In a closed system, an evaporator turns warm surface water into steam under pressure (see Figures 7.7 and 7.8). This steam spins a turbine generator to produce electricity. Water pumps bring deep cold water though pipes to a condenser on the surface. The cold water condenses the steam, and the closed cycle begins again. In an open system, the steam is turned into fresh water, and new surface water is added to the system. A transmission cable carries the electricity to the shore. The OTEC systems must have a temperature difference of about 25°C to operate. This limits the use of OTEC to tropical regions where the surface waters are very warm and there is deep cold water. Hawaii, with its tropical climate, has experimented with OTEC systems since the 1970s. Because of the many challenges to their widespread use, no large or major OTEC systems are in operation today, but several experimental OTEC plants have been built. Pumping the water is a giant engineering challenge. Because of this, OTEC systems are not very energy efficient. It will probably be 10 to 20 years before the technology is available to produce and transmit electricity economically from OTEC systems.

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* Adapted from USDOI, *Ocean Wave Energy*, Minerals Management Service, U.S. Department of Interior, Washington, DC, 2014 (http://www.boem.gov/Renewable-Energy-Program/Renewable-Energy-Guide/Ocean-Wave-Energy.aspx).

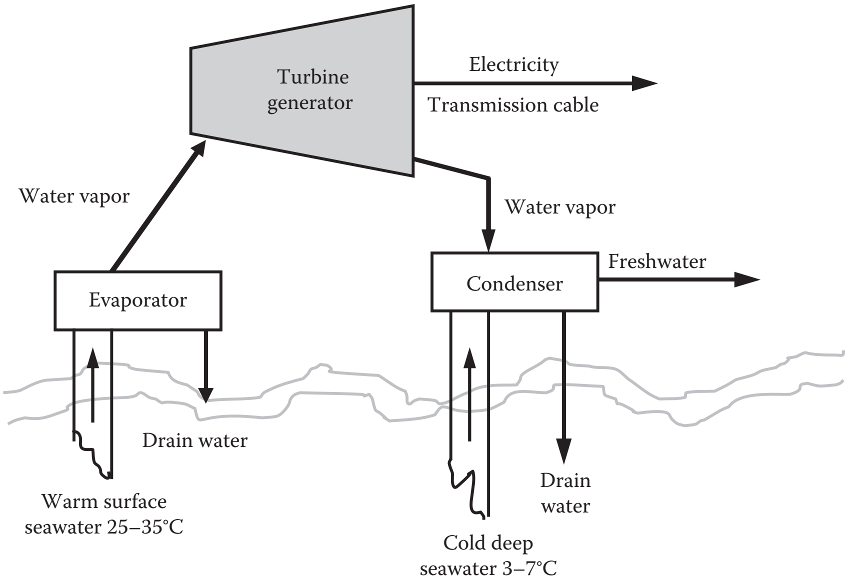

FIGURE 7.7 Schematic of ocean thermal energy conversion system.

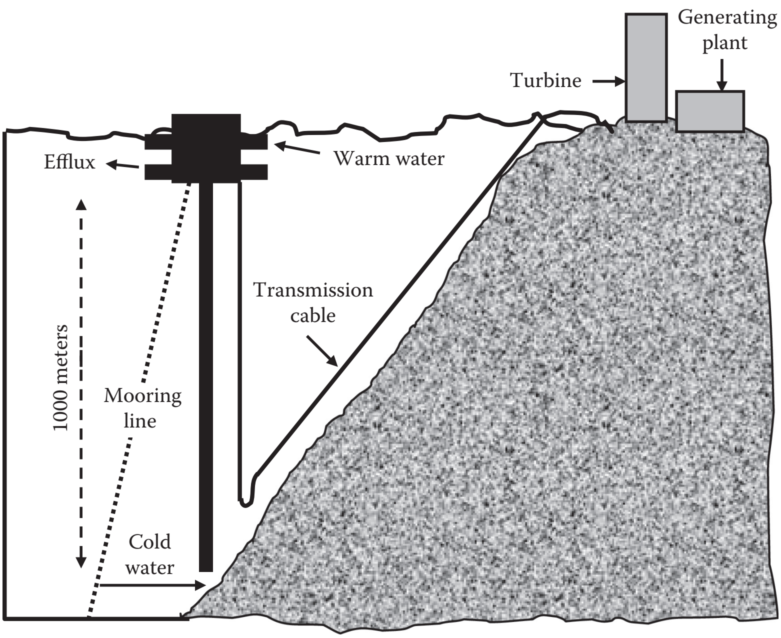

FIGURE 7.8 OTEC floating platform.

Types of OTEC Technologies

The types of OTEC systems include the following:

- *Closed-cycle* systems use fluid with a low-boiling point, such as ammonia, to rotate a turbine to generate electricity. Warm surface seawater is pumped through a heat exchanger where the lower boiling point fluid is vaporized. The expanding vapor turns the turbogenerator. Deep, cold seawater pumped through a second heat exchanger condenses the vapor back into a liquid, which is then recycled through the system.
- *Open-cycle* systems use the warm surface water of tropical oceans to make electricity. When warm seawater is placed in a low-pressure container, it boils. The expanding steam drives a low-pressure turbine attached to an electrical generator. The steam, which has left its salt behind in the lower pressure container, is almost pure fresh water. It is condensed back into a liquid by exposure to cold temperatures from deep ocean water.
- *Hybrid* systems combine the features of both the closed-cycle and open-cycle systems. In a hybrid system, warm seawater enters a vacuum chamber where it is flash-evaporated into steam, similar to the open-cycle evaporation process. The steam vaporizes a lower boiling point fluid (in a closed-cycle loop) that drives a turbine to produce electricity.

OCEAN ENERGY AND HYDROKINETIC TECHNOLOGY IMPACTS*

This section summarizes the potential (generalized) environmental impacts of new ocean energy and hydrokinetic technologies. Environmental issues that apply to all technologies include the following:

- Alteration of river or ocean currents or waves
- Alteration of substrates and sediment transport and deposition
- Impacts of habitat alterations on benthic organisms
- Impacts of noise
- Effects of electromagnetic fields
- Toxic effects of chemicals
- Interference with migratory animals
- Potential for injury to aquatic organisms from strike or impingement due to designs that incorporate moving rotors or blades (see Figure 7.9)
- Impacts of ocean thermal energy conversion

* Adapted from USEPA, *Report to Congress on the Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies*, U.S. Environmental Protection Agency, Washington, DC, 2009 (http://www1.eere.energy.gov/water/pdfs/doe_eisa_633b.pdf).

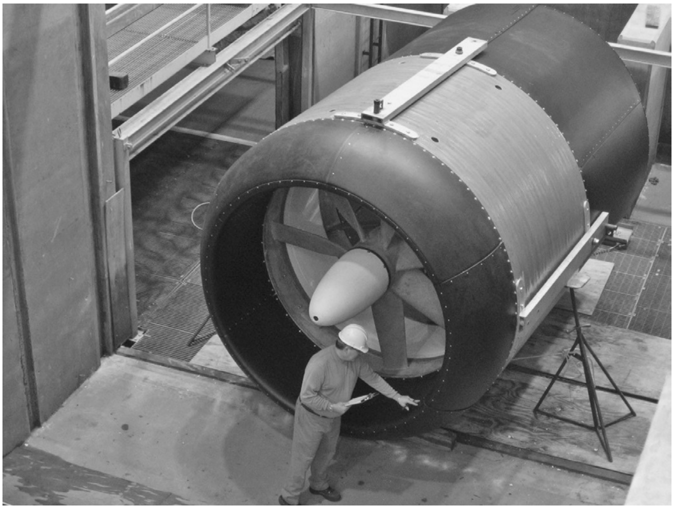

FIGURE 7.9 Free-flow water current turbine used in rivers and canals. (From NREL, *Image Gallery*, National Renewable Energy Laboratory, Washington, DC, 2014, http://images.nrel.gov/.)

Alteration of River or Ocean Currents or Waves

The extraction of kinetic energy from river and ocean currents or tides will reduce water velocities in the vicinity (i.e., near field) of the project (Bryden et al., 2004). Large numbers of devices in a river will reduce water velocities, increase water surface elevations, and decrease flood conveyance capacity. These effects would be proportional to the number and size of structures installed in the water. Rotors, foils, mooring and electrical cables, and field structures will all act as impediments to water movement. The resulting reduction in water velocities could, in turn, affect the transport and deposition of sediment, organisms living on or in the bottom sediments, and plants and animals in the water column. Conversely, moving rotors and foils might increase mixing in systems where salinity or temperature gradients are well defined. Changes in water velocity and turbulence will vary greatly, depending on distance from the structure. For small numbers of units, the changes are expected to dissipate quickly with distance and are expected to be only localized; however, for large arrays, the cumulative effects may extend to a greater area. The alterations of circulation/mixing patterns caused by large numbers of structures might cause changes in nutrient inputs and water quality, which could in turn lead to eutrophication, hypoxia, and effects on the aquatic food web.

The presence of floating wave energy converters will alter wave heights and structures, both in the near field (within meters of the units or project) and, if installed in large numbers, potentially in the far field (extending meters to kilometers out from the project). The above-water structures of wave energy converters will act as a localized barrier to wind and thus reduce wind–wave interactions. Many of the changes would not directly relate to environmental impacts; for example, impacts

on navigational conditions, wave loads on adjacent structures, and recreation on nearby beaches (e.g., surfing, swimming) might be expected (Michel et al., 2007). Reduced wave action could alter bottom erosion and sediment transport and deposition (Largier et al., 2008).

Wave measurements at operating wave energy conversion projects have not yet been made, and the data will be technology and project-size specific. The potential reductions in wave heights are probably smaller than those for wind turbines due to the low profiles of wave energy devices. For example, ASR, Ltd. (2007) predicted that operation of wave energy conversion (WEC) devices at the proposed Wave Hub (a wave power research facility off the coast of Cornwall, U.K.; http://www.wavehub.co.uk/) would reduce wave height at shorelines 5 to 20 kilometers away by 3 to 6%. Operation of six wave energy conversion buoys, a version of OPT's PowerBuoy®, in Hawaii was not predicted to impact oceanographic conditions (Department of the Navy, 2003). This conclusion was based on modeling analyses of wave height reduction due to both wave scattering and energy absorption. The proposed large spacing of buoy cylinders (51.5 m apart, compared to a buoy diameter of 4.5 m) resulted in predicted wave height reductions of 0.5% for a wave period (i.e., time between the passage of consecutive wave crests past a fixed point) of 9 seconds and less than 0.3% for a wave period of 15 seconds. Boehlert et al. (2008) summarized the changes in wave heights that were predicted in various environmental assessments. Recognizing that impacts will be technology and location specific, estimated wave height reductions range from 3 to 15%, with maximum effects closest to the installation and near the shoreline. Millar et al. (2007) used a mathematical model to predict that operation of the Wave Hub, with WECs covering an area 1 km by 3 km located 20 km from shore, could decrease average wave heights by about 1 to 2 centimeters at the coastline. This represents an average decrease in wave height of 1%; a maximum decrease in wave height of 3% was predicted to occur with a 90% energy transmitting wave farm (Smith et al., 2007). Other estimates in other environmental settings predict wave height reductions ranging from 3 to 13% (Nelson, 2008). Largier et al. (2008) concluded that height and incident angle are the most important wave parameters for determining the effects of reducing the energy supply to the coast.

DID YOU KNOW?

The PowerBuoy®, developed by Ocean Power Technologies (OPT), is one of the most widely deployed WEC device designs in the world. A 10-buoy test array of the PB150 PowerBuoy® has been proposed for deployment in Reedsport, Oregon. The PB150 is a utility-scale 150-kilowatt buoy that—in the initial design—contains hydraulic fluid, which is cycled as the buoy moves up and down with the waves. The moving fluid or mechanical parts are used to spin a generator, which produces electricity. The buoy is approximately 35 meters (115 feet) tall, of which approximately 9 meters (30 feet) project above the water's surface), and is 11 meters (36 feet) in diameter. It is held in place by a three-point mooring system (USDOE, 2012).

The effects of reduced wave heights on coastal systems will vary from site to site. It is known that the richness and density of benthic organism are related to such factors as relative tidal range and sediment grain size (Rodil and Lastra, 2004), so changes in wave height can be expected to alter benthic sediments and habitat for benthic organism. Coral reefs reduce wave heights and dissipate wave and tidal energy, thereby creating valuable ecosystems (Lugo-Fernandez et al., 1998; Roberts et al., 1992). In other cases, wave height reductions can have long-term adverse effects. Estuary and lagoon inlets may be particularly sensitive to changes in wave heights. For example, construction of a storm-surge barrier across an estuary in the Netherlands permanently reduced both the tidal range and mean high water level by about 12% from original values, and numerous changes to the affected salt marshes and wetlands soils were observed (de Jong et al., 1994).

Tidal energy converters can also modify wave heights and structure by extracting energy from the underlying current. It has been suggested that the effects of structural drag on currents would not be significant (Minerals Management Service, 2007), but few measurements of the effects of tidal/current energy devices on water velocities have been reported. Some tidal velocity measurements were made near a single, 150-kilowatt (kW) Stingray demonstrator in Yell Sound in the Shetland Islands (Engineering Business, Ltd., 2005). Acoustic Doppler current profilers were installed near the oscillating hydroplane (which travels up and down the water column in response to lift and drag forces) as well as upstream and downstream of the device. Too few velocity measurements were taken for firm conclusions to be made, but the data suggest that 1.5- to 2.0-m/s tidal currents were slowed by about 0.5 m/s downstream from the Stingray. In practice, multiple units will be spaced far enough apart to prevent a drop in performance (turbine output) caused by extraction of kinetic energy and localized water velocity reductions.

Modeling of the Wave Hub project in the United Kingdom suggested a local reduction in marine current velocities of up to 0.8 m/s, with a simultaneous increase in velocities of 0.6 m/s elsewhere (Michel and Burkhard, 2007). Wave energy converters are expected to affect water velocities less than submerged rotors and other, similar designs because only cables and anchors will interfere with the movements of tides and currents.

Tidal energy conversion devices will increase turbulence, which in turn will alter mixing properties, sediment transport, and, potentially, wave properties. In both the near field and far field, extraction of kinetic energy from tides will decrease tidal amplitude, current velocities, and water exchange in proportion to the number of units installed, potentially altering the hydrologic, sediment transport and ecological relationships of rivers, estuaries, and oceans. For example, Polagye et al. (2008) used an idealized estuary to model the effects of kinetic power extraction on estuary-scale fluid mechanics. The predicted effects of kinetic power extraction included: (1) reduction of the volume of water exchanged through the estuary over the tidal cycle, (2) reduction of the tidal range landward of the turbine array, and (3) reduction of the kinetic power density in the tidal channel. These impacts were strongly dependent on the magnitude of kinetic power extraction, estuary geometry, tidal regime, and nonlinear turbine dynamics.

Karsten et al. (2008) estimated that extracting the maximum of 7 gigawatts (GW) of power from the Minas Passage (Bay of Fundy) with in-stream tidal turbines could result in large changes in the tides of the Minas Basin (greater than 30%) and significant far-field changes (greater than 15%). Extracting 4 GW of power was predicted to cause less than a 10% change in tidal amplitudes, and 2.5 GW could be extracted with less than a 5% change. The model of Blanchfield et al. (2007) predicted that extracting the maximum value of 54 megawatts (MW) from the tidal current of Masset Sound (British Columbia) would decrease the water surface elevation within a bay and the maximum flow rate through the channel by approximately 40%. On the other hand, the tidal regime could be kept within 90% of the undisturbed regime by limiting extracted power to approximately 12 MW.

In the extreme far field (i.e., thousands of kilometers), there is an unknown potential for dozens or hundreds of tidal energy extraction devices to alter major ocean current such as the Gulf Stream (Michel et al., 2007). The significance of these potential impacts could be ascertained by predictive modeling and subsequent operational monitoring as projects are installed.

Alteration of Substrates and Sediment Transport and Deposition

Operation of hydrokinetic or ocean energy technologies will extract energy from the water, which will reduce the height of waves or velocity of currents in the local area. This loss of wave/current energy could, in turn, alter sediment transport and the wave climate of nearby shorelines. Moreover, installation of many of the technologies will entail attaching the devices to the bottom by means of pilings or anchors and cables. Transmission of electricity to the shore will be through cables that are either buried in or attached to the seabed. Thus, project installation will temporarily disturb sediments, the significance of which will be proportional to the amount and type of bottom substrate disturbed. There have been few studies of the effects of burying cables from ocean energy technologies, but experience with other buried cables and trawl fishing indicate the possible severity of the impacts. For example, Kogan et al. (2006) surveyed the condition of an armored, 6.6-cm-diameter coaxial cable that was laid on the surface of the seafloor off Half Moon Bay, California. The cable was not anchored to the seabed. Whereas the impacts of laying the cable on the surface of the seabed were probably small, subsequent movements of the cable had continuing impacts on the bottom substrates. For example, cable strumming by wave action in shallower, nearshore areas created incisions in rocky siltstone outcrops ranging from superficial scrapes to vertical grooves and had minor effects on the habitats of aquatic organisms. At greater depths, there was little evidence of effects of the cable on the seafloor, regardless of exposure. Limited self-burial of the unanchored cable occurred over an 8-year period, particularly in deeper waters of the continental shelf.

During operation, changes in current velocities or wave heights will alter sediment transport, erosion, and sedimentation. Due to the complexity of currents and their interaction with structures, operation of the projects will likely increase scour and deposition of fine sediments on both localized and far-field scales. For example, turbulent vortices that are shed immediately downstream from a velocity-reducing

structure (e.g., rotors, pilings, concrete anchor blocks) will cause scour, and this sediment is likely to be deposited further downstream. On average, extraction of kinetic energy from currents and waves is likely to increase sediment deposition in the shadow of the project (Michel et al., 2007), the depth and areal extent of which will depend on local topography, sediment types, and characteristics of the current and the project. Subsequent deposition of sediments is likely to cause shoaling and a shift to a finer sediment grain size on the lee side of wave energy arrays (Boehlert et al., 2008). Scour and deposition should be considered in project development, but many of the high-energy (high-velocity) river and nearshore marine sites that could be utilized for electrical energy production are likely to have substrates with few or no fine sediments. Changes in scour and deposition will alter the habitat for bottom-dwelling plants and animals.

Loss of wave energy may lead to changes in longshore currents, reductions in the width and energy of the surf zone, and changes in beach erosion and deposition patterns. Millar et al. (2007) modeled the wave climate near the Wave Hub electrical grid connection point off the north coast of Cornwall. The installation would be located 20 km off the coast, in water depths of 50 to 60 m. Arrays of WECs connected to the Wave Hub would occupy a 1 km × 3 km site. The mathematical model predicted that an array of WECs would potentially affect the wave climate on the nearby coast on the order of 1 to 2 cm. It is unknown whether such small reductions in the average wave height would measurably alter sediment dynamics along the shore, given the normal variations in waves due to wind and storms.

Water quality will be temporarily affected by increased suspended sediments (turbidity) during installation and initial operation. Suspension of anoxic sediments may result in a temporary and localized decline in the dissolved oxygen content of the water, but dilution by oxygenated water current would minimize the impacts. Water quality may also be compromised by the mobilization of buried contaminated sediments during both construction and operation of the projects. Excavation to install the turbines, anchoring structures, and cables could release contaminants adsorbed to sediments, posing a threat to water quality and aquatic organism. Effects on aquatic biota may range from temporary degradation of water quality (e.g., a decline in dissolved oxygen content) to biotoxicity and bioaccumulation of previously buried contaminants such as metals.

Impacts of Habitat Alterations on Benthic Organisms

Installation and operation of hydrokinetic and marine energy projects can directly displace benthic (i.e., bottom-dwelling) plants and animals or change their habitats by altering water flows, wave structures, or substrate composition. Many of the designs will include a large anchoring system made of concrete or metal, mooring cables, and electrical cables that lead from the offshore facility to the shoreline. Electrical cables might simply be laid on the bottom, or they more likely will be anchored or buried to prevent movement. Large bottom structures will alter water flow, which may result in localized scour and/or deposition. Because these new structures will affect bottom habitats, changes to the benthic community composition and species interactions in the area defined by the project may be expected (Louse et al., 2008).

Displacement of Benthic Organisms by Installation of the Project

Bottom disturbances will result from the temporary anchoring of construction vessels, digging and refilling the trenches for power cables, and installation of permanent anchors, pilings, or other mooring devices. Motile organisms will be displaced and sessile organism destroyed in the limited areas affected by these activities. Displaced organisms may be able to relocate if similar habitats exist nearby and those habitats are not already at carrying capacity. That is, each population has an upper limit on size, called the *carrying capacity*. Carrying capacity can be defined as being the optimum number of individuals of a species that can survive in a specific area over time. A particular pond may be able to support only a dozen frogs based on the food resources for the frogs in the pond. If 30 frogs took up residency in the same pond, at least half of them would probably die because the pond environment would not have enough food for all of them to live. Carrying capacity, symbolized as K, is based on the quantity of food supplies, the physical space available, the degree of predation, and several other environmental factors.

Species with benthic-associated spawning or whose offspring settle into and inhabit benthic habitats are likely to be most vulnerable to disruption during project installation. Temporary increases in suspended sediments and sedimentation down current from the construction area can be expected. The potential effects of suspended sediments and sedimentation on aquatic organism are periodically reviewed (Newcombe and Jensen, 1996; Wilber and Clarke, 2001; Wilber et al., 2005; Wood and Armitage, 1997). When construction is completed, disturbed areas are likely to be recolonized by these same organisms, assuming that the substrate and habitats are restored to a similar state. For example, Lewis et al. (2003) found that numbers of clams and burrowing polychaetes (worms) fully recovered within a year after construction of an estuarine pipeline, although fewer wading birds returned to forage on these invertebrates during the same time period.

Alteration of Habitats for Benthic Organism during Operation

Installation of the project will alter benthic habitats over the longer term if the trenches containing electrical cables are backfilled with sediments of different size or composition than the previous substrate. Permanent structures on the bottom (ranging in size from anchoring systems to seabed-mounted generators or turbine rotors) will supplant the existing habitats. These new structures would replace natural hard substrates or, in the case of previously sandy areas, add to the amount of hard bottom habitat available to benthic algae, invertebrates, and fish. This could attract a community of rocky reef fish and invertebrate species (including biofouling organisms) that would not normally exist at that site. Depending on the situation, the newly created habitat could increase biodiversity or have negative effects by enabling introduced (exotic) benthic species to spread. Marine fouling communities developed on monopiles for offshore wind power plants are significantly different from the benthic communities on adjacent hard substrates (Wihelmsson and Maim, 2008; Wilhelmsson et al., 2006).

Changes in water velocities and sediment transport, erosion, and deposition caused by the presence of new structures will alter benthic habitats, at least on a local scale. This impact may be more extensive and long lasting than the effects of anchor and cable installation. Deposition of sand may impact seagrass beds by increasing mortality and

decreasing the growth rate of plant shoots (Craig et al., 2008). Conversely, deposition of organic matter in the wakes of marine energy devices could encourage the growth of benthic invertebrate communities that are adapted to that substrate. Mussel shell mounts that slough off from oil and gas platforms may create surrounding artificial reefs that attract a large variety of invertebrates (e.g., crabs, sea stars, sea cucumbers, anemones) and fish (Love et al., 1999). Accumulation of shells and organic matter in the areas would depend on the wave and current energy, activities of biota, and numerous other factors (Widdows and Brinsley, 2002). Although the new habitats created by energy conversion structures may enhance the abundance and diversity of invertebrates, predation by fish attracted to artificial structures can greatly reduce the numbers of benthic organisms (Davis et al., 1982).

Movements of mooring or electrical transmission cables along the bottom (sweeping) could be a continual source of habitat disruption during operation of the project. For example, Kogan et al. (2006) found that shallow water wave action shifted a 6.6-cm-diameter, armored coaxial cable that was laid on the surface of the seafloor. The strumming action caused incisions in rocky outcrops, but effects on seafloor organisms were minor. Anemones colonized the cable itself, preferring the hard structure over the nearby sediment-dominated seafloor. Some flatfishes were more abundant near the cable than at control sites, probably because the cable created a more structurally heterogeneous habitat. Sensitive habitats that may be particularly vulnerable to the effects of cable movements include macroalgae and seagrass beds, coral habitats, and other biogenic habitats such as worm reefs and mussel mounds.

Renewable energy projects may also have benefits for some aquatic habitats and populations. The presence of a marine energy conversion project will likely limit most fishing activities and other access in the immediate area. Bottom trawling can disrupt habitats, and benthic communities in areas that are heavily fished tend to be less complex and productive than in areas that are not fished in that way (Jennings et al., 2001; Kaiser et al., 2000). Blyth et al. (2004) found that cessation of towed-gear fishing resulted in significantly greater total species richness and biomass of benthic communities compared to sites that were still fished. The value of these areas in which fishing is precluded (or, at least limited to certain gear types) by the energy project would depend on the species of fish and their mobility. For relatively sedentary animals, reserves less than 1 km across have augmented local fisheries, and reserves in Florida of 16 km^2 and 24 km^2 have sustained more abundant and sizable fish than nearby exploited areas (Gell and Roberts, 2003). On the other hand, the protection of long-lived, late-maturing, or migratory marine fish species may require much larger marine protected areas (greater than 500 km^2) than those envisioned for most energy developments (Blyth-Skyrme et al., 2006; Kaiser, 2005; Nelson, 2008).

Impacts of Noise

Freshwater and marine animals rely on sound for many aspects of their lives including reproduction, feeding, predator and hazard avoidance, communication, and navigation (Popper, 2003; Weilgart, 2007). Consequently, underwater noise generated during installation and operation of a hydrokinetic or ocean energy conversion device has the potential to impact these organisms. Noise may interfere with

sounds animals make to communicate or may drive animals from the area. If severe enough, loud sounds could damage their hearing or cause mortalities. For example, it is known from experience with other marine construction activities that the noise created by pile driving creates sound pressure levels high enough to impact the hearing of harbor porpoises and harbor seals (Thomsen et al., 2006). The effects are less certain for fish (Hastings and Popper, 2005), although fish mortalities have been reported for some pile-driving activities (Caltrans, 2001; Longmuir and Lively, 2001). Noise generated during normal operations is expected to be less powerful but could still disrupt the behavior of marine mammals, sea turtles, and fish at great distances from the source. Changes in animal behavior or physiological stresses could lead to decreased foraging efficiency, abandonment of nearby habitats, decreased reproduction, and increased mortality (National Research Council, 2005)—all of which could have adverse effects on both individuals and populations.

Construction and operation noise may disturb seabirds using the offshore and intertidal environment. Shorebirds will be disturbed by onshore construction and operations, causing them to abandon breeding colonies (Thompson et al., 2008). Pinnipeds such as seals, sea lions, and walruses may abandon onshore sites used for reproduction (rookeries) because of noise and other disturbing activities during installation. On the other hand, some marine mammals and birds may be attracted to the area by underwater sounds, lights, or increased prey availability.

There are many sources of sound and noise in the aquatic environment (National Research Council, 2003; Simmonds et al., 2003). Natural sources include wind, waves, earthquakes, precipitation, cracking ice, and mammal and fish vocalizations. Human-generated ocean noise comes from such diverse sources as recreational, military, and commercial ship traffic; dredging; construction; oil drilling and production; geophysical surveys; sonar; explosions; and ocean research (Johnson et al., 2008). Many of these sounds will be present in an area of new energy developments. Noises generated by marine and hydrokinetic energy technologies should be considered in the context of these background sounds. The additional noises from these energy technologies could result from installation and maintenance of the units, movements of internal machinery, waves striking the buoys, water flow moving over mooring and transmission cables, synchronous and additive nonsynchronous sound from multiple unit arrays, and environmental monitoring using hydroacoustic techniques.

Noise in the Aquatic Environment

There are many ways to express the intensity and frequency of underwater sound waves (Thomsen et al., 2006; Wahlberg and Westerberg, 2005). An underwater acoustic wave is generated by displacement of water particles; consequently, the passage of an acoustic wave creates local pressure oscillations that travel through water with a given sound velocity. These two parameters, pressure and velocity, are used to define the intensity of an acoustic field and therefore are useful for considering the effects of noise on aquatic animals. The intensity of the acoustic field is defined as the vector product of the local pressure fluctuations and the velocity of the particle displacement. A basic unit for measuring the intensity of underwater noise is the *sound pressure level* (SPL). The SPL of a sound, given in decibels (dB), is calculated by

$$\text{SPL (dB)} = 20 \log_{10} (p/p_0)$$

where p is a pressure fluctuation caused by a sound source, and p_0 is the reference pressure, defined in underwater acoustics as 1 μPa at 1 m from the source (Thomsen et al., 2006). Using the above formula, doubling the pressure of a sound (p) results in a 6-dB increase in SPL.

The sound pressure of a continuous signal is often expressed by a root-mean-square (rms) measure, which is the square root of the mean value of squared instantaneous sound pressures integrated over time (Madsen, 2005). Like SPL, the resulting integration of instantaneous sound pressure levels is also expressed in dB re 1 μPa (rms). An rms level of safe exposure to received noise has been established for marine mammals; the lower limits for concern about temporary or permanent hearing impairments in cetaceans and pinnipeds are currently 180 and 190 dB re 1 μPa (rms), respectively (National Marine Fisheries Service, 2003; Southall et al., 2007). However, Madsen (2005) argued that rms safety measures are insufficient and should be supplemented by other estimates of the magnitude of noise (e.g., maximum peak-to-peak SPL in concert with a maximum received energy flux level).

Sound intensity is greatest near the sound source and, in the far field, decreases smoothly with distance. As the acoustic wave propagates through the water, intensity is reduced by geometric spreading (dilution of the energy of the sound wave as it spreads out from the source over a larger and larger area) and, to a lesser extent, absorption, refraction, and reflection (Wahlberg and Westerberg, 2005). Attenuation of sound due to spherical spreading in deep water is estimated by $20 \log_{10} r$, where r is the distance in meters from the source (National Research Council, 2000). Assuming simple spherical spreading (no reflection from the sea surface or bottom) and the consequent transmission loss of SPL, a 190-dB source level would be reduced to 150 dB at 100 m. Close to the source, changes in sound intensity vary in a more complicated fashion, particularly in shallow water, as a result of acoustic interference from natural or man-made sounds or where there are reflective surfaces (seabed and water surface).

DID YOU KNOW?

According to several articles published in *Electrical Engineering* and the *Journal of the Acoustical Society of America*, the decibel suffers from the following disadvantages (Chapman, 2000; Clay, 1999; Hickling, 1999; Horton, 1954):

- The decibel creates confusion.
- The logarithmic form obscures reasoning.
- Decibels are more related to the area of slide rules than that of modern digital processing.
- Decibels are cumbersome and difficult to interpret.

Hickling (1999) concluded, "Decibels are a useless affectation, which is impeding the development of noise control as an engineering discipline."

Sound exposure level (SEL) is a measure of the cumulative physical energy of the sound event which takes into account both intensity and duration. SELs are computed by summing the cumulative sound pressure squared (p^2) over time and normalizing the time to 1 second. Because calculation of the SEL for a given underwater sound source is a way to normalize to 1 second the energy of noise that may be much briefer (such as the powerful, but short impulses caused by pile driving), SEL is typically used to compare noise events of varying durations and intensities.

In addition to intensity, underwater noise will have a range of frequencies (Hz or cycles per second). For convenience, measurements of the potentially wide range of individual frequencies associated with noise are integrated into "critical bands" or filters; the width of a band is often given in 1/3-octave levels (Thomsen et al., 2006). Thus, sounds can be expressed in terms of the intensities (dB) at particular frequency (Hz) bands.

There are four fundamental properties of sound transmission in water that are relevant to consideration of the effects of noise on aquatic animals (National Research Council, 2000):

1. The transmission distance of sound in seawater is determined by a combination of geometric spreading loss and an absorptive loss that is proportional to the sound frequency. Thus, attenuation (weakening) of sound increases as its frequency increases.
2. The speed of a sound wave in water is proportional to the temperature.
3. The sound intensity decreases with distance from the sound source. Transmission loss of energy (intensity) due to spherical spreading in deep water is estimated by $20 \log_{10} r$, where r is the distance in meters from the source.
4. The strength of sound is measured on a logarithmic scale.

From these properties, it can be seen that high-frequency sounds will dissipate faster than low-frequency sounds, and a sound level may decrease by as much as 60 dB at 1 km from the source. Acoustic wave intensity of 180 dB is 10 times less intense than 190 dB, and 170 dB is 100 times less than 190 dB (National Research Council, 2000).

Noise Produced by Ocean Energy Technologies

There is very little information available on sound levels produced by construction and operation of ocean energy conversion structures (Michel et al., 2007). However, reviews of the construction and operation of European offshore wind farms provide useful information on the sensitivity of aquatic organism to underwater noise. For example, Thomsen et al. (2006) reported that pile-driving activities generate brief, but very high, sound pressure levels over a broad band of frequencies (20 to 20,000 Hz). Single pulses are about 50 to 100 ms in duration and occur approximately 30 to 60 times per minute. The SEL at 400 m from the driving of a 1.5-m-diameter pile exceeded 140 dB re 1 µPa over a frequency range of 40 to 3000 Hz (Betke et al., 2004). It usually takes 1 to 2 hours to drive one pile into the bottom. Sounds produced by the pile-driving impacts above the water's surface enter the water from the air and from the submerged portion of the pile; they then propagate through the

water column and into the sediments, from which they pass successively back into the water column. Larger diameter, longer piles require relatively more energy to drive into the sediments, which results in higher noise levels. For example, the SPL associated with driving 3.5-m-diameter piles is expected to be roughly 10 dB greater than for a 1.5-m-diameter pile (Thomsen et al., 2006). Pile-driving sound, while intense and potentially damaging, would occur only during the installation of some marine and hydrokinetic energy devices.

Some ocean energy technologies will be secured to the bottom by means of moorings and anchors drilled into rock. Like pile-driving, hydraulic drilling will occur during a limited time period, and noise generation will be intermittent. The Department of the Navy (2003) summarized underwater SPL measurements of three hydraulic rock drills; frequencies ranged from about 15 Hz to over 39 Hz, and SPLs ranged from about 120 to 170 dB re 1 μPa. SPLs were relatively consistent across the entire frequency range.

During operation, vibrations of the device's gearbox, generator, and other moving components are radiated as sound into the surrounding water. Noise during the operation of wind farms is of much lower intensity than noise during construction (Betke et al., 2004; Thomsen et al., 2006), and the same may be true for hydrokinetic and ocean energy farms; however, this source of noise will be continuous. Measurements of sound levels associated with the operation of hydrokinetic and ocean energy farms have not yet been published. One example of a wave energy technology, the WEC buoy (a version of OPT's PowerBuoy) which has been tested in Hawaii, has many of the mechanical parts contained within an equipment canister or mounted to a structure through mounting pads. Thus, the acoustic energy produced by the equipment is not well coupled to the seawater, which is expected to reduce the amount of radiated noise (Department of the Navy, 2003). Although no measurements had been made, it was predicted that the acoustic output from the WEC buoy system would probably be in the range of 75 to 80 dB re 1 μPa. This SPL is equivalent to light to normal density shipping noise, although the frequency spectrum of the WEC buoy is expected to be shifted to higher frequencies than typical shipping noise. By comparison, Thomsen et al. (2006) reported the ambient noise measured at five different locations in the North Sea. Depending on frequency, SPL values ranged from 85 to 115 dB, with most energy occurring at frequencies less than 100 Hz.

The Environmental Statement for the proposed installation of the Wave Dragon wave energy demonstrator off the coast of Pembrokeshire, U.K., predicted noise levels associated with installation of a concrete caisson (gravity) block and steel cable mooring arrangement, installation of subsea cable, and support activity (Wave Dragon Wales, Ltd., 2007). The installation of gravity blocks is not expected to generate additional noise over and above that of the vessel conducting the operation. Vessel noise will depend on size and design of the ship but is expected to be up to 180 dB re 1 μPa at 1 m. Other predicted installation noise sources and levels stem from operation of the ship's echosounder (220 dB re 1 μPa at 1 m peak-to-peak), cable laying and fixing (159 to 181 dB re 1 μPa at 1 m), and directional drilling (129 dB re 1 μPa rms at 40 m above the drill). There are no measurements available for the noise associated with operation of an overtopping device such as the Wave Dragon. Wave Dragon Wales, Ltd. (2007) predicted that operational noise would result from

the Kaplan-style hydroturbines (an estimated 143 dB re 1 μPa at 1 m), as well as unknown levels and frequencies of sound from wave interactions with the body of the device, hydraulic pumps, and the mooring system.

In 2008, the Ocean Renewable Power Company (ORPC) made limited measurements of underwater noise associated with operation of their 1/3-scale working prototype instream tidal energy conversion device, its turbine generation unit (TGU). The TGU is a single horizontal-axis device with two advanced-design cross-flow turbines that drive a permanent magnet generator. An omnidirectional hydrophone, calibrated for a frequency range of 20 to 250 kHz, was used to take near-field measurements adjacent to the barge from which the turbine was suspended and at approximately 15 m from the turbine. Multiple far-field measurements were also made at distances out to 2.0 km from the barge. Noise measurements were made over one full tidal cycle, with supplemental measurements being taken later (USDOE, 2009). Sound pressure levels at 1/3-octoave frequency bands were used to calculate rms levels and SELs. During times when the turbine generator unit was not operating, background noise ranged from 112 to 138 dB re 1 μPa rms, and SELs ranged from 120 to 140 dB re 1 μPa. A single measurement made when the turbine blades were rotating (at 52 rpm) resulted in an estimate of 132 dB re 1 μPa (rms) and an SEL of 126 dB re 1 μPa at a horizontal distance of 15 m and a water depth of 10 m. These very limited readings suggest that the single 1/3-scale turbine generator unit did not increase noise above ambient levels.

In addition to the sound intensity and frequency spectrum produced by the operation of individual machines, impacts of noise will depend on the geographic location of the project (water depth, type of substrate), the number of units, and the arrangement of multiple-unit arrays. For example, due to noise from surf and surface waves, noise levels in shallow, nearshore areas (≤100 m deep and within 5 km of the shore) are typically somewhat higher for low frequencies (≤1 kHz) and much higher for frequencies above 1 kHz.

Potential Effects of Noise on Aquatic Animals

Because of the complexity of describing underwater sounds, investigators have often used different units to express the effects of sound on aquatic animals and have not always reported precisely the experimental conditions. For example, acoustic signal characteristics that might be relevant to biological effects include frequency content, rise time, pressure and particle velocity time series, zero-to-peak and peak-to-peak amplitude, mean-square amplitude, duration, integral of mean-square amplitude over duration, sound exposure level, and repetition rate (National Research Council, 2003; Thomsen et al., 2006). Each of these sound characteristics may differentially impact different species of aquatic animals, but the relationships are not sufficiently understood to specify which are the most important. Many studies of the effects of noise report the frequency spectrum and some measure of sound intensity (SPL, rms, and/or SEL).

Underwater noise can be detected by fish and marine mammals if the frequency and intensity fall within the range of hearing for the particular species. An organism's hearing ability can be displayed as an audiogram, which plots sound pressure level (dB) against frequency (Hz). Nedwell et al. (2004) compiled audiograms for a number of aquatic organisms. If the pressure level of a generated sound is transmitted

at these frequencies and exceeds the sound pressure level (i.e., above the line) on a given species' audiogram, the organism will be able to detect the sound. There is a wide range of sensitivity to sound among marine fish. Herrings (Clupeoidea) are highly sensitive to sound due to the structure of their swim bladder and auditory apparatus, whereas flatfish such as plaice and dab (Pleuronectidae) that have no swim bladder are relatively insensitive to sound (Nedwell et al., 2004). Possible responses to the received sound may include altered behavior (e.g., attraction, avoidance, interference with normal activities) (Nelson, 2008) or, if the intensity is great enough, hearing damage or mortality. For example, fish kills have been reported in the vicinity of pile-driving activities (Caltrans, 2001; Longmuir and Lively, 2001).

The National Research Council (2000) reviewed studies that demonstrated a wide range of susceptibilities to exposure-induced hearing damage among different marine species. The implications are that critical sound levels will not be able to be extrapolated from studies of a few species (although a set of representative species might be identified), and it will not be possible to identify a single sound level value at which damage to the auditory system will begin in all, or even most, marine mammals. Participants in a recent National Oceanic and Atmospheric Administration (NOAA) workshop (Boehlert et al., 2008) suggested that sounds that are within the range of hearing and "sweep" in frequency are more likely to disturb marine mammals than constant-frequency sounds. Thus, devices that emit a constant frequency may be preferable to ones that vary. They believed that the same may be true, although perhaps to a lesser extent, for sounds that change in amplitude.

Moore and Clarke (2002) compiled information on the reactions of gray whales (*Eschrichtius robustus*) to noise associated with offshore oil and gas development and vessel traffic. Gray whale responses included changes in swim speed and direction to avoid the sound sources, abrupt but temporary cessation of feeding, changes in calling rates and call structure, and changes in surface behavior. They reported a 0.5 probability of avoidance when continuous noise levels exceeded about 120 dB re 1 μPa and when intermittent noise levels exceeded about 170 dB re 1 μPa. They found little evidence that gray whales travel far or remain disturbed for long as a result of noises of this nature

Weilgart (2007) reviewed the literature on the effects of ocean noise on cetaceans (whales, dolphins, porpoises), focusing on underwater explosions, shipping, seismic exploration by the oil and gas industries, and naval sonar operations. She noted that strandings and mortalities of cetaceans have been observed even when estimated received sound levels were not high enough to cause hearing damage. This suggests that a change in diving patterns may have resulted in injuries due to gas and fat emboli (a fat droplet that enters the blood stream). That is, aversive noise may prompt cetaceans to rise to the surface too rapidly, and the rapid decompression causes nitrogen gas supersaturation and the subsequent formation of bubbles (emboli) in their tissues (Fernandez et al., 2005). Other adverse (but not directly lethal) impacts could include increase stress levels, abandonment of important habitats, masking of important sounds, and changes in vocal behavior that may lead to reduced foraging efficiency or mating opportunities. Weilgart (2007) pointed out that responses of cetaceans to ocean noise are highly variable among species, age classes, and behavioral states, and many examples of apparent tolerance of noise have been documented.

Nowacek et al. (2007) reviewed the literature on the behavioral, acoustic, and physiological effects of anthropogenic noise on cetaceans and concluded that the noise sources of primary concern are ships, seismic exploration, sonars, and some acoustic harassment devices (AHDs) that are employed to reduce the by-catch of small cetaceans and seals by commercial fishing gear.

Two marine mammals whose hearing and susceptibility to noise have been studied are the harbor porpoise (*Phocoena phocoena*) and the harbor seal (*Phoca vitulina*). Both species inhabit shallow coastal waters in the north Atlantic and North Pacific. Harbor porpoises are found as far south as Central California on the West Coast. The hearing of the harbor porpoise ranges from below 1 kHz to around 140 kHz. In the United States, harbor seals range from Alaska to Southern California on the West Coast, and as far south as South Carolina on the East Coast. Harbor seal hearing ranges from less than 0.1 kHz to around 100 kHz (Thomsen et al., 2006). Sounds produced by marine energy devices that are outside of these frequency ranges would not be detected by these species.

Thomsen et al. (2006) compared the underwater noise associated with pile driving to the audiograms of harbor porpoises and harbor seals and concluded that pile-driving noise would likely be detectable at least 80 km away from the source. The zone of masking (the area within which the noise is strong enough to interfere with the detection of other sounds) may differ between the two species. Because the echolocation (sonar) used by harbor porpoises is in a frequency range (120 to 150 kHz) where pile-driving noises have little or no energy, they considered masking of echolocation to be unlikely. On the other hand, harbor seals communicate at frequencies ranging from 0.2 to 3.5 kHz, which is within the range of the highest pile-driving sound pressure levels; thus, harbor seals may have their communications masked at considerable distances by pile-driving activities.

The responses of green turtles (*Chelonia mydas*) and loggerhead turtles (*Caretta caretta*) to the sounds of air guns used for marine seismic surveys were studied by McCauley et al. (2000a,b). They found that above a noise level of 166 dB re 1 μPa rms the turtles noticeably increased their swimming activity, and above 175 dB re 1 μPa rms their behavior became more erratic, possibly indicating that the turtles were in an agitated state. On the other hand, Weir (2007) was not able to detect an impact on turtles of the sounds produced by air guns in geophysical seismic surveys. Caged squid (*Sepioteuthis australis*) showed a strong startle response to an air gun at a received level of 174 dB re 1 μPa rms. When sound levels were ramped up (rather than a sudden nearby startup), the squid showed behavioral responses (e.g., rapid swimming) at sound levels as low as approximately 156 dB re 1 μPa rms but did not display the startle response seen in the other tests.

Hastings and Popper (2005) reviewed the literature on the effects of underwater sounds on fish, particularly noises associated with pile driving. The limited number of quantitative studies found evidence of changes in the hearing capabilities of some fish, damage to the sensory structure of the inner ear, or, for fish close to the sources, mortality. They concluded that the body of scientific and commercial data is inadequate to develop more than the most preliminary criteria to protect fish from pile-driving sounds and suggested the types of studies that could be conducted to address the information gaps. Similarly, Viada et al. (2008) found very little information on the

potential impacts on sea turtles of underwater explosives. Although explosives produce greater sound pressures than pile driving and are unlikely to be used in most ocean energy installations, studies of their effects provide general information about the peak pressures and distances that have been used to establish safety zones for turtles.

Wahlberg and Westerberg (2005) compared source level and underwater measurements of sounds from offshore windmills to information about the hearing capabilities of three species of fish: goldfish, Atlantic salmon, and cod. They predicted that these fish could detect offshore windmills at a maximum distance of about 0.4 to 25 km, depending on wind speed, type and number of windmills, water depth, and substrate. They could find no evidence that the underwater sounds emitted by windmill operation would cause temporary or permanent hearing loss in these species, even at a distance of a few meters, although sound intensities might cause permanent avoidance within ranges of about 4 m. They noted that shipping causes considerably higher sound intensities than operating windmills (although the noise from shipping is transient), and noises from installation may have much more significant impacts on fish than those from operation.

In the Environmental Assessment of the proposed Wave Energy Technology (WET) Project, the Department of the Navy (2003) considered the sounds made by hydraulic rock drilling to be detectable by humpback whales, bottlenose dolphins, Hawaiian spinner dolphins, and green sea turtles. Assuming a transmission loss due to spherical spreading, drilling sound pressure levels of 160 dB re 1 μPa would decrease by about 40 dB at 100 m from the source. They regarded a SPL of 120 dB re 1 μPa to be below the level that would affect these four species. In fact, they reported that other construction activities involving similar drilling attracted marine life (fish and sea turtles, in particular), perhaps because bottom organisms were stirred up by the drilling.

There are considerable information gaps regarding the effects of noise generated by marine and hydrokinetic energy technologies on cetaceans, pinnipeds, turtles, and fish. Sound levels from these devices have not been measured, but it is likely that installation will create more noise than operation, at least for those technologies that require pile driving. Operational noise from generators, rotating equipment, and other moving parts may have frequencies and magnitudes comparable to those measured at offshore wind farms; however, the underwater noise created by a wind turbine is transmitted down through the pilings, whereas noises from marine and hydrokinetic devices are likely to be greater because they are at least partially submerged. It is probable that noise from marine energy projects may be less than the intermittent noises associated with shipping and many other anthropogenic sound sources (e.g., seismic exploration, explosions, commercial, naval sonar).

The resolution of noise impacts will require information about the device's acoustic signature (e.g., sound pressure levels across the full range of frequencies) for both individual units and multiple-unit arrays, similar characterization of ambient (background) noise in the vicinity of the project, the hearing sensitivity (e.g., audiograms) of fish and marine mammals that inhabit the area, and information about the behavioral response to anthropogenic noise (e.g., avoidance, attraction, changes in schooling behavior or migration routes). Simmonds et al. (2003) described the types of *in situ* monitoring that could be carried out to develop information on the effects of underwater noise arising from a variety of activities. The studies include monitoring

marine mammal activity in parallel with sound level monitoring during construction and operation. Baseline sound surveys would be needed against which to measure the added effects of energy generation. It will be important to measure the acoustic characteristics produced by both single units and multiple units in an array, due to the possibility of synchronous or asynchronous, additive noise produced by the array (Boehlert et al., 2008). Minimally, the operational monitoring would quantify the sound pressure levels across the entire range of sound frequencies for a variety of ocean and river conditions in order to assess how meteorological, current strength, and wave height conditions affect sound generation and sound masking. The monitoring effort should consider the effects of marine fouling on noise production, particularly as it relates to mooring cables.

Impacts of Electromagnetic Fields

Underwater cables will be used to transmit electricity between turbines in an array (inter-turbine cables), between the array and a submerged step-up transformer (if part of the design), and from the transformer or array to the shore (CMACS, 2003). Ohman et al. (2007) categorized submarine electric cables into the following types: telecommunications cables; high-voltage, direct-current (HVDC) cables; alternating-current, three-phase power cables; and low-voltage cables. All types of cable will emit electromagnetic fields (EMFs) in the surrounding water. The electric current traveling through the cables will induce magnetic fields in the immediate vicinity, which can in turn induce a secondary electrical field when animals move through the magnetic fields (CMACS, 2003).

Nature of the Underwater Electromagnetic Field

In 1819, Hans Christian Oersted, a Danish scientist, discovered that a field of magnetic force exists around a single wire conductor carrying an electric current. The electromagnetic field created by electric current passing through a cable is composed of both an electric field (E field) and an induced magnetic field (B field). Although E fields can be contained within undamaged insulation surrounding the cable, B fields are unavoidable and will in turn induce a secondary electric field (iE field). Thus, it is important to distinguish between the two constituents of the EMF (E and B) and the induced field (iE) (Figure 7.10). Because the electric field is a measure of how the voltage changes when a measurement point is moved in a given direction, E and iE are expressed as volts/meter (V/m).

The intensity of a magnetic field can be expressed as magnetic field strength or magnetic flux density (CMACS, 2003). The magnetic field can be visualized as field lines, and the field strength (measured in amperes/meter [A/m]) corresponds to the density of the field lines. Magnetic flux density is a measure of the density of magnetic lines or force, or magnetic flux lines, passing through an area. Magnetic flux density (measured in teslas [T]) diminishes with increasing distance from a straight current-carrying wire. At a given location in the vicinity of a current-carrying wire, the magnetic flux density is directly proportional to the current in amperes. Thus, the magnetic field B is directly linked to the magnetic flux density that is flowing in a given direction.

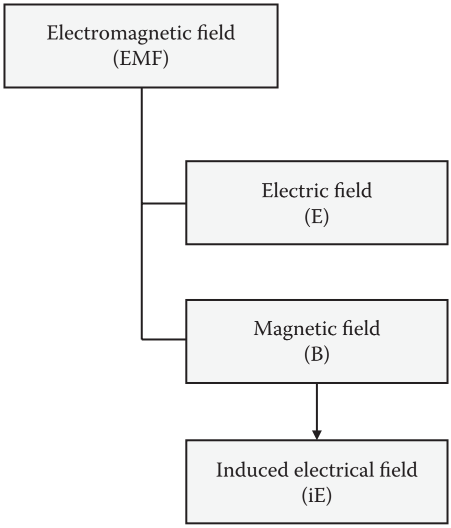

FIGURE 7.10 Simplified view of the fields associated with submarine power cables. (Adapted from Gill, A.B. et al., *COWRIE 1.5 Electromagnetic Fields Review: The Potential Effects of Electromagnetic Fields Generated by Sub-Sea Power Cables Associated with Offshore Wind Farm Developments on Electrically and Magnetically Sensitive Marine Organisms—A Review*, COWRIE–EM Field 2-06-2004, Cranfield University, Cranfield, U.K., 2005.)

When electricity flows (electron flow) through the wire in a cable, every section of the wire has this field of force around it in a plane perpendicular to the wire, as shown in Figure 7.11. The strength of the magnetic field around a wire (cable) carrying a current depends on the current, because it is the current that produces the field. The greater the current flow in a wire, the greater the strength of the magnetic field. A large current will produce many lines of force extending far from the wire, whereas a small current will produce only a few lines close to the wire, as shown in Figure 7.12.

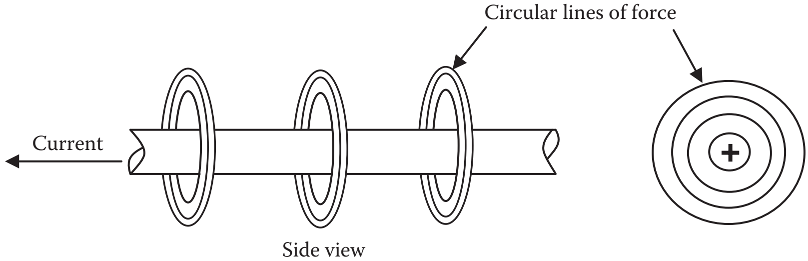

FIGURE 7.11 Circular fields of force around a wire carrying a current are in planes perpendicular to the wire.

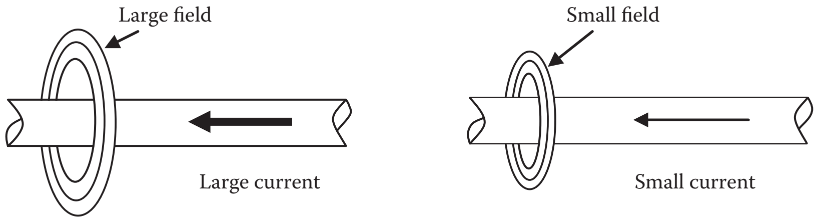

FIGURE 7.12 The strength of the magnetic field around a wire carrying a current depends on the amount of current.

The EMFs associated with new marine and hydrokinetic energy designs have not been quantified; however, there is considerable experience with submarine electrical transmission cables, with some predictions and measurements of their associated electrical and magnetic fields. For example, the Wave Energy Technology (WET) generator in Hawaii will be housed in a canister buoy and connected to shore by a 1190-m-long, 6.5-cm-diameter electrical cable. The cable is designed for three-phase AC transmission, can carry up to 250 kW, and has multiple layers of insulation and armoring to contain the electrical current. Depending on current flow (amperage), at 1 m from the cable, the magnetic field strength was predicted to range from 0.1 to 0.8 A/m and the magnetic flux density would range from 0.16 to 1.0 μT. The estimated strength of the electric field at the surface of the cable (apparently the iE) would range from 1.5 to 10.5 mV/m. The electric field strength, magnetic field strength, and magnetic flux density would all decrease exponentially with distance from the cable.

The Centre for Marine and Coastal Studies (CMACS, 2003) surveyed cable manufacturers and independent investigators to compile estimates of the magnitudes of E, B, and iE fields. Most agreed that the E field can be completely contained within the cable by insulation. Estimates of the B field strength ranged from 0 (by one manufacturer) to 1.7 and 0.61 μT at distances of 0 and 2.5 m from the cable, respectively. By comparison, the Earth's geomagnetic field strength ranges from approximately 20 to 75 μT (Bochert and Zettler, 2006). In another study cited by CMACS (2003), a 150-kV cable carrying a current of 600 A generated an induced electric field (iE) of more than 1 mV/m at a distance of 4 m from the cable; the field extended for approximately 100 m before dissipating. Lower voltage/amperage cables generated similarly large iE fields near the cable, but the fields dissipated much more rapidly with distance.

For short-distance undersea transmission of electricity, three-phase AC power cables are most common; HVDCs are used for longer distance, high-power applications (Ohman et al., 2007). In AC cables the voltage and current alternate sinusoidally at a given frequency (50 or 60 Hz); therefore, the E and B fields are also time varying. That is, like AC current, the magnetic field induced by a three-phase AC current has a cycling polarity, which is not like the natural geomagnetic fields. On the other hand, the E and B fields produced by a direct-current cable (e.g., HVDC) are static. Because the magnetic fields induced by DC and AC cables are different, they are likely to be perceived differently by aquatic organisms.

Because neither sand nor seawater has magnetic properties, burying a cable will not affect the magnitude of the magnetic (B) field; that is, the B fields at the same distance from the cable are identical, whether in water or sediment (CMACS, 2003). On the other hand, due to the higher conductivity of seawater compared to sand, the iE field associated with a buried cable is discontinuous across the sand/water boundary; the iE field strength is greater in water than in sand at a given distance from the cable. For example, for the three-phase AC cable modeled by CMACS (2003), the estimated iE field strengths at 8 m from the cable were 10 μV/m and 1 to 2 μV/m in water and sand, respectively.

The EMF generated by a multi-unit array of marine or hydrokinetic devices will differ from EMFs associated with a single unit or from the single cable sources that have been surveyed. Depending on the power generation device, a project may have electrical cable running vertically through the water column in addition to multiple cables running along the seabed or converging on a subsea pod. The EMF created by a matrix of cables has not been predicted or quantified.

Effects of Electromagnetic Fields on Aquatic Organisms

Electrical Fields

Natural electric fields can occur in the aquatic environment as a result of biochemical, physiological, and neurological processes within an organism or as a result of an organism swimming through a magnetic field (Gill et al., 2005). Some of the elasmobranchs (e.g., sharks, skates, rays) have specialized tissues that enable them to detect electric fields (i.e., electroreception), an ability that allows them to detect prey and potential predators and competitors. Two species of Asian sturgeon have been reported to alter their behavior in changing electric fields (Basov, 1999, 2007). Other fish species (e.g., eels, cod, Atlantic salmon, catfish, paddlefish) respond to induced voltage gradients associated with water movement and geomagnetic emissions (Collin and Whitehead, 2004; Wilkens and Hofmann, 2005), but their electrosensitivity does not appear to be based on the same mechanism as sharks (Gill et al., 2005).

Balayev and Fursa (1980) observed the reaction of 23 species of marine fish to electric currents in the laboratory. Visible reactions occurred following exposure to electric fields ranging from 0.6 to 7.2 V/m and varied depending on the species and orientation to the field. They noted that changes in the fishes' electrocardiograms occurred at field strengths 20 times lower than those that elicited observable behavioral response. Enger et al. (1976) found that European eels (*Anguilla anguilla*) exhibited a decelerated heart rate when exposed to a direct current electrical field with a voltage gradient of about 400 to 600 μV/cm. In contrast, Rommel and McCleave (1972) observed much lower voltage thresholds of response (0.07 to 0.67 μV/cm) in American eels (*Anguilla rostrata*). The eels' electrosensitivity measured by Rommel and McCleave is well within the range of naturally occurring oceanic electric fields of at least 0.10 μV/cm in many currents in the Atlantic Ocean and up to 0.46 μV/cm in the Gulf Stream.

Kalmijn (1982) described the extreme sensitivity of some elasmobranchs to electric fields. For example, the skate (*Raja clavata*) exhibited cardiac response to uniform square-wave fields of 5 Hz at voltage gradients as low as 0.01 μV/cm. Dogfish (*Mustelus canis*) initiated attacks on electrodes from distances in excess of 38 cm and voltage gradients as small as 0.005 μV/cm.

Marra (1989) described the interactions of elasmobranchs with submarine optical communications cables. The cable created an iE field (1 μV/m at 0.1 m) when sharks crossed the magnetic field induced by the cable. The sharks responded by attacking and biting the cable. Marra (1989) was unable to identify the specific stimuli that elicited the attacks but suggested that at close range the sharks interpreted the electrical stimulus of the iE field as prey, which they then attacked.

The weak electric fields produced by swimming movements of zooplankton can be detected by juvenile freshwater paddlefish (*Polyodon spathula*). Wojtenek et al. (2001) used dipole electrodes to create electric fields that simulated those created by water flea (*Daphnia* sp.) swimming. They tested the effects of alternating current oscillations at frequencies ranging from 0.1 to 50 Hz and stimulus intensities ranging from 0.125 to 1.25 μA peak-to-peak amplitude. Paddlefish made significantly more feeding strikes at the electrodes at sinusoidal frequencies of 5 to 15 Hz compared to lower and higher frequencies. Similarly, the highest strike rate occurred at the intermediate electric field strength (stimulus intensity of 0.25 μA peak-to-peak amplitude). Strike rate was reduced at higher water conductivity, and the fish habituated (ceased to react) to repetitive dipole stimuli that were not reinforced by prey capture.

Gill and Taylor (2002) carried out a pilot study of the effects on dogfish of electric fields generated by a DC electrode in a laboratory tanks. They reported that the dogfish avoided constant electric fields as small as 1000 μV/m, which would be produced by 150 kV cables with a current of 600 A. Conversely, the dogfish were attracted to a field of 10 μV/m at 0.1 m from the source, which is similar to the bioelectric fields emitted by dogfish prey. The electrical field created by the three-phase, AC cable modeled by CMACS (2003) would likely be detectable by a dogfish (or other similarly sensitive elasmobranch) at a radial distance of 20 m. It is possible that the ability of fish to discriminate an electrical field is a function of not only the size and intensity but also the frequency (Hz) of the emitted field.

Like elasmobranchs, sturgeon (closely related to paddlefish) can utilize electroreceptor senses to locate prey and may exhibit varying behavior at different electric field frequencies (Basov, 1999). For this reason, electrical fields are a concern as they may impact migration or ability to find prey. The National Marine Fisheries Service (NMFS, 2008) proposed designating critical habitat for the Southern Distinct Population Segment of the threatened North American green sturgeon (*Acipenser medirostris*) along the coastline out to the 110-m isobath line. One of the principal elements in the proposal is safe passage along the migratory corridor. Green sturgeons migrate extensively along the nearshore coast from California to Alaska, and there is concern that these fish may be deterred from migration by either low-frequency sounds or electromagnetic fields created during operation of marine energy facilities.

Magnetic Fields

Many terrestrial and aquatic animals can sense the Earth's magnetic field and appear to use this magnetosensitivity for long-distance migrations. Aquatic species whose long-distance migrations or spatial orientation appear to involve magnetoreception include eels (Westerberg and Begout-Anras, 2000), spiny lobsters (Boles and Lohmann, 2003), elasmobranchs (Kalmijn, 2000), sea turtles (Lohmann and Lohmann, 1996), rainbow trout (Walker et al., 1997), tuna, and cetaceans (Lohmann

et al., 2008a; Wiltschko and Wiltschko, 1995). Four species of Pacific salmon were found to have crystals of magnetite within them, and it is believed that these crystals serve as a compass that orients to the Earth's magnetic field (Mann et al., 1988; Walker et al., 1988). Because some aquatic species use the Earth's magnetic field to navigate or orient themselves in space, there is a potential for the magnetic fields created by the numerous electrical cables associated with offshore power projects to disrupt these movements.

Gill et al. (2005) placed magnetosensitive organisms into two categories: (1) those able to detect the iE field caused by movement through a natural or anthropogenic magnetic field, and (2) those with detection systems based on ferromagnetic minerals (i.e., magnetite or greigite). Johnsen and Lohmann (2005, 2008) add a third possible mechanism for magnetosensitivity—chemical reactions involving proteins known as crytochromes (i.e., a class of flavoproteins that are sensitive to blue light and are involved in circadian rhythm entrainment in plants, insects, and mammals). Those species using the iE mode may do it either passively (i.e., the animal estimates its drift from the electric fields produced by the interaction between tidal/wind-driven currents and the vertical component of the Earth's magnetic field) or actively (i.e., the animal derives its magnetic compass heading from its own interaction with the horizontal component of the Earth's magnetic field). For example, Kalmijn (1982) suggested that the electric fields that elasmobranchs induce by swimming through the Earth's magnetic field may allow them to detect their magnetic compass headings; the resulting voltage gradients may range from 0.05 to 0.5 μV/cm. Detection of a magnetic field based on internal deposits of magnetite occurs in a wide range of animals, including birds, insects, fish, sea turtles, and cetaceans (Bochert and Zettler, 2006; Gould, 1984). There is no evidence to suggest that seals are sensitive to magnetic fields (Gill et al., 2005).

Westerberg and Begout-Aranas (2000) studied the effects of a B field generated by a HVDC power cable on eels (*Anguilla anguilla*). The B field was on the same order of magnitude as the Earth's geomagnetic field and, coming from a DC cable, was also a static field. Approximately 60% of the 25 eels tracked crossed the cable, and the authors concluded that the cable did not appear to act as a barrier to the eel migration. In another behavioral study, Meyer et al. (2004) showed that conditioned sandbar and scalloped hammerhead sharks readily respond to localized magnetic fields of 25 to 100 μT, a range of values that encompasses the strength of the Earth's magnetic field.

Some sea turtles (see Sidebar 7.1) undergo transoceanic migrations before returning to nest on or near the same beaches where they were hatched. Lohmann and Lohmann (1996) showed that sea turtles have the sensory abilities necessary to approximate their global position of a magnetic map. This would allow them to exploit unique combinations of magnetic field intensity and field line inclination in the ocean environmental to determine direction and/or position during their long-distance migrations. Irwin and Lohmann (1996) found that magnetic orientation in loggerhead sea turtles (*Caretta caretta*) can be disrupted at least temporarily by strong magnetic pulses (i.e., five brief pulses of 40,000 μT with a 4-ms rise time). The impact of a changed magnetic environment would depend on the role of magnetic information in the hierarchy of cues used to orient and navigate (Wiltschko and Wiltschko, 1995). Juvenile loggerheads deprived of either magnetic or visual

information were still able to maintain a direction of orientation, but when both cues were removed the turtles were disoriented (Avens and Lohmann, 2003). The magnetic map sense exhibited by hatchlings is also thought to allow female sea turtles to imprint upon the location of their natal beaches so that later in life they can return there to nest. This phenomenon is termed *natal homing* (Lohmann et al., 2008b), and it serves to drive genetic division among subpopulations of the same species. As a result, altering magnetic fields near nesting beaches could potentially result in altered nesting patterns. Given the important role of magnetic information in the movements of sea turtles, impacts of magnetic field disruption could range from minimal (i.e., temporary disorientation near a cable or structure) to significant (i.e., altered nesting patterns and corresponding demographic shifts resulting from large-scale magnetic field changes) and should be carefully considered when siting projects.

SIDEBAR 7.1. With Regard to Turtles

Marine turtles have outlived almost all of the prehistoric animals with which they once shared the planet. Five species of marine turtles frequent the beaches and offshore waters of the southeastern United States:

- *Loggerhead turtles* are the most common turtles to nest in Florida. Over 50,000 loggerhead nests are recorded annually in Florida. This turtle is named for its disproportionately large head, and it feeds on crabs, mollusks, and jellyfish.
- *Green sea turtles* are the second most common turtles in Florida waters. Green sea turtles are the only herbivorous sea turtles. They feed on seagrasses in shallow areas through the Gulf. The lower jaw is serrated to help cut the seagrasses it eats.
- *Kemp's ridley sea turtles* are the rarest sea turtles in the world. They primarily nest on one beach on the Gulf Coast of Mexico and are the smallest species of sea turtle. Scientists have been trying to transplant Kemp's ridley eggs to Texas to establish a new nesting colony. They are the only species of sea turtle known to lay their eggs during the day.
- *Leatherback sea turtles* are the largest sea turtles in the world; they can be over 6 feet long and weigh 1400 pounds. The leatherback does not have a hard shell, but rather a leather-like carapace with bony ridges underneath the skin. The leatherback makes long migrations to and from its nesting beaches in the tropics as far north as Canada. Jellyfish are the favored prey for these turtles.
- *Hawksbill sea turtles* are usually found feeding primarily on sponges in the southern Gulf of Mexico and Caribbean. The hawksbill sea turtle was hunted to near extinction for its beautiful shell which features overlapping scales.

All five are reported to nest, but only the loggerhead and green turtle do so in substantial numbers. Most nesting occurs from southern North Carolina to the middle west coast of Florida, but scattered nesting occurs from Virginia through southern Texas. The beaches of Florida, particularly in Brevard and Indian River counties, host what may be the world's largest population of loggerheads (Dodd, 1995).

Marine turtles, especially juveniles and subadults, use lagoons, estuaries, and bays as feeding grounds. Areas of particular importance include Chesapeake Bay, Virginia (for loggerheads and Kemp's ridleys); Pamlico Sound, North Carolina (for loggerheads); and Mosquito Lagoon, Florida, and Laguna Madre, Texas (for greens). Offshore waters also support important feeding grounds such as Florida Bay and the Cedar Keys, Florida (for green turtles), and the mouth of the Mississippi River and the northeast Gulf of Mexico (for Kemp's ridleys).

Offshore reefs provide feeding and resting habitat (for loggerheads, greens, and hawksbills), and offshore currents, especially the Gulf Stream, are important migratory corridors (for all species, but especially leatherbacks).

Note: Raccoons destroy thousands of sea turtle eggs each year and are the single greatest cause of sea turtle mortality in Florida.

Most marine turtles spend only part of their lives in U.S. waters. For example, hatchling loggerheads ride oceanic currents and gyres (giant circular oceanic surface currents) for many years before returning to feed as subadults in southeastern lagoons. They travel as far as Europe and the Azores, and even enter the Mediterranean Sea, where they are susceptible to longline fishing mortality. Adult loggerheads may leave U.S. waters after nesting and spend years in feeding grounds in the Bahamas and Cuba before returning. Nearly the entire world population of Kemp's ridleys uses a single Mexican beach for nesting, although juveniles and subadults, in particular, spend much time in U.S. offshore waters (Dodd, 1995).

The biological characteristics that make sea turtles difficult to conserve and manage include a long life span, delayed sexual maturity, differential use of habitats among species and over the turtles' life stages, adult migratory travel, high egg and juvenile mortality, concentrated nesting, and vast areal dispersal of young and subadults. Genetic analyses have confirmed that females of most species return to their natal beaches to nest (Bowen et al., 1992, 1993). Nesting assemblages contain unique genetic markers showing a tendency toward isolation from other assemblages (Bowen et al., 1993); thus, Florida green turtles are genetically different from green turtles nesting in Costa Rica and Brazil (Bowen et al., 1992). Nesting on warm sandy beaches puts the turtles in direct conflict with human beach use, and their use of rich offshore waters subjects them to mortality from commercial fisheries (National Research Council, 1990).

Marine turtles have suffered catastrophic declines since the European discovery of the New World (National Research Council, 1990). In a relatively short time, the huge nesting assemblages in the Cayman Islands, Jamaica, and Bermuda were decimated. In the United States, commercial turtle fisheries once operated in south Texas (Doughty, 1984) and in Cedar Keys, the Florida Keys, and Mosquito Lagoon in Florida; these fisheries collapsed from overexploitation of the mostly juvenile green turtle populations. Today, marine turtle populations are threatened worldwide and are under intense pressure in the Caribbean basin and Gulf of Mexico, including Cuba, Mexico, Hispaniola, Bahamas, and Nicaragua. Marine turtles can be conserved only through international efforts and cooperation (Dodd, 1995).

A number of interesting questions related to turtle migration remain unanswered. For example, how do turtles find their way precisely back to their natal beach over their vast travel distance? Do turtles imprint, as salmon do, on olfactory features in the water or is the location pinpointed using geomagnetic information?

Sea turtles have migration patterns somewhat similar to that of salmon. After hatching and entering the sea and facing and surviving the tribulations presented by the elements and predators, and after spending time in their sea feeding grounds, the females return to their natal grounds. Adult females lay eggs in the sand. Turtles may use the geomagnetic field to tell them their location and to lead them to their natal grounds (Goff et al., 1998).

The emphasis of most of these studies is on the value of magnetoreception for navigation; marine and hydrokinetic energy technologies are unlikely to create magnetic fields strong enough to cause physical damage. For example, Bochert and Zettler (2006) summarized several studies on the potential injurious effects of magnetic fields on marine organisms. They subjected several marine benthic species (i.e.,

flounder, blue mussel, prawn, isopods, and crabs) to static (DC-induced) magnetic fields of 3700 μT for several weeks and detected no differences in survival compared to controls. In addition, they exposed shrimp, isopods, echinoderms, polychaetes, and young flounder to a static, 2700 μT magnetic field in laboratory aquaria where the animals could move away from or toward the source of the field. At the end of the 24-hour test period, most of the test species showed a uniform distribution relative to the source, not significantly different from controls. Only one of the species, the benthic isopod *Saduria entomon*, showed a tendency to leave the area of the magnetic field. The oxygen consumption of two North Sea prawn species exposed to both static (DC) and cycling (AC) magnetic fields were not significantly different from controls. Based on these limited studies, Bochert and Zettler (2006) could not detect changes in marine benthic organisms' survival, behavior, or physiological response parameters (e.g., oxygen consumption) resulting from magnetic flux densities that might be encountered near an undersea electrical cable.

The current state of knowledge about the EMF emitted by submarine power cables is too variable and inconclusive to make an informed assessment of the effects on aquatic organisms (CMACS, 2003). Following a thorough review of the literature related to EMFs and extensive contacts with the electrical cable and offshore wind industries, Gill et al. (2005) concluded that there are significant gaps in our knowledge regarding the sources and effects of electrical and magnetic fields in the marine environment. They recommended developing information about likely electrical and magnetic field strengths associated with existing sources (e.g., telecommunications cables, power cables, electrical heating cables for oil and gas pipelines), as well as the generating units, offshore substations and transformers, and submarine cables that are a part of offshore renewable energy projects. They cautioned that networks of cables in close proximity to each other (as would be substations) are likely to have overlapping, and potentially additive, EMF fields. These combined EMF fields would be more difficult to evaluate than those emitted from a single, electrical cable. The small, time-varying B field emitted by a submarine three-phase AC cable may be perceived differently by sensitive marine organisms than the persistent, static, geomagnetic field generated by the Earth (CMACS, 2003).

Toxic Effects of Chemicals

Chemicals that are accidentally or chronically released from hydrokinetic and ocean energy installations could have toxic effects on aquatic organisms. Accidental releases include leaks of hydraulic fluids from a damaged unit or fuel from a vessel due to a collision with the unit; such events are unlikely but could potentially have a high impact (Boehlert et al., 2008). On the other hand, chronic releases of dissolved metals or organic compounds used to control biofouling in marine applications would result in low, predictable concentrations of contaminants over time. Even at low concentrations that are not directly lethal, some contaminants can cause sublethal effects on the sensory systems, growth, and behavior of animals; they may also be bioaccumulated (i.e., filter feeders such as limpets, oysters, and other shellfish concentrate heavy metals or other stable compounds present in dilute concentrations in seawater or freshwater).

Toxicity of Paints, Antifouling Coatings, and Other Chemicals

Biofouling (growth on external surfaces by algae, barnacles, mussels, and other marine organisms) will occur rapidly in ocean applications (Langhamer, 2005; Wilhelmsson and Malm, 2008). Sundberg and Langhamer (2005) observed that a 3-m-diameter buoy may accumulate as much as 300 kg of biomass on the buoy and mooring cables, whereas siting devices in deeper water with even slight currents will exhibit reduced biofouling. The encrustation of biofouling organisms could cause undesirable mechanical wear or changes in the weight, shape, and performance of energy conversion devices that would require increased maintenance or the application of antifouling measures. Encrustation by barnacles and other organisms could increase corrosion and fatigue and decrease electrical generating efficiency.

There are three options for removing marine biofouling: (1) use of antifouling coatings, (2) *in situ* cleaning using a high-pressure jet spray, and (3) removal of the device from the water for cleaning on a floating platform or onshore (Michel et al., 2007). Antifouling coatings hinder the development of marine encrustations by slowly releasing a biocide such as tribuyltin (TBT), copper, or arsenic. As the coatings wear away, they must be reapplied periodically. There are concerns about the immediate toxicity of these biocides to other, non-targeted organisms, and numerous countries and organizations have called for the ban of TBT as an antifouling coating (Antizar-Ladislao, 2008). As a result, alternative coatings are being explored. The release of toxic contaminants from a single unit may be relatively minor, but the cumulative impacts of persistent toxic compounds from dozens or hundreds of units may be considerable (Boehlert et al., 2008). Accumulations of biofouling organisms (e.g., barnacles) removed from the project structures may alter nearby bottom substrates and habitats.

Accidental releases of hydraulic fluids and lubricating oils from inside the energy conversion device or from vessels used to install and service the equipment could have toxic effects. At the least, leaks of inert (non-toxic) oils could cause physical/mechanical effects by coating organisms and blanketing the sediments.

Interference with Animal Movements

Energy developments will add new structures to rivers and oceans that may affect the movements and migrations of aquatic organisms. Hydrokinetic devices, and their associated anchors and cables in a river, could attract or repel animals or interfere with their movements. In addition to seabed structures (e.g., anchors, turbines), many of the ocean energy devices would use mooring lines to attach a floating generator to the ocean bottom and electrical transmission lines to connect multiple devices to each other and to the shoreline. For example, the Minerals Management Service (2007) estimated that wave energy facilities may have as many as 200 to 300 mooring lines securing the wave energy devices to the ocean floor (based on 2 to 3 mooring lines per device and a 100-device facility). Mooring and transmission lines that extend from a floating structure to the ocean floor will create new fish attraction devices in the pelagic zone (i.e., the entire water column of the water body), pose a threat of collision for entanglement to some organisms, and potentially alter both local movements and long-distance migrations of marine animals (Nelson, 2008;

Thompson et al., 2008). Because the transport of planktonic (drifting) life stages is affected by water velocity (DiBacco et al., 2001; Epifanio, 1988), localized reduction of water velocities by large, multi-unit projects could influence recruitment of some species. A variety of aquatic organisms use magnetic, chemical, and hydrodynamic cues for navigation (Cain et al., 2005; Loghmann et al., 2008a). Thus, in addition to mechanical obstructions, the electrical and magnetic fields and current and wave alterations produced by energy technologies could interfere with local movement or long-distance migrations.

Alteration of Local Movement Patterns

Anchors and other permanent structures on the bottom will create new habitats and thus may act as artificial reefs (Wilhelmsson et al., 2006). Artificial reefs are often constructed in order to increase fish production, but some studies suggest that they may be less effective than natural reefs (Carr and Hixon, 1997) and that they may even have deleterious effects on reef fish populations by stimulating overfishing and overexploitation (Grossman et al., 1997).

Similarly, new structures in the pelagic zone (e.g., pilings or mooring cables for floating devices) will create habitat that may act as fish aggregation/attraction devices (FADs). These devices are extremely effective in concentrating fish and making them susceptible to harvest (Dempster and Tacquet, 2004; Michel et al., 2007; Myers et al., 1986). Sea turtles are also known to be attracted to floating objects (Arenas and Hall, 1992). Fish are attracted to the devices as physical structures/shelter, and they may feed on organisms attached to the structures (Boehlert et al., 2008). Artificial lighting used to distinguish structures at night may also attract aquatic organisms.

The aggregation of predators near FADs may adversely affect juvenile salmonids or Dungeness crabs moving through the project area. Wilhelmsson et al. (2006) found that fish abundance in the vicinity of monopiles that supported wind turbines was greater than in surrounding areas, although species richness and diversity were similar. Most of the fish they observed near the structure were small (juvenile gobies), which may in turn attract commercially important fish looking for prey. Dempster (2005) observed considerable temporal variability in the abundance and diversity of fish associated with FADs moored between 3 and 10 km offshore. The variability was often related to the seasonal appearance of large schools of juvenile fish. Fish assemblages differed between times when predators were present or absent; few small fishes were observed near the FADs when predators were present, regardless of the season. Using FADs as an experimental tool, Nelson (2003) found that fish formed larger, more species-rich assemblages around large FADs compared to small ones, and they formed larger assemblages around FADs with fouling biota. Devices enriched with fish accumulated additional recruits more quickly than those in which fish were removed.

It is likely that floating wave energy devices will act as FADs, but the effect on fish populations may be difficult to determine. FADs are attractive to fish because they provide food and shelter (Castro et al., 2002); subsequently, they also attract predators (Dempster, 2005) that can in turn attract commercial and sport fisheries. Without well-designed monitoring, it will be difficult to determine whether an energy park will enhance populations of aquatic organisms (by providing more

habitat to support more fish), will have no overall effect (because it simply draws fish from other, nearby areas), or will decrease fish populations (by facilitating harvest by predators and fishermen). The determination of the effects of FADs at a particular location is complicated by the influence of non-independent factors: proximity of other FADs (e.g., other wave energy units), interconnection of multiple FADs to provide routes for the movement of associated fishes, and temporal dependence (the number of fish present at one sampling date influencing the number at the next sampling date due to fish becoming residents) (Kingsford, 1999). Statistical approaches that could be applied to experiments on the effects of FADs on fish populations and solutions to the independent factor problems were also described.

Because anchoring systems and mooring lines will likely exclude fishing activities, energy parks could serve as marine protected areas. The Pacific Fisheries Management Council (2008) expressed concerns related to the prohibition of commercial fishing at wave energy test areas and suggested that there may be either a reduction in total fishing effort and lost productivity or a displacement of fishing effort to areas outside the areas closed to fishing. Displaced fishermen would likely concentrate their efforts in areas immediately outside the wave park boundaries, resulting in increased pressures on fish and habitats in those nearby areas.

Floating offshore wave energy facilities could create artificial haul-out sites for marine mammals (pinnipeds). Devices with a low profile above the waterline (desirable for aesthetic reasons) may enable seals and sea lions to use them as a haul-out site, particularly if the installations attract the marine mammals by acting as fish-concentrating devices. NOAA considers the creation of such artificial haul-outs as undesirable and recommends the use of deterrents to discourage use by marine mammals.

Floating devices could potentially impede movements of floating marine habitat communities, such as *Sargassum* communities. Masses of floating *Sargassum* algae form unique communities of organisms that serve as important habitats for hatchling sea turtles and juvenile fish (Coston-Clements et al., 1991). Strong current from the Sargasso Sea in the middle of the Atlantic Ocean carry these *Sargassum* communities around the world.

Floating devices with above-water structures may attract seabirds by creating artificial roosting sites or encouraging predation on fish near the FAD (Michel et al., 2007). There is particular concern about collision injuries to marine birds that are attracted to lighted structures at night or in inclement weather (Boehlert et al., 2008; Thompson et al., 2008). Peterson et al. (2006) monitored the interactions of birds and above-water structures at a Danish offshore wind farm from 1999 to 2005 and found that birds generally avoided the wind farms by flying around them, although there were considerable differences among species. The monitoring data suggested that avoidance was reduced at night. The authors obtained few data under conditions of poor visibility because bird migrations slowed or ceased during such times. Birds typically showed avoidance responses to the rotating wind turbine blades. A stochastic model predicted very low rates of Eider collisions with the offshore wind turbines, and the predictions were confirmed by subsequent monitoring (Petersen et al., 2006). Desholm (2006) provided a series of papers that describe techniques for predicting and monitoring interactions of birds and wind turbine structures at sea.

Interference with Migratory Animals

The numerous floating and submerged structures, mooring lines, and transmission cables associated with large ocean energy facilities could interfere with the long-distance migrations of marine animals (e.g., juvenile and adult salmonids, Dungeness crabs, green sturgeon, elasmobranchs, sea turtles, marine mammals, birds) if they are sited along migration corridors. On the U.S. Pacific Coast, effects on gray whales (*Eschrichtius robustus*) may be of particular concern because they migrate within 2.8 km of the shore line. Boehlert et al. (2008) noted that buoys attached to commercial crab pots already represent a major existing risk to gray whales off the coast of Oregon. Lines associated with lobster pots and other fishing gear are a source of injury and mortality to endangered North Atlantic right whales (*Eubalaena glacialis*) on the East Coast of the United States (Caswell et al., 1999; Kraus et al., 2005). Many marine fish species drift or actively migrate long distances in the sea and may interact with ocean energy developments. Anadromous fish (e.g., green sturgeon, salmon, steelhead) and catadromous fish (e.g., eels) migrate through both rivers and oceans and therefore may encounter buoy hydrokinetic devices in the rivers and ocean energy projects (Dadswell et al., 1987).

Entanglement of large, planktonic jellyfish with long tentacles (as well as actively swimming sea turtles and marine mammals) is a potential issue for energy technologies with mooring lines in the pelagic zone. Thin mooring cables are expected to be more dangerous than thick ones because they are more likely to cause lacerations and entanglements, and slack cables are more likely to cause entanglements than taut ones (Boehlert et al., 2008).

Michel et al. (2007) observed that smaller dolphins and pinnipeds could easily move around mooring cables, but larger whales may have difficulty passing through an energy facility with numerous, closely spaced lines. Marine species with proportionately large pectoral fins or flippers may be relatively more vulnerable to mooring lines, based on information from humpback whale entanglements with pot and gill net lines (Johnson et al., 2005). Boehlert et al. (2008) suggested that whales probably do not sense the presence of mooring cables and as a result could strike them or become entangled. In addition, they believed that if the cable density is sufficiently great and spacing is close, cables could have a "wall effect" that could force whales around them, potentially changing their migration routes. Whales and dolphins traveling or feeding together may be at a greater risk than solitary individuals because "ground response" may lead some individuals to follow others into danger (Faber Maunsell and Metoc, 2007).

Wave energy converters deployed near sea turtle nesting beaches have the potential to interfere with the offshore migration of hatchlings. Interference with migration could occur if the energy project acts as a physical barrier or alters wave action, which has been demonstrated to guide hatchlings away from the beach toward the open ocean (Goff et al., 1998; Lohmann et al., 1995; Wang et al., 1998).

Some marine fish species form spawning aggregations at specific sites or times (Coleman et al., 1996; Crawford and Carey, 1985; Cushing, 1969; Domeier and Colin, 1997; Sinclair and Tremblay, 1984). Smith (1972) reported a spawning aggregation consisting of 30,000 to 100,000 Nassau groupers (*Epinephelus striatus*) in the

Bahamas. Because spawning success is important to the viability of populations, the siting and operation of ocean energy facilities would need to avoid interfering with these activities.

Collisions and Strikes

Submerged structures present a collision risk to aquatic organisms and diving birds, and the above-water components of floating structures may be a risk to flying animals. Wilson et al. (2007) defined "collision" as physical contact between a device or its pressure field and an organism that may result in an injury to the organism. They noted that collisions can occur between animals and fixed submerged structures, mooring equipment, surface structures, horizontal- and vertical-axis turbines, and structures that, by their individual design or in combination, may form traps. Harmful effects to animal populations could occur directly (e.g., from strike mortality) or indirectly (e.g., if the loss of prey species to strike reduces food for predators). Attraction of marine mammals and other predators to fish congregations near structures may also expose them to increased risk of collision or blade strike. In an attempt to define the risk of collisions from marine renewable energy devices, Wilson et al. (2007) reviewed information from other industrial and natural activities: power plant cooling intakes, shipping, fishing gear, fish aggregation devices, and wind turbines. They concluded that, although animals may strike any of the physical structures associated with marine renewable energy devices (i.e., vertical or horizontal support piles, duct, nacelles, anchor locks, chains, cables, and floating structures), turbine rotors are the most intuitive sources of significant collision risks with marine vertebrates.

Effects of Rotor Blade Strike on Aquatic Animals

Many of the hydrokinetic and ocean current technologies extract kinetic energy by means of moving/rotating blades. A wide variety of swimming and drifting organisms (e.g., fish, sea turtles, driving birds, cetaceans, seals, otters) may be struck by the blades and suffer injury or mortality (Wilson et al., 2007). Mortality is a function of the probability of strike and the force of the strike. The seriousness of strike is related to the swimming ability of the animal (i.e., ability to avoid the blade), water velocity, number of blades, blade design (i.e., leading edge shape), blade length and thickness, blade spacing, blade movement (rotation) rate, and the part of the rotor that the animals strikes. A vertical axis turbine will have the same leading edge velocity along the entire length of the blade. On the other hand, blade velocity on a horizontal axis turbine will increase from the hub out to the tip. The rotor blade tip has a much higher velocity than the hub because of the greater distance that is covered in each revolution. For example, on a rotor spinning at 20 rpm, the leading edge of the blade 1 m from the center point will be traveling at about 2 m/s—a speed that is likely to be avoidable or undamaging to most organisms. However, a 20-m-diameter rotor spinning at 20 rpm would have a tip velocity of nearly 21 m/s. Fraenkel (2006, 2007b) described a horizontal axis turbine with a maximum rotation speed of 12 to 15 rpm, which results in a maximum blade tip velocity of 12 m/s. Wilson et al. (2007) suggested that rotor blades tips will likely move at or below 12 m/s because greater speeds will incur efficiency losses through cavitation.

The force of the strike is expected to be proportional to the strike velocity; consequently, the potential for injury from a strike would be greatest at the outer periphery of the rotor. Unfortunately, little is known about the magnitude of impact forces that cause injuries to most marine and freshwater organisms (Cada et al., 2005, 2006) or the swimming behavior (e.g., burst speeds) that organisms may use to avoid strikes. Although the blade tip will be moving at the highest velocity and exhibit the greatest strike force, animals may be able to avoid the tip of an unducted rotor. Relatively safe areas of passage through the rotor would be nearest the hub (because of low velocities) and potentially nearest the tip (because of the opportunity for the animal to move outward to avoid strike). The central zone of relatively high blade velocity and relatively less opportunity to avoid strike may be the most dangerous area (Coutant and Cada, 2005). For rotors contained in housings, there would be no opportunity for an organism entrained in the intake flow to escape strike by moving outward from the periphery; safe passage would depend on sensing and evading the intake flow or passing through the rotor between the blades. This suggestion of relatively high- and low-risk passage zones has not been tested and remains speculative until the phenomenon is investigated in field applications.

There have been several studies to estimate the potential of fish strike by rotating blades (e.g., Deng et al., 2005), but all involve conventional hydroelectric turbines that are enclosed in turbine housings and afford little opportunity for flow-entrained organisms to avoid strike. It is likely that both the probability and consequences of organisms striking the rotor blade are greater for a conventional turbine than for an unducted current energy turbine, due to the greater opportunities for organisms to avoid approaching the turbine rotor or moving outward from the periphery. However, passage through a conventional turbine poses only a single exposure to the rotor, whereas passage through a project consisting of large numbers of hydrokinetic energy turbines represents a larger risk of strike that has not been investigated.

Wilson et al. (2007) described a simple model to estimate the probability of aquatic animals entering the path of a marine turbine. The mode is based on the density of the animals and the water volume swept by the rotor. The volume swept by the turbine can be estimated from the radius of the rotor and the velocity of the animals and the turbine blades. They emphasized that their model predicts the probability of an animal entering the region swept by a rotor, not collisions. Entry into the path toward the rotor may lead to a collision but only if the animal does not take evasive action or has not already sensed the presence of the turbine and avoided the encounter. Applying this simplified model (no avoidance or evasive action) to a hypothetical field of 100 turbines, each with a two-bladed rotor 16 m in diameter, they predicted that 2% of the herring population and 3.6 to 10.7% of the porpoise population near the Scottish coast would encounter a rotating blade. At this time, there is no information about the degree to which marine animals may sense the presence of turbines, take appropriate evasive maneuvers, or suffer injury in response to a collision. Wilson et al. (2007) suggested that marine vertebrates may see or hear the device at some distance and avoid the area, or they may evade the structure by dodging or swerving when in closer range.

The potential injurious effects of turbine rotors have been compared to those of ship propellers, which are common in the aquatic environment. Fraenkel (2007a) pointed out that in contrast to ship propellers the rotors of hydrokinetic and current energy

devices are much less energetic. He estimated that a tidal turbine rotor at a good site will absorb about 4 kW/m^2 of swept area from the current, whereas typical ship propellers release over 100 kW/m^2 of swept area into the water column. In addition to the greater power density, a ship propeller and ship hull generate suction that can pull objects toward them, increasing the area of influence for strike (Fraenkel, 2006).

Effects of Water Pressure Changes and Cavitation

In addition to direct strike, there is a potential for adverse effects due to sudden water pressure changes associated with movement of the blade. For example, if the local water pressures immediately behind the turbine blades drop below the vapor pressure of water, cavitation will occur. Cavitation is the process of forming water vapor bubbles in areas of extreme low pressure within liquids. As a turbine blade rotates, cavitation can occur in areas of low pressure (i.e., downstream surface of blades) causing increased local velocities, abrupt changes in the direction of flow, and roughness or surface irregularities (USACE, 1995). Once formed, cavitation bubbles stream from the area of formation and flow to regions of higher pressure where they collapse. The violent collapse of cavitation bubbles creates shock waves, the intensity of which depends on bubble size, water pressure in the region of collapse, and dissolved gas content. Within enclosed, conventional hydroelectric turbines, forces generated by cavitation bubble collapse may reach tens of thousands of kilopascals at the instant and point of collapse (Hamilton, 1983; Rodrigue, 1986). Cavitation is an undesirable condition that will reduce the efficiency of the turbine and damage blades as well as nearby organisms. Properly operating turbines would not cavitate, and the zone of low pressure that might be injurious to organisms would be relatively small. The pressure drops associated with the blades of hydrokinetic turbines have not been measured in field applications, but experimental evidence suggests that tidal turbines may experience strong and unstable sheet and cloud cavitation, as well as tip vortices at a shallow depth of submergence (Wang et al., 2007). If this occurs, aquatic organisms passing near the cavitation zones in the immediate blade area may be injured. The likelihood of cavitation-related injuries would depend on the extent of cavitation and the ability of aquatic organisms to avoid the area—the collapse of cavitation vapor bubbles creates noise which may act as a deterrent.

Impacts of Ocean Thermal Energy Conversion

An OTEC technology operates a low-temperature heat engine based on the temperature differences between warm surface water and cold deep water (Holdren et al., 1980). This type of project consists of pumps and ducts for transferring large volumes of water (several times more flow than is needed for a once-through cooling system of a comparably sized steam electric power plant), large heat exchangers, and a working fluid that can be vaporized and recondensed (i.e., ammonia, propane, Freon®, or water). Electrical energy could be transported from offshore systems via subsea cables or alternatively could be converted to chemical energy *in situ* (e.g., hydrogen, ammonia, methanol) and transported to shore in tankers (Pelc and Fujita, 2002).

Effects on Ocean Ecosystems

Impacts of construction of an OTEC facility will depend on whether the project is located onshore or offshore. An offshore facility would require the installation of large, long water conduits on the seabed to access deep water. Alternatively, OTEC projects located on offshore platforms would depend on subsea cables to transfer electricity to shore. The installation and maintenance of pipelines and electrical cables would disturb bottom habitats and generate EMFs. Structures could become colonized with marine organisms and attract fish. Depending on the location of the warm water intake and discharges, these fish might be more susceptible to entrainment, impingement, or contact with the discharge plume.

The potential environmental effects of OTEC operation have been considered by a number of authors (Abbasi and Abbasi, 2000; Harrison, 1987; Holdren et al., 1980; Myers et al., 1986; Pelc and Fujita, 2002). Myers et al. (1986) provided the most comprehensive assessment of the possible effects on the marine environment resulting from operation of the types of OTEC facilities that were contemplated in the early 1980s. Most of the likely effects were expected to be physical and chemical changes in the ocean surface waters arising from the transfer of large volumes of cool, deep water. Abbasi and Abbasi (2000) suggested that OTEC plants will displace about 4 m^3/s of water per megawatt of electrify output from both the surface layer and the deep ocean layer, and then discharge the water at some intermediate depth. The warm water intake would be located at a depth of about 10 to 20 m, and the cold water intake might extend to a depth of 750 to 1000 m (Myers et al., 1986). The large transfer of water may disturb the thermal structure of the ocean near the plant, change salinity gradients, and change the amounts of dissolved gases, dissolved minerals, and turbidity. The transfer will result in an artificial upwelling of nutrient-rich deep water, which may increase marine productivity in the area. The stimulation of marine productivity may be especially strong in tropical waters, where nutrient levels are often low, and could have detrimental effects on nearby sensitive habitats such as coral reefs. Moreover, carbon dioxide will also be released when the deep water is warmed and subjected to lower pressures at the surface. The possible amounts of carbon dioxide released have not been rigorously quantified; some estimate that the quantities will be minute (Pelc and Fujita, 2002), and others suggest that the contribution will be relatively large (Holdren et al., 1980). The relatively high carbon dioxide and low dissolved oxygen content of the deep water may alter pH and dissolved oxygen concentrations in a surface mixing zone.

The large heat exchangers will have to be treated with biocides (e.g., chlorine or hypochlorite) in order to prevent the growth of bacterial slimes and other biofouling organisms; volumes of biocides would be proportional to the large volume of heating and cooling water. Degradation of the heat exchanger materials will result in chronic releases of metals (e.g., copper, nickel, aluminum). Accidental release of the working fluid that is evaporated and condensed to drive the turbine could have toxic effects. The potential for acute and chronic toxicity and bioaccumulation of metals from deep ocean water will have to be considered (Fast et al., 1990).

Ocean thermal energy conversion projects would be sources of waterborne noise, arising from operation of ammonia turbines, seawater pumps, support systems associated with the energy-producing cycle, and in some cases propulsion machinery for dynamic positioning of the OTEC platform. Janota and Thompson (1983) measured noise from OTEC-1, a 1-MWe test facility that was moored near Keahole Point, Hawaii. The most significant sources of noise from the small project resulted from the interaction of inflow turbulence with the seawater pumps and from thrusters used for dynamic positioning. Based on their measurements, Janota and Thompson (1983) predicted that a 160-MWe OTEC plant would radiate less than 0.05 acoustic W of broadband sound in the frequency range of 10 to 1000 Hz, which is at least an order of magnitude less than that which is produced by a typical ocean-going freighter. Similarly, Rucker and Friedl (1985) predicted that pump noise (at 10 Hz) from a 40-MWe OTEC plant would be reduced from 136 dB to 78 dB at about 0.8 km; this is less than ambient noise at a sea state of 1 (very gentle sea with waves less than 0.3 m in height).

Large marine organisms may be impinged on the screens that protect the OTEC intakes, and smaller organisms (e.g., zooplankton, fish eggs, larvae) will pass through the screens and be entrained in the heat-exchanger system (Abbasi and Abbasi, 2000). The number of organisms entrained in the water will depend on their concentrations in the intake areas; more aquatic organisms are likely to be impinged and entrained at the surface water intake than from the deep water intake. Due to the large flow rates of water at the warm water intake, impingement and entrainment will especially need to be monitored there. As with steam electric power plants, the heat exchanger-entrained organisms will be susceptible to mechanical damage in the piping and to rapid changes in temperature, pressure, salinity, and dissolved gases that may cause mortality. For example, the temperature of cold, deep water is expected to increase by about 2 to 3°C after passing through the heat exchangers; likewise, the temperature of shallow, warm water is expected to decrease by the same amount. Myers et al. (1986) noted that there is insufficient information to judge the impacts of a 2 to 3°C temperature shock but assumed that most organisms will probably not be directly impacted by this amount of temperature change. However, secondary entrainment into the discharge plume will also expose marine organisms to chemical, physical, and temperature stresses. A mixed discharge of warm and cold water could subject organisms entrained from the warm surface waters to a drop of 10°C, which would likely cause lethal cold shock for some species. Few organisms are expected to be entrained in the deep, cold water flow, but those that do will be subjected to potentially lethal pressure decreases of 70 to 100 atmospheres (7100 to 10,100 kilopascals) (Myers et al., 1986).

ENVIRONMENTAL IMPACTS OF HYDROKINETIC ENERGY*

In the previous section, we provided a general discussion of potential environmental impacts of hydrokinetic energy technology. In this section, we provide a discussion of many of the specific impacts related to site evaluation, construction, and operations and maintenance (O&M) activities.

* Adapted from Tribal Energy and Environmental Information Clearinghouse, http://teeic.indianaffairs.gov/er/hydrokinetic/impact/siteeval/index.htm.

Hydrokinetic Energy Site Evaluation Impacts

Site evaluation phase activities, such as monitoring and site characterization, are temporary and are conducted at a smaller scale than those during the construction and operation phases. Potential impacts from these activities are presented below, by the type of affected resource. The impacts described are for typical site evaluation activities, such as drilling to characterize the seabed or riverbed. Onshore site characterization activities would be limited to a topographic survey to establish onshore site design and placement for an operations and maintenance facility, substation, and electric transmission lines. If road construction were necessary during this phase, potential impacts would be similar in character to those for the construction phase, but generally of smaller magnitude.

Air Quality

Impacts on air quality during site evaluation activities would be limited to barges conducting surveys and vehicular traffic to proposed sites for all hydrokinetic energy land-based facilities. These air pollutant emissions would be minor, of short duration, and intermittent.

Cultural Resources

Cultural material present within the project area could be impacted by any seafloor, riverbed, or ground disturbance. Such disturbance could result from drilling and sampling activities and, for land-based activities, vehicular and pedestrian traffic. These activities would be relatively limited in scope during this phase. Surveys conducted during this phase to evaluate the presence and significance of cultural resources in the area would assist developers in designing the project to avoid or minimize impacts on these resources.

Ecological Resources

Impacts on ecological resources would be minimal during site evaluation because of the limited nature of the activities. For offshore projects (e.g., wave barrage, tidal turbine projects) and river projects, the potential effects of low-energy geological and geophysical surveys on marine mammals, sea turtles, and fish could include behavior responses such as avoidance and deflections in travel direction. A few individuals could be injured or killed by collisions with the survey vessels. Those individuals displaced because of avoidance behaviors during survey are likely to return within relatively short periods following cessation of survey activities. Marine mammals, sea turtles, and fish could be exposed to discharges or accidental fuel releases from survey vessels and to accidentally released solid debris. Such spills would be small and would not be expected to measurably affect marine or river wildlife. Land-based activities could give rise to the introduction and spread of invasive vegetation as a result of vehicular traffic. Soil borings would destroy vegetation and disturb wildlife. Overall, site evaluations are not expected to cause significant impacts on terrestrial or aquatic biota. Surveys conducted during this phase to evaluate the presence and significance of ecological resources in the area would assist developers in properly locating the facility and its components.

Water Resources

Survey ships could contribute small amounts of fuel or oil to the ocean or river through bilge discharges or leaks. Anchoring of the ships can cause sediment from the seabed or riverbed to enter the water column. Negligible to minor impact on water quality would be expected. Relatively limited amounts of water would be used if drilling were required; this water could be obtained locally or it could be trucked in with the drilling equipment. Land-based site evaluation activities are anticipated to have minimal or no impact on water resources, local water quality, water flows, and surface water/groundwater interactions.

Land Use

Very few offshore and onshore site evaluation activities are expected; consequently, no impacts on existing land uses are anticipated.

Soils and Geologic Resources

Seabed, riverbed, and onshore ground disturbances would be minimal during the site evaluation phase and, as a result, impacts on seabed and riverbed sediments or soils are unlikely to occur. Site characterization activities would also be unlikely to activate geological hazards.

Paleontological Resources

Paleontological resources present within the project area could be impacted by any seafloor, riverbed, or ground disturbance. Such disturbance could result from drilling and sampling activities and, for land-based activities, vehicular and pedestrian traffic. These activities would be very limited in scope during this phase and would not be likely to affect paleontological resources. Surveys conducted during this phase to evaluate the presence and significance of paleontological resources in the area would assist developers in designing the project to avoid or minimize impacts on these resources.

Transportation

Impacts on transportation are anticipated to be insignificant during the site evaluation phase from the one or two survey vessels that might be deployed at any one time. Vehicular traffic would be temporary and intermittent and would be limited to very low volumes of heavy- and medium-duty equipment and personal vehicles.

Visual Resources

Site evaluation activities would have temporary and minor visual effects caused by the presence of survey vessels, workers, vehicles, and equipment.

Socioeconomics

Site evaluation activities are temporary and limited and would not result in socioeconomic impacts on employment, local services, or property values.

Environmental Justice

Site evaluation activities are limited and would not result in significant adverse impacts in any resource area; therefore, environmental justice impacts are not expected at this phase.

Acoustics (Noise)

Onshore and offshore drilling activities for all hydrokinetic energy facilities, if required, would generate the most noise during this phase, but impacts would be much lower than those that could occur during construction. Surveys using air-gun arrays may generate low-frequency noise that may be detected by marine mammals, sea turtles, and fish within the survey area. Other sea and river geophysical surveys and installation of wave-measuring devices equipped with recording equipment would generate some ship and boat noise.

Hazardous Materials and Waste Management

The only hazardous material associated with site evaluation activities would be the fuel for boats, barges, and vehicles. Impacts from operational discharges, accidental fuel releases, and accidentally released solid debris are expected to be small or nonexistent if appropriate management practices are followed.

Hydrokinetic Energy Facility Construction Impacts

Typical activities during the wave or tidal turbine energy farm construction phase include assembling hydrokinetic units on shore, transporting each device to its designated location offshore, anchoring it to the seabed, connecting each device electrically to a central junction box, laying or burying submarine transmission and signal cable, and construction of onshore substation and electrical transmission lines to connect to the grid. Activities required for river in-stream facilities are essentially the same but are conducted in a river rather than offshore. For a barrage facility, a dam would be constructed across the inlet or estuary to contain the incoming tidal flow and a powerhouse would be constructed to produce hydroelectric energy. Onshore activities include ground clearing, grading, excavation, vehicular traffic, and construction of facilities.

Air Quality

Offshore activities that generate emissions include ship, boat, and barge traffic to and from the hydrokinetic energy facility site, installation of the hydrokinetic energy devices and their associated anchoring devices, and the laying of underwater cables. Air emissions result from the operation of ship engines and on-ship equipment such as cranes, generators, and air compressors. In most cases, an air quality permit would not be required for offshore facility construction. However, in areas of non-attainment for any criteria pollutants, the states have authority to regulate nearshore activities. Emissions generated during the construction phase of land-based facilities (including docks, equipment storage, and assembly area) include the following:

- Vehicle emissions
- Diesel emissions from large construction equipment and generators
- Volatile organic compound (VOC) releases from the storage and transfer of vehicle/equipment fuels
- Small amounts of carbon monoxide, nitrogen oxides, and particulates from blasting activities
- Fugitive dust from many sources, such as disturbing and moving soils (clearing, grading, excavation, trenching, backfilling, dumping, and truck and equipment traffic), mixing concrete, use of unvegetated soil piles, drilling, and pile driving

These emissions would also be expected during construction of a barrage facility. A permit may be required from the state or local air agency to control or mitigate these emissions, especially in non-attainment areas.

Cultural Resources

For offshore projects, trenching, dredging, and placement of hydrokinetic energy devices and associated components could impact shipwrecks or buried archeological artifacts. For onshore projects, impacts on cultural resources could occur from site preparation (e.g., clearing, excavation, grading) and construction of transmission-related facilities. For either offshore or onshore projects, visual impacts could also result from disruption of a historical setting that is important to the integrity of a historic structure, such as a lighthouse. Potential cultural resource impacts include the following:

- Complete destruction of the resource if present in areas undergoing surface disturbance or excavation
- Unauthorized removal of artifacts or vandalism to cultural resource sites resulting from increases in human access to previously inaccessible areas
- Visual impacts resulting from vegetation cleaning, increased industry, and the presence of large-scale equipment, machinery, and vehicles (if the affected cultural resources have an associated landscape or other visual component that contributes to their significance, such as a sacred landscape or historic trail)

Ecological Resources

Wave and Tidal Turbine Energy Farms

The potential effects of construction activities associated with the placement of wave and tidal turbine energy devices on marine mammals, sea turtles, and fish may include behavioral responses such as avoidance and deflections in travel direction. Noise and vibrations generated during the various activities could disturb the normal behaviors and mask sounds from other members of the same species or from predators. Coastal birds could be displaced from offshore feeding habitats; however, most birds would be likely to return within relatively short periods following cessation of construction activities. A few could be injured or killed by collisions with the survey vessels.

The movement and deposition of sediment during construction activities on the seafloor could kill benthic organisms, a source of food for fish. Effects to fish could potentially occur if spawning or nursery grounds are disturbed during construction or if resuspended sediments cause smothering of habitat. The area of seafloor disturbance from anchoring systems relative to the surface area occupied would be small.

Marine mammals, sea turtles, fish, and seabirds could be exposed to discharges or accidental fuel releases from construction vessels and to accidentally released solid debris. Such spills would be small and quickly diluted and would not be expected to measurably affect marine mammal or fish populations.

Onshore impacts from construction could affect terrestrial vegetation and wildlife, but the overall impact is anticipated to be minimal because permanent onshore facilities are expected to be small. Wildlife would be most affected by habitat reduction within the project site, access roads, and transmission line rights-of-way. Wildlife within surrounding habitats might also be affected if the construction activity (and associated noise) disturbs normal behaviors, such as feeding and reproduction. Impacts on wildlife are expected to be minor.

Turtles nest along the south Atlantic and Gulf coastlines. Nests containing eggs and emerging hatchlings could be affected by construction activities onshore. Lighting from the construction areas could disorient the hatchlings and increase their exposure to predators. The minimal amount of onsite construction would limit the impact to no more than a few nests.

River In-Stream Facilities

The potential effects of the placement of river in-stream energy devices and associated construction on fish may include behavioral responses such as avoidance and deflections in travel direction. Noise and vibrations generated during the various construction activities, especially placement of supporting structures and installation of submarine transmission lines, could disturb the normal behavior. Those displaced because of avoidance behaviors during construction are likely to return within relatively short periods following cessation of construction activities.

The movement and deposition of sediment during construction activities on the riverbed could kill benthic organisms, a source of food for fish. Effects to fish could potentially occur if spawning or nursery grounds are disturbed during construction or if resuspended sediments cause smothering of habitat. The area of riverbed disturbance would be very small relative to the availability of similar habitat in surrounding areas.

Terrestrial wildlife would be most affected by habitat reduction within the project site, access roads, and transmission line rights-of-way. Wildlife within surrounding habitats might also be affected if the construction activity (and associated noise) disturbs normal behaviors, such as feeding and reproduction. Impacts on wildlife are expected to be minor.

Barrage Facilities

Dam construction at a barrage facility would not increase the amount of wetted area inundated within the embayment, but it would alter the period of time that water is held in the embayment and could alter the aquatic environment of the embayment. These alterations could lead to habitat loss for terrestrial wildlife and bird species

and/or degradation for aquatic species. Underwater habitat would be altered and marine species could be injured or killed during construction of the intake and dam. The ability of fish and marine mammals to enter and leave the embayment would be substantially altered. The significance of construction impacts on fish, marine mammals, and saltwater wetland-dependent birds and terrestrial species is likely to be site specific. Terrestrial wildlife also would be affected by habitat reduction caused by construction of land-based facilities within the project site, including access roads and transmission line rights-of-way. Wildlife within surrounding habitats might also be affected if the construction activity (and associated noise) disturbs normal behaviors, such as feeding and reproduction.

Water Resources

Water Use

Water would be used onshore for dust control when clearing vegetation and grading and for road traffic, for making concrete, and for domestic use by the construction crew. Water would likely be trucked in from offsite. The quantity of water required would be small.

Water Quality

Vessels used for transport and installation of hydrokinetic energy devices and components could contribute small amounts of fuel or oil to the ocean through bilge discharges or leaks. Anchoring of construction ships, and installation of anchoring devices and electrics cables, can cause sediment from the seabed to enter the water column. Onshore activities that cause soil erosion or discharges of waste or sanitary water could affect water quality. Negligible to minor impact on water quality would be expected.

Land Use

The wave and tidal turbine energy farm could occupy from 17 to 250 acres of ocean surface. The facility would exclude commercial shipping and, possibly, fishing activities. A river in-stream facility could occupy about 5 acres and could affect commercial shipping, recreation, and fishing activities. A barrage facility would impact the area behind the dam and would exclude commercial and recreational ships and boats from entering the previously accessible estuary unless a ship lock were constructed. Existing onshore land use during construction would be affected by intrusive impacts such as ground clearing, increased traffic, noise, dust, and human activity, as well as by changes in the visual landscape. In particular, these impacts could affect those seeking recreational opportunities on the shore or in the water. Generally, offshore and onshore impacts associated with these types of facilities are expected to be minor.

Soils and Geologic Resources

Seabed and riverbed disturbance would result from drilling or pile driving required for anchoring the hydrokinetic energy devices and from excavation required to bury electrical cable. The area disturbed is a small portion of the area occupied by the

hydrokinetic energy facility. Construction activities would also be unlikely to activate geological hazards. Surface disturbance, heavy equipment traffic, and changes to surface runoff patterns during construction of onshore facilities could cause soil erosion. Impacts of soil erosion could include soil nutrient loss and reduce water quality in nearby surface water bodies.

Visual Resources

Viewers onshore and offshore would observe an increase in vessel traffic transporting hydrokinetic energy devices, components, and works to the site. The activity during installation would also be noticed. Wave, tidal, and in-river facilities are generally low-profile structures and, although visible, may not be as objectionable as larger, more visible structures. The overall effect on visual resources is also related to existing uses (especially land-based residential uses) that would have a view of the hydrokinetic energy farm areas and will require site-specific assessment. Construction of the dam at a barrage site would change the character of the water basin and could create visual concerns for nearby residents or recreational users. Possible sources of visual impacts during construction of onshore facilities include ground disturbance, construction of highly visible facilities, vegetation removal, road construction, and increased traffic. Increased truck and vessel traffic and human activity at the port facility supporting project construction would also be visible, although it is anticipated this would only be a short-term impact.

Paleontological Resources

For offshore projects, trenching, dredging, and placement of hydrokinetic energy devices and associated components could impact paleontological resources. For onshore projects, impacts on paleontological resources could occur directly from the construction activities and increased accessibility to fossil locations. Potential impacts include the following:

- Complete destruction of the resource if present in areas undergoing surface disturbance or excavation
- Unauthorized removal of paleontological resources or vandalism to the site as a result of increased human access to previously inaccessible areas, if significant paleontological resources are present

Transportation

Traffic at the port would increase as wave or tidal energy devices and components are delivered prior to assembly transport to the project site. Vessel traffic will increase during the construction phase. The same effect would occur with river in-stream projects although, because they are generally much smaller installations, the impacts on transportation would be less significant. Short-term increases in the use of local roadways would occur during the onshore construction period. Barrage projects would be relatively large projects and would likely require more labor for construction. This would cause an increase in traffic on local roads and potentially could disrupt local traffic use.

Socioeconomics

Direct impacts would include the creation of new jobs for construction workers and the associated income and taxes generated by the hydrokinetic energy facilities. Indirect impacts would occur as a result of the new economic development and would include new jobs at businesses that support the expanded workforce to provide project materials, and associated income and taxes. An influx of new workers could strain the existing community infrastructure and social services; however, because most hydrokinetic projects are relatively small, the workforce required is also expected to be relatively small and the impacts, therefore, are expected to be minor.

Environmental Justice

If significant impacts occurred in any resource areas, and these impacts disproportionately affected minority or low-income populations, then there could be an environmental justice impact. Issues of potential concern during construction are noise, dust, and visual impacts from the construction site and possible impacts associated with the construction of new access roads. Additional impacts could include limitations on access to the area for tribal recreation, subsistence, and traditional activities. Environmental justice impacts are dependent upon vulnerable populations being located within the area of influence of a project and are, therefore, site specific.

Acoustics (Noise)

Underwater and above-water noise sources include boat, ship, and barge activity associated with transporting workers, materials, and hydrokinetic energy devices to the offshore site, installing hydrokinetic facilities, and the laying of electrical and signal cables. Human receptors on the ocean shore likely would be far enough away for any impacts to be minor. Human receptors on the river shore could be close to the activities required for locating and anchoring river in-stream turbines. If pile driving is required for anchoring hydrokinetic energy devices or for construction of offshore power-gathering stations, the noise could be audible at the shoreline and might be annoying to populations. This impact would be intermittent. Techniques for laying cable could require use of air guns, rock cutters, or shaped explosive charges. The noise could be intense but would occur over a very short time period.

Onshore noise would result from preassembly of the hydrokinetic energy devices and from the construction of onshore facilities. The primary source of noise during construction of onshore facilities, transmission lines, and a barrage facility would be from equipment operation (e.g., rollers, bulldozers, diesel engines). Other sources of noise would include vehicular traffic, tree felling, and blasting. Whether the noise levels from these activities exceed U.S. Environmental Protection Agency (USEPA) guidelines or local ordinances would depend on the distance to the nearest residence and the effectiveness of any mitigating measures to reduce noise levels. If occurring near a residential area, noise levels from blasting and some equipment operation could exceed the USEPA guidelines but would be intermittent and extend for only a limited time.

Adverse impacts due to noise could occur if the site is located near a sensitive area, such as a park, wilderness, or other protected area. The primary impacts from noise would be localized disturbances to wildlife, recreationists, and residents.

Hazardous Materials and Waste Management

Hazardous material associated with installation of hydrokinetic energy devices and construction of associated support components would include fuels, lubricants, and hydraulic fluids contained in the hydrokinetic energy devices or used in ships and construction equipment. Impacts from accidental spills, accidental fuel releases, and releases of solid debris are expected to be minor if appropriate management practices are followed. Garbage and sanitary waste generated onboard the vessels and barges would be returned to shore for disposal. Solid and industrial waste would be generated during onshore construction activities. The solid wastes would likely be nonhazardous and consist mostly of containers, packaging materials, and waste from equipment assembly and construction crews. Industrial wastes would include minor amounts of fuels, spent vehicle and equipment fluids (lubricating oils, hydraulic fluids, battery electrolytes, glycol coolants), and spent solvents. These materials would be transported offsite for disposal, but impacts could result if the wastes were not properly handled and were released to the environment. No impacts are expected from proper handling of all wastes.

Hydrokinetic Energy Facility Operations and Maintenance Impacts

Typical activities during the hydrokinetic energy facility operational phase include operation of the hydrokinetic energy devices, power generation, and associated maintenance activities that would require operations from a vessel or barge when components are being maintained, repaired, or replaced.

Air Quality

There are no direct air emissions from the operation of hydrokinetic energy facilities. Air emissions result from the operation of maintenance ship engines and on-ship equipment such as cranes, generators, and air compressors. Onshore vehicular traffic will continue to produce small amounts of fugitive dust and tailpipe emissions during maintenance activities. These emissions would not likely exceed air quality standards and impacts on air quality would be minor.

Cultural Resources

The operation and maintenance of offshore facilities would have no direct impact on cultural resources unless previously undisturbed areas are disturbed. Potential indirect impacts associated with the operation and maintenance of onshore facilities would be limited to unauthorized collection of artifacts made possible by access roads if they make remote lands accessible to the public. Visual impacts resulting from the presence of a large wave, tidal turbine, river in-stream energy facility, or barrage facility and transmission lines could affect some cultural resources, such as sacred landscapes or historic trails.

Ecological Resources

Wave and Tidal Energy Farms

The presence of a wave or tidal turbine energy farm could cause some marine mammals to avoid the area. Collisions with maintenance vessels and underground structures are anticipated to be rare. Overtopping wave energy devices could trap hatching sea turtles and fish, resulting in injury or death. Impacts on the marine populations are expected to be minor to moderate depending on the specific site. Some whale species migrate along the Pacific coast from 1.5 miles to 2 miles (2.5 to 3 km) offshore. Any wave or tidal turbine facility located in this zone could impact whale migration.

Noise levels from wave energy devices would be similar to those from ship traffic but would be continuous for the life of the wave farm. This could result in long-term avoidance by wildlife, which could lead to abandonment of feeding or mating grounds. Noise from submerged tidal turbines would be low due to the low rotational speed of the turbine blades. Marine mammals, sea turtles, fish, and seabirds could be exposed to discharges or accidental fuel releases from maintenance vessels and to accidentally released solid debris. Such spills would be small and quickly diluted and would not be expected to measurably affect these wildlife populations.

Depending on the design of the facilities, wave energy devices or any above-water portions of tidal energy devices could become the host for seabird colonies or may be used as haul-out areas for sea lions. Underwater structures may also create an artificial habitat for benthic species. This could complicate the maintenance and repair of wave energy devices. Electromagnetic fields from the transmission cable can be detected by some fish and might result in attraction or avoidance. Such impacts would be negligible to minor. Onshore impacts from operation could affect vegetation and wildlife by habitat reduction within the project site, access roads, and transmission line rights-of-way. Turtles nest along the south Atlantic and Gulf coastline, and nests and emerging hatchlings could be affected by maintenance activities onshore. Outdoor lighting from onshore facilities could disorient the hatchlings and increase their exposure to predators.

River In-Stream Facilities

Fish behavior is influenced primarily by the natural current in the river and only secondarily by the rotating mechanisms in the turbines. Proper location of the turbines would have minimal impact on fish movement or abundance. Allowance of sufficient turbine spacing in a turbine farm or in the river may minimize impact on fish. Noise generated by the turbines would have minimal effects on aquatic biota. The turbines are not expected to affect terrestrial wildlife since they are mostly, or completely, submerged. Wildlife would be most affected by habitat reduction within the onshore project site, access roads, and transmission line rights-of-way. Impacts on wildlife are expected to be minor.

Barrage Facilities

Dam construction at a barrage factory would not increase the amount of wetted area inundated within embayment, but it would alter the period of time that water is held in the embayment and could alter the aquatic environment of the embayment. These

alterations could lead to habitat loss for terrestrial wildlife and bird species and/or degradation for aquatic species. Fish could be injured or killed during operation of the intake or during power generation. Because of a reduction in natural fishing of sediment, increases in sedimentation within the embayment may also adversely affect embayment ecosystems. The ability of fish and marine mammals to enter and leave the embayment would likely be substantially altered. The significance of operational impacts on fish, marine mammals, and saltwater wetland-dependent birds and terrestrial species would likely be site specific.

Water Resources

Water Use

Water use at the port would be required for normal operation, including fire protection, cleaning and maintenance of equipment, and consumptive use by personnel. Water would also be required for consumptive use on the vessels.

Water Quality

Vessels used for maintenance of hydrokinetic energy devices and components could contribute small amounts of fuel or oil to the ocean or river through bilge discharges or leaks. Damage to a hydrokinetic energy device, which may contain petroleum-based materials, could result in water contamination. Anchoring of the ships can cause sediment from the seabed to enter the water column. Onshore activities that could affect water quality are those that cause soil erosion or discharges of waste or sanitary water. Negligible or minor impact on water quality would be expected.

Land Use

All types of hydrokinetic facilities would likely exclude traditional uses of the areas where they are constructed. Commercial shipping, fishing, and recreation uses may be the most likely uses that could be affected. Depending on the nature and visibility of the facilities, the visual impacts of hydrokinetic development might also create conflicts with existing shore-based uses.

Soils and Geologic Resources

Seabed or riverbed disturbance would be minimal from maintenance activities, and sediments are unlikely to be affected. Maintenance activities would also be unlikely to activate geological hazards. A wave energy farm could cause a reduction in wave height of 10 to 15%, and this reduction could result in an interruption of the natural sediment transport along the shore, increasing erosion and drift. The impact is greater the closer the wave farm is to the shore and is greater for floating devices oriented parallel to the shore. Tidal and river in-stream turbines will cause turbulence downstream that might cause scour of the seabed or riverbed if the units are located near the bottom. During operation, the soil and geologic conditions would stabilize at onshore facilities. Soil erosion and soil compaction are both likely to continue to occur along access roads.

Paleontological Resources

The operation and maintenance of offshore facilities would have no direct impacts on paleontological resources unless additional undisturbed areas are developed. Potential indirect impacts associated with the operation and maintenance of onshore facilities would be limited to unauthorized collection of fossils made possible by access roads if they make remote lands accessible to the public.

Transportation

No noticeable impacts on transportation are likely during operations. Maintenance vessels would service the hydrokinetic energy devices at regular intervals, but the additional levels of activity resulting from this are anticipated to be small. Infrequent, but routine, truck shipments of component replacements to the dock during maintenance procedures are likely over the period of operation.

Visual Resources

Visual impacts of the operation of hydrokinetic energy devices would be the same as those identified for construction activities, with the exception of the increase in vessel and vehicle traffic associated with construction.

Socioeconomics

Direct impacts would include the creation of new jobs for operation and maintenance workers and the associated income and taxes paid. Indirect impacts are those impacts that would occur as a result of the new economic development and would include things such as new jobs at businesses that support the workforce or that provide project materials, and the associated income and taxes. However, the total number of operations and maintenance jobs likely would be small; therefore, the associated socioeconomic impacts are anticipated to be minimal.

Environmental Justice

If significant impacts occurred in any resource areas as a result of the operation of hydrokinetic facilities, and these impacts disproportionately affect minority or low-income populations, then there could be an environmental justice impact. Issues of potential concern during operations are noise, ecological, and visual impacts. Additional impacts include limitations on access to the area for tribal activities.

Acoustics (Noise)

Underwater and above-water noise sources include ship and barge noise associated with transporting workers for maintenance activities, which would require frequent (and possibly daily) trips to the wave or tidal turbine energy farm or to the river in-stream turbines. Wave energy device noise would result from the flexing action of attenuators and point absorbers, from compressed air released from oscillating water column turbines, and from the impact of waves on terminator and overtopping devices. Underwater noise from the operation of tidal or river in-stream turbines is expected to be low because the rotational speed of the turbine blades is low. Overall, noise from operation of the hydrokinetic energy devices is expected to be

low. Onshore transformers would produce a humming noise and cooling fan noise. Sources of noise during operation of a barrage facility would be the turbines, generators, and transformers

Hazardous Materials and Waste Management

Hazardous material associated with the operation and maintenance of hydrokinetic energy devices and associated support compounds would include the fuel for boats, vessels, and barges, and lubricants and hydraulic fluids contained in the wave or tidal energy devices. Impacts from accidental spills, accidental fuel releases, and releases of solid debris are expected to be minor if appropriate management practices are followed. Garbage and sanitary waste generated onboard the vessels and barges would be returned to shore for disposal. Industrial wastes are generated during routine maintenance (used fluids, cleaning agents, and solvents). These wastes typically would be put in containers, characterized and labeled, possibly stored briefly, and transported by a licensed hauler to an appropriate permitted offsite disposal facility as a standard practice. Adverse impacts could result if these wastes were not properly handled and were released to the environment. Given current standards the impact of this is expected to be minor.

Impacts on Human Health and Safety

With regard to the site evaluation phase, the primary hazard is the risk of drowning while working on or above water. The potential health and safety risks that could result in injuries and fatalities include onboard accidents, collisions between the survey ship and marine vessels, and natural events such as hurricanes, earthquakes, tsunamis, and severe storms. Occupational and public health and safety risks normally associated with construction and outdoor activities (working in potential weather extremes and possible contact with natural hazards, such as uneven terrain and dangerous plant, animals, or insects) exist but are very limited during the site evaluation phase because of the limited range of activities and number of workers.

The primary hazard associated with hydrokinetic energy device installation and construction of associated components is the risk of drowning while working on or above water. The potential health and safety risks that could result in injuries and fatalities include onboard accidents, collisions between the vessel or barge and marine vessels, and natural events such as hurricanes, earthquakes, tsunamis, and severe storms. Potential onshore impacts on workers would be similar to those expected for any construction project involving earth moving, large equipment, and construction and installation of industrial facilities. Most accidents in the construction industry result from overexertion, falls, or being struck by equipment. Construction-related illnesses could also result from exposure to chemical substances from spills. In addition, health and safety issues include working in potential weather extremes and possible contact with natural hazards, such as uneven terrain and dangerous plants, animals, or insects. All personnel involved with the construction would utilize appropriate safety equipment and would be properly trained in required Occupational Safety and Health Administration (OSHA) practices.

The primary hazard associated with operation and maintenance of hydrokinetic energy devices and associated components is the risk of drowning while working on or above water. The potential health and safety risks that could result in injuries and fatalities include onboard accidents, collisions between the vessel or barge and marine vessels, and natural events, such as hurricanes, earthquakes, tsunamis, and severe storms. Also, other marine vessels could collide with the wave energy devices. Deploying navigational aids such as lighting and foghorns would minimize vessel collisions with wave energy devices. All personnel involved with the operations and maintenance activities would utilize appropriate safety equipment and would be properly trained in required Occupational Safety and Health Administration (OSHA) practices.

MARINE AND HYDROKINETIC ENERGY: THE BOTTOM LINE

The three forms of ocean energy—tidal, wave, and ocean thermal energy conversion (OTEC) systems—are all renewable. This is a significant advantage over fossil fuels and other energy forms that pollute the environment. Although all three forms of ocean energy show promise for future development, it is the OTEC systems that appear to be most beneficial for use at the present time. OTEC systems provide both economic and noneconomic benefits. On the other hand, OTEC power plants have the potential to cause major adverse impacts on ocean water quality. Such plants would require entrainment and discharging enormous quantities of seawater. Sea surface temperatures in the vicinity of an OTEC plant could be lowered by the discharge of effluent from the cold-water pipe. Biocides, such as chlorine, may be irritating or toxic to organisms. OTEC plants could result in an upwelling of nutrients from the bottom and the subsequent growth of large algal blooms (Abbasi and Abbasi, 2000). The bottom line? Few marine and hydrokinetic renewable energy technologies have been tested at full scale, and it is therefore difficult to resolve all of the uncertainties about their specific environmental effects.

THOUGHT-PROVOKING QUESTIONS

7.1 Is tidal energy a beneficial source of renewable energy? Explain your answer.
7.2 It has been said that tidal energy is expensive. Does it matter?
7.3 Tidal energy systems must be located near coastal areas. Is the tradeoff of lost land area worth it?

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8 Fuel Cells

I believe that water will one day be employed as a fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light.

—Jules Verne (*Mysterious Island*, 1874)

I believe fuel cell vehicles will finally end the hundred-year reign of the internal combustion engine as the dominant source of power for personal transportation. It's going to be a winning situation all the way around—consumers will get an efficient power source, communities will get zero emissions, and automakers will get another major business opportunity—a growth opportunity.

—William C. Ford, Jr., Ford Chairman, International Auto Show, 2000

INTRODUCTION TO HYDROGEN FUEL CELLS*

Containing only one electron and one proton, hydrogen, chemical symbol H, is the simplest element on earth. Hydrogen as is a diatomic molecule—each molecule has two atoms of hydrogen (which is why pure hydrogen is commonly expressed as H_2). Although abundant on Earth as an element, hydrogen combines readily with other elements and is almost always found as part of another substance, such as water hydrocarbons or alcohols. Hydrogen is also found in biomass, which includes all plants and animals.

- Hydrogen is an energy carrier, not an energy source. Hydrogen can store and deliver usable energy, but it does not typically exist by itself in nature; it must be produced from compounds that contain it. Its production is not inexpensive.
- Hydrogen can be produced using diverse, domestic resources including nuclear energy, natural gas and coal, and biomass and other renewables, including solar, wind, hydroelectric, and geothermal energy. This diversity of domestic energy sources makes hydrogen a promising energy carrier and important to our nation's energy security. It is expected and desirable for hydrogen to be produced using a variety of resources and process technologies (or pathways).

* Adapted from EERE, *Hydrogen Production*, Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy, Washington, DC, 2014 (http://www1.eere.energy.gov/hydrogenandfuelcells/production/basics.html); Spellman, F.R. and Bieber, R., *The Science of Renewable Energy*, CRC Press, Boca Raton, FL, 2011.

- The U.S. Department of Energy (USDOE) focuses on hydrogen-production technologies that result in near-zero net greenhouse gas emissions and use renewable energy sources, nuclear energy, and coal (when combined with carbon sequestration). To ensure sufficient clean energy for our overall energy needs, energy efficiency is also important.
- Hydrogen can be produced via various process technologies, including thermal (natural gas reforming, renewable liquid and bio-oil processing, and biomass and coal gasification), electrolytic (water splitting using a variety of energy resources), and photolytic (splitting water using sunlight via biological and electrochemical materials).
- Hydrogen can be produced in large, central facilities (50 to 300 miles from point of use) or in smaller semi-central facilities (located within 25 to 100 miles of use), or it can be distributed (near or at the point of use).
- To be successful in the marketplace, hydrogen must be cost competitive with the available alternatives. In the light-duty vehicle transportation market, this competitive requirement means that hydrogen needs to be available untaxed at $2 to $3 per gasoline gallon equivalent (GGE). This price would result in hydrogen fuel cell vehicles having the same cost to the consumer on a cost-per-mile-driven basis as a comparable conventional internal-combustion engine or hybrid vehicle.
- The USDOE is engaged in the research and development of a variety of hydrogen production technologies. Some are further along in development than others—some can be cost competitive for the transition period (beginning in 2015), and others are considered long-term technologies (cost-competitive after 2030).

Infrastructure is required to move hydrogen from the location where it is produced to the dispenser at a refueling station or stationary power site. Infrastructure includes the pipelines, trucks, railcars, ships, and barges that deliver fuel, as well as the facilities and equipment required to load and unload them. Delivery technology for a hydrogen infrastructure is currently available commercially, and several U.S. companies are delivering bulk hydrogen today. Some of the infrastructure is already in place because hydrogen has long been used in industrial applications, but it is not sufficient to support widespread consumer use of hydrogen as an energy carrier. Because hydrogen has a relatively low volumetric energy density, its transportation, storage, and final delivery to the point of use represent significant costs and result in some of the energy inefficiencies associated with using it as an energy carrier.

Options and trade-offs for hydrogen delivery from the production facilities to the point of use are complex. The choice of a hydrogen production strategy greatly affects the cost and method of delivery; for example, larger, centralized facilities can produce hydrogen at relatively low cost due to economies of scale, but the delivery costs are higher than for smaller, localized production facilities. Although these smaller production facilities would have relatively lower delivery costs, their hydrogen production costs are likely to be higher, as lower volume production means higher equipment costs on a per-unit-of-hydrogen basis.

Key challenges to hydrogen delivery include reducing delivery costs, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage. Further research is needed to analyze the trade-offs between the hydrogen production options and the hydrogen delivery options taken together as a system. Building a national hydrogen delivery infrastructure is a big challenge. Such an infrastructure will take time to develop and will likely include combinations of various technologies. Delivery infrastructure needs and resources will vary by region and type of market (e.g., urban, interstate, or rural). Infrastructure options will evolve as the demand for hydrogen grows and as delivery technologies develop and improve.

HYDROGEN STORAGE

Storing enough hydrogen on board a vehicle to achieve a driving range of greater than 300 miles is a significant challenge. On a weight basis, hydrogen has nearly three times the energy content of gasoline (120 MJ/kg for hydrogen vs. 44 MJ/kg for gasoline); however, on a volume basis, the situation is reversed (8 MJ/L for liquid hydrogen vs. 32 MJ/L for gasoline). On-board hydrogen storage in the range of 5 to 13 kg is required to encompass the full platform of light-duty vehicles. Hydrogen can be stored as either a gas or a liquid. Storage as a gas typically requires high-pressure tanks (5000- to 10,000-psi tank pressure). Storage of hydrogen as a liquid requires cryogenic temperatures, because the boiling point of hydrogen at 1 atmosphere pressure is –252.8°C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption). In adsorption, hydrogen is attached to the surface of a material as either hydrogen molecules or hydrogen atoms. In absorption, hydrogen is dissociated into H atoms, and then the hydrogen atoms are incorporated into the solid lattice framework. Hydrogen storage in solids may make it possible to store large quantities of hydrogen in smaller volumes at low pressures and at temperatures close to room temperature. It is also possible to achieve volumetric storage densities greater than those of liquid hydrogen because the hydrogen molecule is dissociated into atomic hydrogen within a metal hydride lattice structure. Finally, hydrogen can be stored through the reaction of hydrogen-containing materials with water (or other compounds such as alcohols). In this case, the hydrogen is effectively stored in both the material and the water. The terms *chemical hydrogen storage* and *chemical hydride* are used to describe this form of hydrogen storage. It is also possible to store hydrogen in the chemical structures of liquids and solids.

HOW A HYDROGEN FUEL CELL WORKS

A fuel cell uses the chemical energy of hydrogen to cleanly and efficiently produce electricity. Fuel cells have a variety of potential applications; for example, they can provide energy for systems as large as utility power stations or as small as laptop computers. Fuel cells offer several benefits over conventional combustion-based technologies currently used in many power plants and passenger vehicles. They produce much smaller quantities of greenhouse gases and none of the air pollutants that create smog and cause health problems. If pure hydrogen is used as a fuel, fuel cells emit only heat and water as byproducts.

DID YOU KNOW?

Hydrogen fuel cell vehicles (FCVs) emit approximately the same amount of water per mile as vehicles using gasoline-powered internal combustion engines (ICEs).

A hydrogen fuel cell is a device that uses hydrogen (or hydrogen-rich fuel) and oxygen to create electricity through an electrochemical process. A single fuel cell consists of an electrolyte and two catalyst-coated electrodes (a porous anode and a cathode). The various types of fuel cells all work similarly:

- Hydrogen (or hydrogen-rich fuel) is fed to an anode, where a catalyst separates the negatively charged hydrogen electrons from positively charged ions.
- At the cathode, oxygen combines with electrons and, in some cases, with species such as protons or water, resulting in water or hydroxide ions, respectively.
- For polymer electrolyte membrane and phosphoric acid fuel cells, protons move through the electrolyte to the cathode, where they combine with oxygen and electrons to produce water and heat.
- For alkaline, molten carbonate, and solid oxide fuel cells, negative ions travel through the electrolyte to the anode, where they combine with hydrogen to generate water and electrons.
- The electrons from the anode cannot pass through the electrolyte to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current.

ENVIRONMENTAL IMPACTS OF FUEL CELLS

Beyond the expectation that hydrogen leakage from its use in fuel cells could greatly impact the hydrogen cycle and could, when oxidized in the stratosphere, cool the stratosphere and create more clouds, delaying the break up of the polar vortex at the poles and making the holes in the ozone layer larger and longer lasting, little is understood about how hydrogen leakage would affect the environment. For example, much uncertainty exists over the extent of the impact of hydrogen emissions on soil absorption of hydrogen from the atmosphere. This concept is important because if we use extensive quantities of hydrogen for fuel cells, absorption of hydrogen by soils could have a compensatory effect on any possible anthropogenic emissions. Again, it is important to emphasize that little is understood about how hydrogen leakage would affect the environment.

PROPERTIES OF HYDROGEN

Hydrogen has unique physical and chemical properties that present benefits and challenges to its successful widespread adoption as a fuel. Hydrogen is the lightest and smallest element in the universe. Hydrogen is 14 times lighter than air and rises at a speed of almost 20 m/s, 6 times faster than natural gas, which means that when released it rises and disperses quickly. Hydrogen is also odorless, colorless, and tasteless, making it undetectable by human senses. For these reasons, hydrogen systems are designed with ventilation and leak detection. Natural gas is also odorless, colorless, and tasteless, but a sulfur-containing odorant is added so people can detect it. There is no known odorant light enough to travel with hydrogen at an equal dispersion rate, so odorants are not used to provide a detection method. Many odorants can also contaminate fuel cells.

THOUGHT-PROVOKING QUESTION

8.1 Are hydrogen fuel cells a viable energy option? Explain.

REFERENCES AND RECOMMENDED READING

NREL. (2009). *Ultracapacitors*. Washington, DC: National Renewable Energy Laboratory (http://www.nrel.gov/vehiclesandfuels/energystorage/ultracapacitors.html?print).

9 Carbon Capture and Sequestration

You cannot get through a single day without having an impact on the world around you—for better or for worse. What you do makes a difference.

—Jane Goodall

Human activities, especially the burning of fossil fuels such as coal, oil, and gas, have caused a substantial increase in the concentration of carbon dioxide (CO_2) in the atmosphere. This increase in atmospheric CO_2—from about 280 to more than 380 parts per million (ppm) over the last 250 years—is causing measureable global warming. Potential adverse impacts include sea-level rise; increased frequency and intensity of wildfires, floods, droughts, and tropical storms; changes in the amount, timing, and distribution of rain, snow, and runoff; and disturbance of coastal marine and other ecosystems. Rising atmospheric CO_2 is also increasing the absorption of CO_2 by seawater, causing the ocean to become more acidic, with potentially disruptive effects on marine plankton and coral reefs. Technically and economically feasible strategies are needed to mitigate the consequences of increased atmospheric CO_2.

USGS (2008)

Above all we should, in the century since Darwin, have come to know that man, while captain of the adventuring ship, is hardly the sole object of its quest, and that his prior assumptions to this effect arose from the simple necessity of whistling in the dark. These things, I say, should have come to us. I fear they have not come to many.

—Aldo Leopold (*A Sand County Almanac, and Sketches Here and There*, 1948)

INTRODUCTION TO CARBON CAPTURE AND SEQUESTRATION

The reader might wonder what carbon capture and sequestration (CCS) might have to do with the environmental impacts of renewable energy. Renewable energy has two pluses: (1) it is a possible source of energy now and in the future (it is renewable and sustainable) and will be called on to replace nonrenewable hydrocarbon energy sources as they are depleted; and (2) renewable energy produces little or no waste products such as carbon dioxide or other chemical pollutants, so it has minimal impact on the environment. It is the latter of these two pluses that is related to carbon capture and sequestration. That is, at the present time and in the near future we have (and will continue to have) an ongoing increase in atmospheric carbon dioxide. Many scientists agree that global climate change is occurring and that to prevent its most serious effects we must begin immediately to significantly reduce our greenhouse gas (GHG) emissions. One major contributor to climate change is the release of the greenhouse gas carbon dioxide (CO_2). This is the essence of the carbon capture and

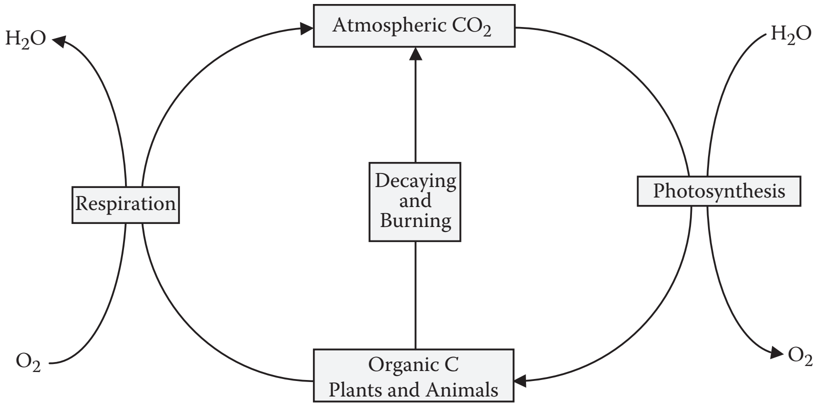

FIGURE 9.1 The global carbon cycle. Carbon naturally moves, or cycles, between the atmosphere and vegetation, soils, and the oceans over time scales ranging from years to millennia and longer. Human activities, primarily the burning of fossil fuels and clearing of forests, have increased the transfer of carbon as CO_2 to the atmosphere. Although some of the anthropogenic CO_2 is removed from the atmosphere by the natural uptake processes ("sinks") of the carbon cycle, much of it remains in the atmosphere and causes rising CO_2 concentrations. The goal of deliberate carbon sequestration is to decrease the net flux of CO_2 to the atmosphere by sequestering carbon in the oceans, vegetation, soils, and porous rock formations. (From USGS, *Carbon Sequestration to Mitigate Climate Change*, U.S. Geological Survey, Washington, DC, 2008.)

sequestration process: capturing and sequestering carbon dioxide. Further, to control atmospheric carbon dioxide requires deliberate mitigation with an approach that combines reducing emissions by utilizing renewable sources and by increasing capture and storage.

The term *carbon sequestration* is used to describe both natural and deliberate processes by which CO_2 is either removed from the atmosphere or diverted from emission sources and stored in the ocean, terrestrial environments (vegetation, soils, and sediments), and geologic formations. Before human-caused CO_2 emissions began to occur, the natural processes that make up the global carbon cycle (see Figure 9.1) maintained a near balance between the uptake of CO_2 and its release back to the atmosphere. However, existing CO_2 uptake mechanisms (sometimes called CO_2 or carbon *sinks*) are insufficient to offset the accelerating pace of emissions related to human activities. Annual carbon emissions from burning fossil fuels in the United States are about 1.6 gigatons (billion metric tons), whereas annual uptake amounts are only about 0.5 gigatons, resulting in a net release of about 1.1 gigatons per year (see Figure 9.2).

Scientists at the U.S. Geological Survey (USGS) and elsewhere are working to assess both the potential capacities and the potential limitations of the various forms of carbon sequestration and to evaluate their geologic, hydrologic, and ecological consequences. The USGS is providing information needed by decision makers and resource managers to maximize carbon storage while minimizing undesirable impacts on humans and their physical and biological environment.

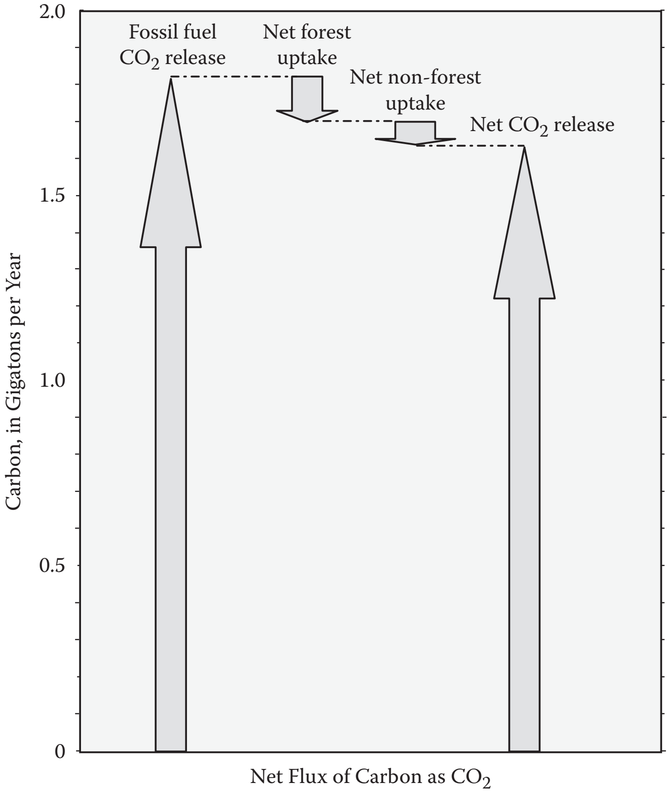

FIGURE 9.2 Estimated annual net CO_2 emissions and uptake in the United States in 2003, according to the U.S. Climate Change Science Program. U.S. fossil fuel CO_2 emissions accounted for more than 20% of the global total in 2003. Net uptake fluxes (photosynthesis minus oxidation) are shown for forest and non-forest areas. The largest net U.S. CO_2 uptake was associated with regrowing forests and harvesting wood products. Non-forest net carbon uptake—including accumulation in shrubs, agricultural soils, wetlands, rivers, and reservoirs—was smaller and more uncertain. (From USGS, *Carbon Sequestration to Mitigate Climate Change*, U.S. Geological Survey, Washington, DC, 2008.)

TERRESTRIAL CARBON SEQUESTRATION

Terrestrial sequestration (sometimes termed *biological sequestration*) is the removal of gaseous carbon dioxide from the atmosphere and binding it in living tissue by plants. Terrestrial sequestration is typically accomplished through forest and soil conservation practices that enhance the storage of carbon (such as restoring and establishing new forests, wetlands, and grasslands) or reduce CO_2 emissions (such as reducing agricultural tillage and suppressing wildfires). In the United States, these practices are implemented to meet a variety of land-management objectives. Although the net terrestrial uptake fluxes shown in Figure 9.2 offset about 30% of U.S. fossil fuel CO_2 emissions, only a small fraction of this uptake results from

DID YOU KNOW?

The world's oceans are the primary long-term sink for human-caused CO_2 emissions, currently accounting for a global net uptake of about 2 gigatons of carbon annually. This uptake is not a result of deliberate sequestration but instead occurs naturally through chemical reactions between seawater and CO_2 in the atmosphere. The absorption of atmospheric CO_2 causes the oceans to become more acidic. *Ocean acidification* (OA) is the term given to the chemical changes in the ocean as a result of carbon dioxide emissions. Many marine organisms and ecosystems depend on the formation of carbonate skeletons and sediments that are vulnerable to dissolution in acidic waters (see Figure 9.3). Laboratory and field measurements indicate that CO_2-induced acidification may eventually cause the rate of dissolution of carbonate to exceed its rate of formation in these ecosystems. The impacts of ocean acidification and deliberate ocean fertilization on coastal and marine food webs and other resources are poorly understood. Scientists are studying the effects of oceanic carbon sequestration on these important environments.

activities undertaken specifically to sequester carbon. The largest net uptake is due primarily to ongoing natural regrowth of forests that were harvested during the 19th and early 20th centuries.

Existing terrestrial carbon storage is susceptible to disturbances such as fire, disease, and change in climate and land use. Boreal forests, also known as *taiga*, and northern peatlands, which store nearly half the total terrestrial carbon in North American, are already experiencing substantial warming, resulting in large-scale thawing of permafrost and dramatic changes in aquatic and forest ecosystems. USGS scientists have estimated that at least 10 gigatons of soil carbon in Alaska are stored in organic soils that are extremely vulnerable to fire and decomposition under warming conditions.

The capacity of terrestrial ecosystems to sequester additional carbon is uncertain. An upper estimate of potential terrestrial sequestration in the United States might be the amount of carbon that would be accumulated if U.S. forests and soils were restored to their historic levels before they were depleted by logging and cultivation.

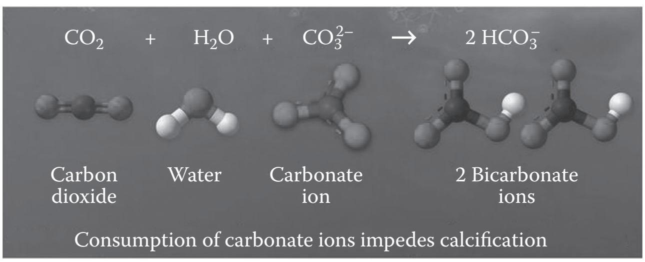

FIGURE 9.3 Ocean acidification. (From NOAA, *Ocean Acidification: The Other Carbon Dioxide Problem*, National Oceanic and Atmospheric Administration, Washington, DC, 2014, http://pmel.noaa.gov/co2/story/Ocean+Acidification.)

These amounts (about 32 and 7 gigatons for forests and soils, respectively) are probably not attainable by deliberate sequestration because restoration on this scale would displace a large percentage of U.S. agriculture and disrupt many other present-day activities. Decisions about terrestrial carbon sequestration require careful considerations of priorities and trade-offs among multiple resources. For example, converting farmlands to forests or wetlands may increase carbon sequestration, enhance wildlife habitat and water quality, and increase flood storage and recreational potential—but the loss of farmlands would decrease crop production. Converting existing conservation lands to intensive cultivation, while perhaps producing valuable corps (for example, for biofuels), may diminish wildlife habitat, reduce water quality and supply, and increase CO_2 emissions. Scientists are working to determine the effects of climate and land-use change on potential carbon sequestration and ecosystem benefits and to provide information about these effects for use in resource planning.

SIDEBAR 9.1. Urban Forests and Carbon Sequestration*

The urban environment presents important considerations for terrestrial carbon sequestration and global climate change. Over half of the world's population lives in urban areas (Population Reference Bureau, 2012). Because cities are more dense and walkable, urban per capita emissions of greenhouse gases (GHGs) are almost always substantially lower than average per capita emissions for the countries in which they are located (Cities Alliance, 2007; Romero-Lankao, 2008). Urban areas are more likely than non-urban areas to have adequate emergency services and so may be better equipped to provide critical assistance to residents in the case of climate-related stress and events such as heat waves, floods, storms, and disease outbreaks (Myers et al., 2013). However, cities are still major sources of GHG emissions (Dodman, 2009). Studies suggest that cities account for 40 to 70% of all GHG emissions worldwide due to resource consumption and energy, infrastructure, and transportation demands (USEPA, 2009). Highly concentrated urban areas, especially in coastal regions and in developing countries, are disproportionately vulnerable to extreme weather and infectious disease.

The term *urban forest* refers to all trees within a densely populated area, including trees in parks, on streetways, and on private property. Although the composition, health, age, extent, and costs of urban forests vary considerably among different cities, all urban forests offer some common environmental, economic, and social benefits. Urban forests play an important role in climate change mitigation and adaptation. Active stewardship of a community's forestry assets can strengthen local resilience to climate change while creating more sustainable and desirable places to live. Trees in a community help to reduce air and water pollution, alter heating cooling costs, and increase real estate values. Trees can improve physical and mental health and strengthen social connections, and they are associated with reduced crime rates. Trees, community gardens, and other green spaces get people outside, helping foster active living and neighborhood pride.

Like any forest, urban forests help mitigate climate change by capturing and storing atmospheric carbon dioxide during photosynthesis and by influencing energy needs for heating and cooling buildings. Trees typically reduce cooling costs, but they can increase or decrease winter heating use depending on their location around a building and whether they are evergreen or deciduous. In the contiguous United States alone, urban trees store over 708 million tons of carbon (approximately 12.6% of annual carbon dioxide emissions in the United States) and capture an additional 28.2 million tons of carbon (approximately 0.05% of annual

* Adapted from Safford, H. et al., *Urban Forests and Climate Change*, U.S. Department of Agriculture, Washington, DC, 2013.

emissions) per year (Nowak et al., 2013; USEPA, 2014). The value of urban carbon sequestration is substantial: approximately $2 billion per year, with a total current carbon storage value of over $50 billion (Nowak et al., 2013). Shading and reduction of wind speed by trees can help to reduce carbon emissions by reducing summer air conditioning and winter heating demand and, in turn, the level of emissions from supplying power plants (Nowak et al., 2010). Shading can also extend the useful life of street pavement by as much as ten years, thereby reducing emissions associated with the petroleum-intensive materials and operation of heavy equipment required to repave roads and haul away waste (McPherson and Muchnick, 2005). Establishing 100 million mature trees around residences in the United States would save an estimated $2 billion annually in reduced energy costs (Akbari et al., 1992; Population Reference Bureau, 2012). However, this level of tree planting would only offset less than 1% of U.S. emissions over a 50-year period (Nowak and Crane, 2002).

The sustainable use of wood, food, and other goods provided by the local urban forest may also help mitigate climate change by displacing imports associated with higher levels of carbon dioxide emitted during production and transport. Urban wood is a valuable and underutilized resource. At current utilization rates, forest products manufactured from felled urban trees are estimated to save several hundred million tons of CO_2 over a 30-year period. Furthermore, wood chips made from low-quality urban wood may be combusted for heat and power to displace an additional 2.1 million tons of fossil fuel emissions per year (Sherrill and Bratkovitch, 2011).

Urban forests enable cities to better adapt to the effect of climate change on temperature patterns and weather events. Cities are generally warmer than their surroundings (typically by about 1 to 2°C, although this difference can be as high as 10°C under certain climatic conditions), meaning that average temperature increases caused by global warming are frequently amplified in urban areas (Bristow et al., 2012; Kovats and Akhtar, 2008). Urban forests help control this "heat island" effect by providing shade, by reducing urban albedo (the fraction of solar radiation reflected back into the environment), and through cooling evapotranspiration (Bristow et al., 2012; Novak et al., 2010; Romero-Lankao, 2008). Cities are also particularly susceptible to climate-related threats such as storms and flooding. Urban trees can help control runoff from these by catching rain in their canopies and increasing the infiltration rate of deposited precipitation. Reducing stormwater flow reduces stress on urban sewer systems by limiting the risk of hazardous combined sewer overflows (Fazio, 2010). Furthermore, well-maintained urban forests help buffer high winds, control erosion, and reduce drought (Cullington and Gye, 2010; Fazio, 2010; Nowak et al., 2010).

Urban forests provide critical social and cultural benefits that may strengthen community resilience to climate change. Street trees can hold spiritual value, promote social interaction, and contribute to a sense of place and family for local residents (Dandy, 2010). Overall, forested urban areas appear to have potentially stronger and more stable communities (Dandy, 2010). Community stability is essential to the development of effective long-term sustainable strategies for addressing climate change (Williamson et al., 2010). For example, neighborhoods with stronger social networks are more likely to check on the elderly and other vulnerable residents during heat waves and other emergencies (Klinenberg, 2002).

Urban forests help control the causes and consequences of climate-related threats; however, forests may also be negatively impacted by climate change. Although increased carbon dioxide levels and water temperature may initially promote urban tree growth by accelerating photosynthesis, too much warming in the absence of adequate water and nutrients stresses trees and retards future development (Tubby and Webber, 2010). Warmer winter temperatures increase the likelihood of winter kill, in which trees, responding to their altered environment, prematurely begin to circulate water and nutrients in their vascular tissue. If rapid cooling follows these unnatural warm periods, tissues will freeze and trees will sustain injury or death.

Warmer winter temperatures favor many populations of tree pest and pathogen species normally kept at low levels by cold winter temperatures (Tubby and Webber, 2010). Although climate change may reduce populations of some species, many others are better able than their arboreal host to adapt to changing environments due to their short lifecycles and rapid evolutionary capacity (Cullington and Gye, 2010; Tubby and Webber, 2010). The consequences of these population changes are compounded by the fact that hot, dry environments enrich carbohydrate concentrations in tree foliage, making urban trees more attractive to pests and pathogens (Tubby and Webber, 2010).

Climate change alters water cycles in ways that impact urban forests. Increased winter precipitation puts urban forests at greater risk from physical damage due to increased snow and ice loading (Johnston, 2004). Increased summer evaporation and transpiration create water shortages often exacerbated by urban soil compaction and impermeable surfaces. More frequent and intense extreme weather events increase the likelihood of severe flooding, which may uproot trees and cause injury or death to tree root systems if waterlogged soils persist for prolonged periods (Johnston, 2004).

Especially cold regions may benefit from increased tourism, agricultural productivity, and ease of transport as a result of climate change (Romero-Lankao, 2008). The potential positive implications of climate change, however, are far eclipsed by the negative (Parry et al., 2007). Rising temperatures, increased pest and pathogen activity, and water-cycle changes impose physiological stresses on urban forests that compromise forest ability to deliver ecosystems services that protect against climate change. Climate change will also continue to alter species ranges and regeneration rates, further affecting the health and composition of urban forests (Nowak, 2010; Ordonez et al., 2010). Proactive management is necessary to protect urban forests against climate-related threats and to sustain desired urban forest structures for future generations.

GEOLOGIC CARBON SEQUESTRATION

Geologic sequestration begins with capturing carbon dioxide from the exhaust of fossil fuel power plants and other major sources. The captured carbon dioxide is piped 1 to 4 kilometers below the land surface and injected into porous rock formations. Compared to the rates of terrestrial carbon uptake shown in Figures 9.1 and 9.2, geologic sequestration is currently used to store only small amounts of carbon per year. Much larger rates of sequestration are envisioned to take advantage of the potential permanence and capacity of geologic storage.

The permanence of geologic sequestration depends on the effectiveness of several carbon dioxide trapping mechanisms. After carbon dioxide is injected underground, it will rise buoyantly until it is trapped beneath an impermeable barrier, or seal. In principle, this physical trapping mechanism, which is identical to the natural geologic trapping of oil and gas, can retain carbon dioxide for thousands to millions of years. Some of the injected carbon dioxide will eventually dissolve in groundwater, and some may be trapped in the form of carbonate minerals formed by chemical reactions with the surrounding rock. All of these processes are susceptible to change over time following carbon dioxide injection. Scientists are studying the permanence of these trapping mechanisms and developing methods to determine the potential for geologically sequestered carbon dioxide to leak back to the atmosphere.

The capacity for geologic carbon sequestration is constrained by the volume and distribution of potential storage sites. According to the U.S. Department of Energy, the total storage capacity of physical traps associated with depleted oil and gas reservoirs in the United States is limited to about 38 gigatons of carbon and is geographically distributed in locations that are distant from most U.S. fossil fuel power plants. The potential U.S. storage capacity of deep porous rock formations that contain saline groundwater is much larger (estimated by the U.S. Department of Energy to be about 900 to 3400 gigatons of carbon) and more widely distributed, but less is known about the effectiveness of trapping mechanisms at these sites. Unmineable coal beds have also been proposed for potential carbon dioxide storage, but more information is needed about the storage characteristics and impacts of carbon dioxide injection in these formations. Scientists are developing methods to refine estimates of the national capacity for geologic carbon sequestration.

To fully assess the potential for geologic carbon sequestration, economic costs and environmental risks must be taken into account. Infrastructure costs will depend on the locations of suitable storage sites. Environmental risks may include seismic disturbances, deformation of the land surface, contamination of portable water supplies, and adverse effects on ecosystems and human health. Many of these environmental risks and potential environmental impacts are discussed in the sections that follow.

POTENTIAL IMPACTS OF TERRESTRIAL SEQUESTRATION

Potential environmental impacts associated with terrestrial sequestration include ground disturbance and the loss of soil resources due to erosion; equipment-related noise; visual impacts; air emissions; disturbance of ecological, cultural, and paleontological resources; and conflicts with current or proposed land uses. Establishing and managing a terrestrial sequestration plot could involve ground clearing (removal of vegetative cover) to prepare the ground for planting, grading, vehicular traffic, and pedestrian traffic. Management could require the use of water for dust control, and in some cases water could be required to establish and maintain seeds, seedlings, or crops. The addition of soil additives such as fertilizer and pesticides could have an impact on water quality. Equipment used to maintain a terrestrial sequestration plot could be a source of noise and air emissions and create a visual impact if frequent and conspicuous use was required.

Ecological, cultural, and paleontological resources could be impacted, especially if a terrestrial sequestration plot is going to replace an established ecological habitat or otherwise impact undisturbed land that hosts important cultural or paleontological resources. Impacts on land use could occur if there were conflicts with existing land use plans—for example, if land zoned for future commercial or housing development is used to establish a forest sequestration plot.

Soil resources can also be impacted by terrestrial sequestration. The careful management of a sequestration plot should result in an improvement of soil resources, but poor management practices could adversely impact soils and the viability of the sequestration project. Practices such as no-till cultivation and planting, crop rotation, and the use of cover crops should result in the maintenance of soil organic material

and nutrients and an increase in the relative health of soil resources. Some management practices, however, could involve the use of hazardous materials such as herbicides to kill a cover crop before planting the terrestrial sequestration crop.

POTENTIAL IMPACTS OF GEOLOGIC SEQUESTRATION

The potential impacts of geologic sequestration, including the transportation of carbon, are discussed in this section. For this discussion, it is assumed that carbon capture would likely occur at a single power generating station. Because captured carbon may have to be transported for some distance away from the power station, transport, in general, has been evaluated. The significance of the impacts depends upon factors such as the number and size of transport pipelines and injection wells, the amount of land disturbed by drilling and transport activities, the amount of land occupied by facilities over the life of the sequestration project, the project's location with respect to other resources (e.g., wildlife use, distance to surface water bodies), and so forth.

Geologic Sequestration Exploration Impacts

Activities during the exploration phase (including seismic surveys, testing, and exploratory drilling) are temporary and are conducted at a smaller scale than those at the drilling/construction, sequestration, and decommissioning/reclamation phases. The impacts described for each resource would result from typical exploration activities, such as localized ground clearing, vehicular traffic, seismic testing, positioning of equipment, and exploratory drilling. Most impacts during the exploration phase would be associated with the development of access roads and exploratory wells. Impacts on resources would be similar in character, but lesser in magnitude, to those for the drilling phase. Potential impacts from these activities are presented below, by the type of affected resource.

Air Quality

Impacts on air quality during exploration activities would include emissions and dust from earth-moving equipment, vehicles, seismic surveys, well completion and testing, and drill rig exhaust. Pollutants would include particulates, oxides of nitrogen, carbon monoxide, sulfur dioxide, and volatile organic compounds (VOCs). Nitrogen oxides and VOCs may combine to form ground-level ozone. Impacts would depend on the amount, duration, location, and characteristics of the emission and the meteorological conditions (e.g., wind speed and direction, precipitation, relative humidity). Emissions during this phase would not have a measurable impact on climate change.

Cultural Resources

During the exploration phase, soil surface and subsurface disturbance is minimal. Cultural resources buried below the surface are unlikely to be affected; however, material present on the surface could be disturbed by vehicular traffic, ground clearing, and pedestrian activity (including collection of artifacts). Exploration activities could affect areas of interest to Native Americans, depending on the placement of equipment and level of visual intrusion. Surveys conducted during

this phase to evaluate the presence and significance of cultural resources in the area would assist developers in siting project facilities, in order to avoid or minimize impacts on these resources.

Ecological Resources

Impacts on ecological resources (vegetation, wildlife, aquatic biota, special status species, and their habitats) would be minimal and localized during exploration due to the limited nature of the activities. The introduction or spread of some nonnative invasive vegetation could occur as a result of vehicular traffic but would be relatively limited in extent. Seismic surveys could disturb wildlife. Exploratory well establishment would destroy vegetation and impact wildlife. Surveys conducted during this phase to evaluate the presence and significance of ecological resources in the area would assist developers in siting project facilities to avoid or minimize impacts on these resources.

Water Resources

Minimal impact on water resources (water quality, water flows, and surface water/groundwater interactions) would be anticipated from exploration activities. Exploratory wellbores may provide a path for surface contaminants to come into contact with groundwater or for waters from subsurface formations to commingle. They may also decrease pressure in water wells and affect their quality. Very little produced water would likely be generated during the exploration phase. Most water needed to support drilling operations could be trucked in from offsite.

Land Use

Temporary and localized impacts on land use would result from exploration activities. These activities could create a temporary disturbance in the immediate vicinity of a surveying or monitoring site or an exploratory well (e.g., disturb recreational activities or livestock grazing). Exploration activities are unlikely to affect mining activities, military operations, or aviation.

Soils and Geologic Resources

Surface effects from vehicular traffic could occur in areas that contain special (e.g., cryptobiotic) soils. The loss of biological crusts can substantially increase water and wind erosion. Also, soil compaction due to development activities at the exploratory well pads and along access roads would reduce aeration, permeability, and water-holding capacity of the soils and cause an increase in surface runoff, potentially causing increased sheet, rill, and gully erosion. The excavation and reapplication of surface soils could cause the mixing of shallow soil horizons, resulting in a blending of soil characteristics and types. This blending would modify physical characteristics of the soils, including structure, texture, and rock content, which could lead to reduced permeability and increased runoff from these areas. Potential impacts on geologic and mineral resources would include depletion of hydrocarbons and sand and gravel resources. It is unlikely that exploration activities would activate geological hazards. Impacts on soils and geologic resources would be proportional to the amount of disturbance. The amount of surface disturbance and use of geologic materials during exploration would be minimal.

Paleontological Resources

Paleontological resources are nonrenewable resources. Disturbance of such resources, whether it is through mechanical surface disturbance, erosion, or paleontological excavation, irrevocably alters or destroys them. Direct impacts on paleontological resources would include surface disturbance during seismic surveys, the drilling of exploratory wells, and the construction of access roads and other ancillary facilities. The amount of subsurface disturbance is minimal during the exploration phase, and paleontological resources buried below the surface are unlikely to be affected. Fossil material present on the surface could be disturbed by vehicular traffic, ground clearing, and pedestrian activities (including collection of fossils). Surveys conducted during this phase to evaluate the presence and significance of paleontological resources in the area would assists developers in siting project facilities in order to avoid or minimize impacts on these resources.

Transportation

No impacts on transportation are anticipated during the exploration phase. Transportation activities would be temporary and intermittent and limited to low volumes of light utility trucks and personal vehicles.

Visual Resources

Impacts on visual resources would be considered adverse if the landscape were substantially degraded or modified. Exploration activities would have only temporary and minor visual effects, resulting from the presence of drill rigs, workers, vehicles, and other equipment.

Socioeconomics

As the activities conducted during the exploration phase are temporary and limited in scope, they would not result in significant socioeconomic impacts on employment, local services, or property values.

Environmental Justice

Exploration activities are limited and would not result in significant adverse impacts in any resource area; therefore, environmental justice is not expected to be an issue during this phase.

Acoustics (Noise)

Primary sources of noise associated with exploration include earth-moving equipment, vehicle traffic, seismic survey, blasting, and drill rig operations.

Hazardous Materials and Waste Management

Seismic and exploratory well crews may generate waste (e.g., plastic, paper, containers, fuel leaks/spills, food, human waste). Wastes produced by exploratory drilling would be similar but would occur to a lesser extent than those produced during drilling and operation of injection wells. The would include drilling fluid and muds, used oil and filters, spilled fuel, drill cuttings, spent and unused solvents, scrap metal, solid waste, and garbage.

Geologic Sequestration Drilling/Construction Impacts

Typical activities during the drilling/construction phase of a sequestration project include ground clearing and removal of vegetative cover, grading, drilling, waste management, vehicular and pedestrian traffic, and construction and installation of facilities. Activities conducted in locations other than at the injection well-pad site may include excavation and blasting for construction materials (sands, gravels), access road and storage area construction, and construction of pipelines, compressor stations, pumping stations, and other facilities (e.g., office buildings). Potential impacts from these activities are presented below, by the type of affected resource.

Air Quality

Emissions generated during the drilling/construction phase include vehicle emissions; diesel emissions from large construction equipment and generators, storage/dispensing of fuel, and, if installed at this stage, flare stacks; small amounts of carbon monoxide, nitrogen oxides, and particulates from blasting activities; and dust from many sources, such as disturbing and moving soils (clearing, grading, excavation, trenching, backfilling, dumping, and truck and equipment traffic), mixing concrete, and drilling. During windless conditions (especially in areas of thermal inversion), project-related odors may be detectable at more than a mile from the source. Excess increases in dust could decrease forage palatability for wildlife and livestock and increase the potential for dust pneumonia.

Cultural Resources

Potential impacts on cultural resources during the drilling/construction phase could include the following:

- Destruction of cultural resources in areas undergoing surface disturbance
- Unauthorized removal of artifacts or vandalism as a result of human access to previously inaccessible areas (resulting in lost opportunities to expand scientific study and educational and interpretive uses of these resources)
- Visual impacts resulting from large areas of exposed surface, increases in dust, and the presence of large-scale equipment, machinery, and vehicles for cultural resources that have an associated landscape component that contributes to their significance (e.g., sacred landscapes, historic trails)

Although the potential for encountering buried sites is relatively low, the possibility that buried sites would be disturbed during pipeline, access road, or well-pad construction does exist. Unless the buried site is detected early in the surface-disturbing activities, the impact on the site can be considerable. Disturbance that uncovers cultural resources of significant importance that would otherwise have remained buried and unavailable could be viewed as a beneficial impact. Vibration, resulting from increased traffic and drilling/development activities, may also have effects on rock art and other associated sites (e.g., sites with standing architecture).

Ecological Resources

Impacts on ecological resources would be proportional to the amount of surface disturbance and habitat fragmentation. Vegetation and topsoil would be removed for the development of well pads, access roads, pipelines, and other ancillary facilities. This would lead to a loss of wildlife habitat, reduction in plant diversity, potential for increased erosion, and potential for the introduction of invasive or noxious weeds. The recovery of vegetation following interim and final reclamation would vary by community (e.g., grasslands would recover before sagebrush or forest habitats). Indirect impacts on vegetation would include increased deposition of dust, spread of invasive and noxious weeds, and the increased potential for wildfires. Dust settling on vegetation may alter or limit a plant's ability to photosynthesize or reproduce. Over time, a composition of native and/or invasive vegetation would become established in areas disturbed by wildfire. Although injection field development would likely increase the spread of invasive and noxious weeds by increasing traffic and human activity, the potential impacts could be partially reduced by interim reclamation and implementation of mitigation measures. Adverse impacts on fish and wildlife could occur during the drilling/construction phase due to

- Erosion and runoff
- Dust
- Noise
- Introduction and spread on invasive nonnative vegetation
- Modification, fragmentation, and reduction of habitat
- Mortality of biota
- Exposure to contaminants
- Interference with behavioral activities
- Increased harassment and/or poaching

Depletion of surface waters from perennial streams could result in a reduction of water flow, which could lead to habitat loss and/or degradation of aquatic species.

Water Resources

Impacts on water resources could occur due to water quality degradation from increases in turbidity, sedimentation, and salinity; spills; cross-aquifer mixing; and water quantity depletion. During the drilling/construction phase, water would be required for dust control, making concrete, consumptive use by the construction crew, and drilling wells. Depending on availability, it may be trucked in from offsite or obtained from local groundwater wells or nearby surface water bodies. Where surface waters are used to meet drilling and construction needs, depletion of stream flows could occur. Drilling and well completion can require the use of drilling fluids that could, if not managed properly, contaminate soils and surface water features. Drilling activities may affect surface and groundwater flows. If a well is completed improperly, such that subsurface formations are not sealed off by the well casing and cement, aquifers can be impacted by other nonpotable formation waters.

The interaction between surface water and groundwater may also be affected if the two are hydrologically connected, potentially resulting in unwanted dewatering or recharging. Soils compacted on existing roads, new access roads, and well pads generate more runoff than undisturbed sites. The increased runoff could lead to slightly higher peak storm flows into streams, potentially increasing erosion of the channel banks. The increased runoff could also lead to more efficient sediment delivery and increase turbidity during storm events. During drilling and construction, water quality can be affected by

- Activities that cause soil erosion or dust that can be washed into water bodies
- Weathering of newly exposed soils, causing leaching and oxidation that can release chemicals into the water
- Increased salinity levels resulting from increased sediment loading
- Discharges of waste or sanitary water
- Use of herbicides and dust suppressants (e.g., magnesium chloride)
- Contaminant spills

Land Use

Land use impacts would occur during the drilling/construction phase if there are conflicts with existing land use plans and community goals; existing recreational, educational, religious, scientific, or other use areas; or existing commercial land use (e.g., agriculture, grazing, mineral extraction). In general, the development of large-scale geologic sequestration facilities and transport pipelines is expected to change the character of the landscape from a rural to a more industrialized setting. Existing land use would be affected by intrusive impacts such as increased traffic, noise, dust, and human activity, as well as by changes in the visual landscape. In particular, these impacts could affect recreationists seeking solitude or recreational opportunities in a relatively pristine landscape. Ranchers or farmers could be affected by loss of available grazing or crop lands, the potential for the introduction of invasive and noxious plants that could affect livestock forage availability, and a possible increase in livestock/vehicle collisions. In forested areas, drilling could result in the long-term loss of timber resources. The expanded access road system could increase the numbers of off-highway vehicle (OHV) users, hunters, and other recreationists in the area. Although the change in landscape character could discourage hunters who prefer a more remote backcountry setting, the potential for illegal hunting activities could increase due to the expanded access road system. Construction and drilling noise could potentially be heard 20 miles (32 kilometers) or more from the project area. It would be barely audible at this distance, but it could affect residents' and recreationists' perception of solitude. Most land use impacts that occur during the drilling/construction phase would continue throughout the life of the sequestration project. Overall, land use impacts could range from minimal to significant depending on both the areal extent of the project, the density of injection wells and other ancillary facilities, and the compatibility of the project with the existing land uses.

Soils and Geologic Resources

Potential impacts on soils during the drilling/construction phase would occur due to the removal of vegetation, mixing of soil horizons, soil compaction, increased susceptibility of the soils to wind and water erosion, contamination of soils from spills of hazardous materials (e.g., drilling mud, fluids used to hydraulically fracture subsurface formations), loss of topsoil productivity, and disturbance of biological soil crusts. Impacts on soils would be proportionate to the amount of disturbance. Sands, gravels, and quarry stone could be excavated for use in the construction of access roads, foundations, and ancillary structures, in addition to well pads and storage areas. Construction of well pads, pipelines, compressors or pumping stations, access roads, and other project facilities could cause topographic changes. These changes would be minor but long term. Well pads located on canyon rims of the side slopes of canyons could result in bedrock disturbances. Additional bedrock disturbance could occur due to the construction of access roads, pipelines, rock borrow pits, and other ancillary facilities. Possible geological hazards (earthquakes, landslides, and subsidence) could be activated by drilling and blasting. Altering drainage patterns could also accelerate erosion and create slope instability.

Paleontological Resources

Impacts on paleontological resources can occur directly from construction and drilling activities or indirectly as a result of soil erosion and increased accessibility to fossil localities (e.g., unauthorized removal of fossil resources or vandalism to the resource). This would result in lost opportunities to expand scientific study and educational interpretive uses of these resources. Disturbance that uncovers paleontological resources of significant importance that would otherwise have remained buried and unavailable could be viewed as a beneficial impact. Direct impacts on unknown paleontological resources can be anticipated to be proportional to the total area impacted by construction and drilling activities.

Transportation

Development of a geologic sequestration project would result in the need to construct or improve access roads and would result in an increase in industrial traffic (e.g., hundreds of truck loads or more per well site). Overweight and oversized loads could cause temporary disruptions and could require extensive modifications to roads or bridges (e.g., widening roads or fortifying bridges to accommodate the size or weight of truck loads). An overall increase in heavy truck traffic would accelerate the deterioration of pavement, requiring local government agencies to schedule pavement repair or replacement more frequently than under the existing traffic conditions. Increased traffic would also result in a potential for increased accidents within the project area. The locations at which accidents are most likely to occur are intersections used by project-related vehicles to turn onto or off of highways from access roads. Conflicts between industrial traffic and other traffic are likely to occur, especially on weekends, holidays, and seasons of high use by recreationists. Increased recreational use of the area could contribute to a gradual increase in traffic on the access roads. Over 1000 truckloads per well could be expected during the drilling/construction phase.

Visual Resources

During the drilling/construction phase, impacts on visual resources would occur as a result of the addition of well pads, pipelines, access roads, and other facilities which would result in an industrial landscape throughout the project area. Additional components that would adversely affect the visual character of the landscape are pumping units, compressor stations, aggregate borrow areas, equipment storage areas, and, if needed, worker housing units and airstrips. Project facilities would introduce new elements of form, line, color, and texture into the landscape, which would dominate foreground views. In some instances, the facilities would also be visible from greater distances and could, occasionally, dominate the view. Vehicles and the dust they generate would also contribute to visual impacts. Because drilling activities typically take place 24 hours per day, visual impacts would include lighting of drill rigs during nighttime hours. Nighttime lighting on drill rigs would be visible from long distances.

Socioeconomics

Drilling/construction phase activities would contribute to the local economy by providing employment opportunities, monies to local contractors, and recycled revenues through the local economy. Additional revenues could be generated in the form of carbon avoidance-type emission credits sold by the sequestration facility operator in a commodity market. Taxes collected by federal, state, and local governments could also be involved for transportation, injection, and regulation of the sequestration project. Indirect impacts could occur as a result of the new economic development (e.g., new jobs at businesses that support the expanded workforce or that provide project materials). Depending on the source of the workforce, local increases in population could occur. Development of an injection well field also could potentially affect property values, either positively from increased employment effects or negatively from proximity to the field and any associated or perceived adverse environmental effects (e.g., noise of compressor stations, visual effects, air quality). Some economic losses could occur if recreationists (including hunters and fishermen) avoid the area. Increased growth of the transient population could contribute to increased criminal activities in the project area (e.g., robberies, drugs).

Environmental Justice

If significant impacts were to occur in any of the resource areas and these were to disproportionately affect minority or low-income populations, there could be an environmental justice impact. It is anticipated that the drilling/construction phase could benefit low-income, minority, and tribal populations by creating job opportunities and stimulating local economic growth via project revenues and increased tourism. However, noise, dust, visual impacts, and habitat destruction could have an adverse effect on traditional tribal life ways and religious and cultural sites. Development of wells and ancillary facilities could affect the natural character of previously undisturbed areas and transform the landscape into a more industrialized setting. Drilling and construction activities could impact the use of cultural sites for traditional tribal activities (hunting and plant-gathering activities and areas in which artifacts, rock art, or other significant cultural sites are located).

Acoustics (Noise)

Primary sources of noise during the drilling/construction phase would be equipment (bulldozers, drill rigs, and diesel engines). Other sources of noise include vehicular traffic and blasting. Blasting activities typically would be very limited, the possible exception being in areas where the terrain is hilly and bedrock shallow. With the exception of blasting, noise would be restricted to the immediate vicinity of the work in progress. Noise from blasting would be sporadic and of short duration but would carry for long distances. If noise-producing activities occur near a residential area, noise levels from blasting, drilling, and other activities could exceed U.S. Environmental Protection Agency (USEPA) guidelines. The movement of heavy vehicles and drilling could result in frequent or continuous noise. Drilling noise would occur continuously for 24 hours per day for one to two months or more depending on the depth of the formation. Exploratory wells that end up becoming injection wells would continue to generate noise during the sequestration phase.

Hazardous Materials and Waste Management

Solid and industrial wastes would be generated during the drilling/construction phase. Much of the solid wastes would be expected to be nonhazardous, considering of containers and packaging materials, miscellaneous wastes from equipment assembly and the presence of construction crews (food wrappers and scraps), and woody vegetation. Industrial wastes would include minor amounts of paints, coatings, and spent solvents. Most of these materials would likely be transported offsite for disposal. In forested areas, commercial-grade timber could be sold, while slash may be spread or burned near the well site. Drilling wastes include hydraulic fluids, pipe dope, used oils and oil filters, rigwash, spilled fuel, drill cuttings, drums and containers, spent and unused solvents, paint and paint washes, sandblast media, scrap metal, solid waste, and garbage. Wastes associated with drilling fluids include oil derivatives, such as polycyclic aromatic hydrocarbons (PAHs), spilled chemicals, suspended and dissolved solids, phenols, cadmium, chromium, copper, lead, mercury, nickel, and drilling mud additives, including potentially harmful contaminants such as chromate and barite. Adverse impacts could result if hazardous wastes are not properly handled and are released to the environment.

Geologic Sequestration Operations Impacts

Typical activities during the operations phase include operation of wells and compressor stations or pump stations, waste management, and maintenance and replacement of facility components. Impacts could also result from the fact that a geologic sequestration project could be linked to an enhanced oil recovery or enhanced coalbed methane recovery project.

Air Quality

The primary emission sources during the operations phase would include compressor and pumping station operations, vehicle traffic, and operating wells. Venting of carbon dioxide may occur during injection and pipeline maintenance operations.

Cultural Resources

During the operations phase, impacts on cultural resources could occur primarily from the unauthorized collection of artifacts and from visual impacts. In the latter case, the presence of the aboveground structures could impact cultural resources with an associated landscape component that contributes to their significance, such as a sacred landscape or historic trail. Damage to localities caused by off-highway vehicle (OHV) use could also occur. The potential for indirect impacts (e.g., vandalism, unauthorized collecting) would be greater during the operations phase compared to the drilling/construction phase, due to the longer duration of the operations phase.

Ecological Resources

During the operations phase, adverse impacts on ecological resources could result from

- Disturbance of wildlife from noise and human activity
- Exposure of biota to contaminants
- Mortality of biota from colliding with aboveground facilities or vehicles

Ecological resources may continue to be affected by the reduction in habitat quality associated with habitat fragmentation due to the presence of operating wells, pipelines, ancillary facilities, and access roads. In addition, the presence of access roads may increase human use of surrounding areas, which, in turn, could impact ecological resources in the surrounding areas through

- Introduction and spread of invasive nonnative vegetation
- Fragmentation of habitat
- Disturbance of biota
- Increase in hunting (including poaching)
- Increased potential for fire

The presence of an injection well field could also interfere with migratory and other behaviors of some wildlife. In some coal bed methane production areas, methane gas or carbon dioxide gas could seep up into fields and create dead zones. High levels of carbon dioxide could asphyxiate wildlife in their burrows.

Water Resources

During the life of an injection well, the integrity of the well casing and cement will determine the potential for adverse impacts on groundwater. If subsurface formations are not sealed off by the well casing and cement, aquifers can be impacted by other nonpotable formation waters, hydraulic fracturing fluids, or the injected carbon dioxide. Other potential impacts on water availability and quality during the operations phase would include possible minor degradation of water quality resulting from vehicular traffic and machinery operations during maintenance (e.g., erosion, sedimentation) or herbicide contamination resulting from improper application. A spill or blowout could potentially cause extensive contamination of surface waters or a shallow aquifer. Contaminated groundwater could potentially be discharged into

springs or as base flow into stream channels, leading to surface water contamination. Recovered waters used for hydraulic fracturing could cause altered surface water quality or an increase in flows in normally dry water bodies such as ephemeral drainages, if they are disposed of by discharge to the surface.

With regard to hydraulic fracturing wastewater discharge into the environment, a point of interest is that the Clean Water Act (CWA) made it unlawful to discharge any pollutant from a point source into the navigable waters of the United States unless done in accordance with a specific approved permit. The National Pollutant Discharge Elimination System (NPDES) permit program controls discharges from point sources that are discrete conveyances, such as pipes or man-made ditches. Industrial, municipal, and other facilities such as shale gas production sites or commercial facilities that handle the disposal or treatment of shale gas produced water must obtain permits if they intend to discharge directly into surface water. Large facilities usually have individual NPDES permits. Discharges from some smaller facilities may be eligible for inclusion under general permits that authorize a category of discharge under the CWA within a geographic area. A general permit is not specifically tailored to an individual discharger. Most oil and gas production facilities with related discharges are authorized under general permits because there are typically numerous sites with common discharges in a geographic area.

Land Use

Land use impacts during the operations phase would be an extension of those that occurred during the drilling/construction phase; however, to some extent, land can revert to its original uses after the major drilling/construction phase is over. For example, farmers can graze livestock or grow crops around the well sites. Other industrial projects would likely be excluded within the sequestration project area. Recreation activities (e.g., OHV use, hunting) are possible, although gun and archery restrictions would probably exist. Operations may conflict with livestock and farming operations.

Soils and Geologic Resources

Following construction and drilling, disturbed portions of well and ancillary facility sites not required for operations would be revegetated. This would help to stabilize soil and geologic conditions. Routine impacts on soils during the operations phase would be limited largely to soil erosion impacts caused by vehicular traffic. Any excavations required for maintenance would cause impacts similar to those from the drilling/construction phase, but to a lesser spatial and temporal extent. The accidental spill of product or other wastes would likely cause soil contamination. Except in the case of a large spill, soil contamination would be localized and limited in extent and magnitude. In areas where interim reclamation is implemented (e.g., reclamation of an individual well that is no longer needed), ground cover by herbaceous species could reestablish within 1 to 5 years following seeding of native plant species and diligent weed control efforts, thus reducing soil erosion. Operations might preclude or interfere with mineral development activities in the project area, including oil and gas development and mining activities. Possible geological hazards (earthquakes, landslide, and subsidence) could be activated by injection activities.

Paleontological Resources

Impacts on paleontological resources during the operations phase would be limited primarily to unauthorized collection of fossils. This threat is present once the access roads are constructed, making remote areas more accessible to the public. Damage to localities caused by OHV use could also occur. The potential for indirect impacts (e.g., vandalism, unauthorized collecting) would be greater during the operations phase compared to the drilling/construction phase, due to its longer duration.

Transportation

Impacts on transportation during the operations phase would be similar to those for the drilling/construction phase. However, unless carbon dioxide is transported to the site by truck or rail, daily traffic levels, particularly heavy truck traffic, would be expected to be lower during the operations phase compared to the drilling/construction phase. For the most part, heavy truck traffic would be limited to periodic visits to a well site for workovers and formation treatment. The use of pipelines to convey carbon dioxide to the operating site would reduce the volume of traffic during the operations phase. If a pipeline is not used for the injection well field, multiple truckloads per day would be needed.

Visual Resources

Once operating facilities are installed, portions of well pads, access roads, and pipeline rights-of-way (ROWs) that are not needed for operations would be reclaimed; however, much of the disturbed area would continue to contrast with the natural form, line, color, and texture of the surrounding landscape. This would impact undisturbed vistas and areas of solitude. The aboveground portions of an injection well would be highly visible in rural or natural landscapes, many of which may have a few other comparable structures. The artificial appearance of an injection well may have visually incongruous "industrial" associations for some, particularly in a predominately natural landscape. Any nighttime lighting would be visible from long distances. During the operations phase, indirect impacts on visual resources would occur as a result of sequestration activities (e.g., industrial traffic, heavy equipment use, dust); however, human activity would be substantially lower than during the drilling/construction phase.

Socioeconomics

Direct socioeconomic impact would include the creation of new jobs and the associated royalties and taxes paid for carbon emission avoidance created by the sequestration project. Indirect impacts are those impacts that would occur as a result of the new economic development and would include new jobs at businesses that support the expanded workforce or that provide project materials, and associated taxes. Potential impacts on the value of residential properties located adjacent to an oil or gas field would continue during this phase.

Environmental Justice

Possible environmental justice impacts during the operations phase include the alteration of scenic quality in areas of traditional or cultural significance to minority populations. Noise and health and safety impacts are also potential sources of disproportionate impacts for minority or low-income populations.

Acoustics (Noise)

The main sources of noise during the operations phase would include compressor and pumping stations, producing wells (including occasional flaring), and vehicle traffic. Compressor stations produce noise levels ranging from 64 to 86 dBA at the station and from 58 to 75 dBA at about 1 mile (1.6 kilometers) from the station. Use of remote telemetry equipment would reduce daily traffic and associated noise levels within the project area. The primary impacts from noise would be localized disturbances to wildlife, recreationists, and residents. Noise associated with cavitation is a major concern for landowners, livestock, and wildlife.

Hazardous Materials and Waste Management

Industrial wastes are generated during routine operations (lubricating oils, hydraulic fluids, coolants, solvents, and cleaning agents). These wastes are typically placed in containers, characterized and labeled, possibly stored briefly, and transported by a licensed hauler to an appropriate permitted offsite disposal facility as a standard practice. Impacts could result if these wastes are not properly handled and are released to the environment. Environmental contamination could result from accidental spills of herbicides or other chemicals. Chemicals in open pits used to store wastes may pose a threat to wildlife and livestock.

Should geologic sequestration become common, a wide diversity of geologic formations is likely to be encountered. Depending on the nature of the formation targeted for injection, it may be necessary to increase the injectivity of carbon dioxide by using hydraulic fracturing. Hydraulic fracturing fluids can contain innocuous constituents, such as sand and water, and potentially toxic substances, such as diesel fuel (which contains benzene, ethylbenzene, toluene, xylenes, naphthalene, and other chemicals), polycyclic aromatic hydrocarbons (PAHs), methanol, formaldehyde, ethylene glycol, glycol ethers, hydrochloric acid, and sodium hydroxide. Because some aspects of a hydraulic fracturing operation are considered proprietary, information about the specific constituents used in a given hydrofracturing operation may not be available, thus causing some concern over the risks presented by this practice. Some of the hydrofracture fluids used to increase the injectivity of a carbon dioxide injection well would probably be pumped out of the well and then be managed at the surface in tanks of impoundments; however, some of the fluids would remain in the underground formation. For example, in the process of producing hydrocarbons and produced water, about 20 to 40% of the fluids used for hydrofracturing may remain underground. Thus, should hydraulic fracturing be used in a carbon sequestration injection well, these fluids could have an impact on underground water sources that are close (horizontally or vertically) to the injection well.

During the operations phase, scale and sludge wastes can accumulate inside pipelines and storage vessels. They must be removed periodically from the equipment for disposal. These wastes may be transported to offsite disposal facilities. In some instances, they may be disposed of via landspreading, a practice that entails spreading the wastes over the surface of the disposal area and mixing it with the top few inches of soil.

IMPACTS ON HUMAN HEALTH AND SAFETY

The potential impacts on human health and safety resulting from exploration activities could include occupational accidents and injuries, vehicle or aircraft accidents, exposure to weather extremes, wildlife encounters, trips and falls on uneven terrain, adverse health effects from dust generation and emissions, and contact with hazardous materials (e.g., from spills). The potential for these impacts to occur would be low due to the limited range of activities and small number of workers required during exploration.

Potential impacts on worker and public health and safety during the drilling phase would be similar to other projects that involve earth moving, use of large equipment, transportation of overweight and oversized materials, and construction and installation of industrial facilities. In particular, the risks would be very similar to those associated with oil and gas drilling activities. Statistical data on occupational accidents and fatalities for the oil and gas extraction labor category are available from the U.S. Bureau of Labor Statistics. In 2005, the oil and gas industry experienced a nationwide rate of 2.1 accidents per 100 full-time workers and 25.6 fatalities per 100,000 workers. The potential for occupational accidents and mortality would be highest during peak drilling periods. Drilling and construction activities also present the potential for well fires or explosions. Well blowouts are rare, but are typically caused by unsafe work practices and can be extremely dangerous (e.g., they can destroy rigs and kill nearby workers). If natural gas is in the blowout materials, the fluid may ignite from an engine spark or other source of flame. Blowouts may take days to months to cap and control. Also, increased human activity and increased public access could result in a higher potential for wildfires in the project area. Workers could also be exposed to air pollutants and could have body contact with product or other chemicals. Reckless driving by workers would also create safety hazards. In addition, health and safety issues include working in potential weather extremes and possible contact with natural hazards, such as uneven terrain and dangerous plants, animals, or insects.

Possible impacts on health and safety while operating an injection field include accidental injury or death to workers and, to a lesser extent, the public (e.g., from OHV collisions with project components, vehicle collisions with workers). Health impacts could result from water contamination, dust and other air emissions, noise, soil contamination, and stress (e.g., associated with living near an industrial zone). Potential fires and explosions would cause safety hazards. In addition, health and safety issues include working in potential weather extremes and possible contact with natural hazards, such as uneven terrain and dangerous plants, animals, or insects.

THOUGHT-PROVOKING QUESTIONS

9.1 Do you think terrestrial carbon sequestration is an effective way to begin to reduce the global effect of atmospheric carbon dioxide? Explain.

9.2 Do you think geological carbon sequestration is an effective way to begin to reduce the global effect of atmospheric carbon dioxide? Explain.

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Glossary*

A

Absorber: In a photovoltaic device, the material that readily absorbs photons to generate charge carriers (free electrons or holes).

AC: Alternating current.

Acid hydrolysis: A chemical process in which acid is used to convert cellulose or starch to sugar.

Acid mine drainage: A cause of water pollution that results when sulfur-bearing minerals associated with coal are exposed to air and water and form sulfuric acid and ferrous sulfate. The ferrous sulfate can further react to form ferric hydroxide, or yellow boy, a yellow–orange iron precipitate found in streams and rivers polluted by acid mine drainage.

Acid rain: Also called *acid precipitation* or *acid deposition*, acid rain is precipitation containing harmful amounts of nitric and sulfuric acids formed primarily by sulfur dioxide and nitrogen oxides released into the atmosphere when fossil fuels are burned. It can be wet precipitation (rain, snow, or fog) or dry precipitation (absorbed gaseous and particulate matter, aerosol particles, or dust). Acid rain has a pH below 5.6. Normal rain has a pH of about 5.6, which is slightly acidic. The term pH is a measure of acidity or alkalinity and ranges from 0 to 14. A pH measurement of 7 is regarded as neutral. Measurements below 7 indicate increased acidity, and those above 7 indicate increased alkalinity.

Acre-foot: The volume of water that will cover an area of 1 acre to a depth of 1 foot.

Acreage: An area, measured in acres, that is subject to ownership or control by those holding total or fractional shares of working interests. Acreage is considered developed when development has been completed. A distinction may be made between gross acreage and net acreage:

Gross—All acreage covered by any working interest, regardless of the percentage of ownership in the interest.

Net—Gross acreage adjusted to reflect the percentage of ownership in the working interest in the acreage.

Active power: The component of electric power that performs work, typically measured in kilowatts (kW) or megawatts (MW). Also known as *real power*. The terms "active" or "real" are used to modify the base term "power" to differentiate it from reactive power.

* Some definitions are adapted from EERE, *Glossary of Energy-Related Terms*, Office of Energy Efficiency & Renewable Energy, Washington, DC, 2014 (http://energy.gov/eere/energybasics/articles/glossary-energy-related-terms); EIA, *Glossary*, U.S. Energy Information Administration, Washington, DC, 2014 (http://www.eia.gov/tools/glossary/index.cfm?id=A).

Active solar: As an energy source, energy from the sun is collected and stored using mechanical pumps or fans to circulate heat-laden fluids or air between solar collectors and a building.

Adaptation: Adjustment to environmental conditions.

Adaptive management: Approach that focuses on learning and adapting through partnerships of managers, scientists, and other stakeholders who learn together how to create and maintain sustainable ecosystems. Adaptive management helps science managers maintain flexibility in their decisions, knowing that uncertainties exist; provides managers the latitude to change direction; improves our understanding of ecological systems to achieve management objectives; and is about taking action to improve progress toward desired outcomes.

Advanced regeneration: Tree seedlings or small saplings that develop in the understory prior to removal of the overstory.

Adverse water conditions: Reduced stream flow, lack of rain in the drainage basin, or low water supply behind a pondage or reservoir dam resulting in a reduced gross head that limits the production of hydroelectric power or forces restrictions to be placed on multipurpose reservoirs or other water uses.

Adverse weather conditions: Reduced streamflow, lack of rain in the drainage basin, or lower water supply behind a pondage or reservoir dam resulting in a reduced gross head that limits the production of hydroelectric power or forces restrictions to be placed on multipurpose reservoirs or other water uses.

AFC: *See* Alkaline fuel cell.

AFUE: *See* Annual fuel utilization efficiency.

Agglomerating character: Agglomeration describes the caking properties of coal. Agglomerating character is determined by examination and testing of the residue when a small powdered sample is heated to 950°C under specific conditions. If the sample is agglomerating, the residue will be coherent, show swelling or cell structure, and be capable of supporting a 500-gram weight without pulverizing.

Agriculture: An energy-consuming subsector of the industrial sector that consists of all facilities and equipment engaged in growing crops and raising animals.

Air cleaner: A device using filters or electrostatic precipitators to remove indoor air pollutants such as tobacco smoke, dust, and pollen. Most portable units are 40 watts when operated on low speed and 100 watts on high speed.

Air collector: A medium-temperature collector used predominantly in space heating, it utilizes pumped air as the heat-transfer medium.

Air pollution abatement equipment: Equipment used to reduce or eliminate airborne pollutants, including particulate matter (dust, smoke, fly ash, dirt, etc.), sulfur oxides, nitrogen oxides (NO_x), carbon monoxide, hydrocarbons, odors, and other pollutants.

Air temperature adjustment: Change in air temperature associated with a change in tree canopy cover (°C per 1% change in tree canopy cover).

Albedo: The ratio of light reflected by a surface to the light falling on it.

Alcohol: A general class of hydrocarbons containing a hydroxyl group (OH). There are many types of alcohols (e.g., butanol, ethanol, methanol).

Alcohol fuels: Alcohol can be blended with gasoline for use as transportation fuel and can be produced from a wide variety of organic feedstock. The common alcohol fuels are methanol and ethanol. Methanol can be produced from coal, natural gas, wood, and organic waste. Ethanol is commonly made from agricultural plants (primarily corn) containing sugar.

Alkaline fuel cell (AFC): A type of hydrogen/oxygen fuel cell in which the electrolyte is concentrated potassium hydroxide (KOH) and the hydroxide ions (OH) are transported from the cathode to the anode.

Alkylate: The product of an alkylation reaction. It usually refers to the high-octane product from alkylation units. This alkylate is used in blending high-octane gasoline.

Alkylation: A refining process for chemically combining isobutene with olefin hydrocarbons (e.g., propylene, butylenes) through the control of temperature and pressure in the presence of an acid catalyst, usually sulfuric acid or hydrofluoric acid. The product alkylate, an isoparaffin, has high octane value and is blended with motor and aviation gasoline to improve the antiknock value of the fuel.

Alternating current (AC): An electric current that reverses its direction at regularly recurring intervals, usually 50 or 60 times per second.

Alternative fuel: For transportation applications, alternative fuels include the following: methanol, denatured ethanol, and other alcohols; fuel mixtures containing 85% or more by volume of methanol, denatured ethanol, and other alcohols with gasoline or other fuels; natural gas; liquefied petroleum gas (propane); hydrogen; coal-derived liquid fuels; fuels (other than alcohol) derived from biological materials (biofuels such as soy diesel fuel); electricity (including electricity from solar energy); and "any other fuel the Secretary determines, by rule, is substantially not petroleum and would yield substantial energy security benefits and substantial environmental benefits." The term "alternative fuel" does not include alcohol or other blended portions of primarily petroleum-based fuels used as oxygenates or extenders (i.e., MTBE, ETBE, other ethers, and the 10% ethanol portion of gasohol).

Alternator: A device that turns the rotation of a shaft into alternating current (AC).

Ambient: Natural condition of the environment at any given time.

Ampere (amp): A unit of electrical current; it can be compared to the rate of water flowing through a pipe (liters per minute).

Ampere-hour: Amperes times hour; used to measure energy production over time and battery capacity.

Amphorous silicon: An alloy of silica and hydrogen, with a disordered, noncrystalline internal atomic arrangement, that can be deposited in thin layers (a few micrometers in thickness) by a number of a deposition methods to produce thin-film photovoltaic cells on glass, metal, or plastic substrates.

Anadromous fish: Fish that spend a large portion of their life cycle in the ocean and return to freshwater to breed (*anadromous* is derived from the Greek for "up-running").

Anaerobic decomposition: Decomposition in the absence of oxygen, as in an anaerobic digester or a lagoon; it produces carbon dioxide and methane.

Anaerobic digestion: A biochemical process by which organic matter is decomposed by bacteria in the absence of oxygen, producing methane and other byproducts.

Anaerobic lagoon: A liquid-based organic waste management installation characterized by waste residing in water at a depth of at least 6 feet for periods of 30 to 200 days.

Anemometer: Wind speed measurement device used to send data to a controller. Also used to conduct wind site surveys.

Angle of attack: In wind turbine operation, the angle of the airflow relative to the blade.

Angle of incidence: The angle that a ray of sun makes with a line perpendicular to the surface. For example, a surface that directly faces the sun has a solar angle of incidence of zero, but if the surface is parallel to the sun (for example, sunrise striking a horizontal rooftop), the angle of incidence is 90°.

Anion: A negatively charged ion; an ion that is attracted to the anode.

Annual fuel utilization efficiency (AFUE): A measure of space heating equipment efficiency defined as the fraction of energy output/energy input.

Annual removals: The net volume of growing stock trees removed from the inventory during a specified year by harvesting, cultural operations such as timber land improvement, or land clearing.

Annualized growth rate: Calculated as $(x_n/x_1)^{1/n}$, where x is the value under consideration and n is the number of periods.

Anode: The electrode at which oxidation (a loss of electrons) takes place. For fuel cells and other galvanic cells, the anode is the negative terminal; for electrolytic cells, the anode is the positive terminal.

Anthropogenic: Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.

Anuran: Of or relating to frogs and toads.

API gravity: American Petroleum Institute measure of specific gravity of crude oil or condensate in degrees; an arbitrary scale expressing the gravity of density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API; it is calculated as follows:

$$\text{Degrees API} = (141.5/\text{Sp. Gr. @ } 60°\text{F}/60°\text{F}) - 131.5$$

Apparent power: The product of the voltage (in volts) and the current (in amperes). It is comprised of both active and reactive power. It is measured in volt-amperes and often expressed in kilovolt-amperes (kVA) or megavolt-amperes (MVA).

Appropriate use: A proposed or existing use on a refuge that meets at least one of the following conditions: (1) the use is a wildlife-dependent one, or (2) the use contributes to fulfilling the refuge purpose.

Aquatic: Growing in, living in, or dependent upon water.

Aquifer: Water-bearing stratum of permeable sand, rock, or gravel.

Arbitrage: The simultaneous purchase and sale of identical or similar assets across two or more markets in order to profit from a temporary price discrepancy.

Aromatics: Hydrocarbons characterized by unsaturated ring structures of carbon atoms. Commercial petroleum aromatics are benzene, toluene, and xylene (BTX).

Asexual reproduction: The naturally occurring ability of some plant species to reproduce asexually through seeds, meaning that the embryos develop without a male gamete. This ensures that the seeds will produce plants identical to the mother plant.

Atmospheric crude oil distillation: The refining process of separating crude oil components at atmospheric pressure by heating to temperatures of about 600 to 750°F (depending on the nature of the crude oil and desired products) and subsequent condensing of the fractions by cooling.

Attenuator: A long floating structure like a terminator, but it is oriented parallel to the waves rather than normal to them. It rides the waves like a ship, and movements of the device at its bow and along its length can be restrained so as to extract energy. The theoretical advantage of the attenuator over the terminator is that its area normal to the waves is small so the forces it experiences are much lower.

Availability factor: A percentage representing the number of hours a generating unit is available to produce power (regardless of the amount of power) in a given period, compared to the number of hours in the period.

Average stream flow: The rate, usually expressed in cubic feet per second, at which water passes a given point in a stream over a set period of time.

Average water conditions: The amount and distribution of precipitation within a drainage basin and the runoff conditions present as determined by reviewing the area water supply records over a long period of time.

Avian: Of or having to do with birds.

Avifauna: All birds of a given region.

Azimuth angle: The angle between true south and the point on the horizon directly below the sun.

B

Bagasse: The fibrous material remaining after extraction of the juice from sugarcane; often burned by sugar mills as a source of energy.

Barrel: A unit of volume equal to 42 U.S. gallons.

Barrier: Any obstruction to fish passage (i.e., an aquatic barrier).

Baseload plants: Electricity-generating units that are operated to meet the constant or minimum load on the system. The cost of energy from such units is usually the lowest available to the system.

Basin: The land surrounding and draining into a water body.

Benzene (C_6H_6): An aromatic hydrocarbon present in a small proportion in some crude oils and made commercially from petroleum by the catalytic reforming of naphthenes in petroleum naphtha. Also made from coal in the

manufacture of coke. Used as a solvent in the manufacture of detergents, synthetic fibers, and petrochemicals and as a component of high-octane gasoline.

Bilateral agreement: A written agreement signed by two parties that specifies the terms for exchanging energy.

Binary cycle: Binary geothermal systems use extracted hot water or steam to heat a secondary fluid to drive the power turbine.

Biobased product: As defined by the Farm Security and Rural Investment Act (FSRIA), it is a product determined by the U.S. Secretary of Agriculture to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agriculture materials (including plant, animal, and marine materials) or forestry materials.

Biochemical conversion: The use of fermentation or anaerobic digestion to produce fuels and chemicals from organic sources.

Biodiesel: Fuel derived from vegetable oils or animals fats. It is produced when a vegetable oil or animal fat is chemically reacted with an alcohol.

Biodiversity conservation: The goal of conservation biology, which is to retain indefinitely as much of the Earth's biodiversity as possible, with an emphasis on biotic elements most vulnerable to human impacts.

Bioenergy: Useful, renewable energy produced from organic matter, which may be either used directly as a fuel or processed into liquids and gases.

Biofuels: Liquid fuels and blending components produced from biomass (plant) feedstocks; used primarily for transportation.

Biogas: A combustible gas derived from decomposing biological waste. Biogas normally consists of 50 to 60% methane.

Biogenic: Produced by biological processes of living organisms.

Biogenic emissions: Emissions that are naturally occurring and are not significantly affected by human actions or activity.

Biological diversity or biodiversity: The variety of life and its processes, including the variety of living organisms, the genetic differences among them, and the communities and ecosystems in which they occur.

Biological integrity: Biotic composition, structure, and functioning at the genetic, organism, and community levels comparable with historic conditions, including the natural biological processes that shape genomes, organisms, and communities.

Biomass: Any organic non-fossil material of biological origin constituting a renewable energy source. Produced from organic matter that is available on a renewable or recurring basis, including agricultural crops and trees, wood and wood residues, plants (including aquatic plants), grasses, animal manure, municipal residues, and other residue materials. Biomass is generally produced in a sustainable manner from water and carbon dioxide by photosynthesis. The three main categories of biomass are primary, secondary, and tertiary.

Biomass-based diesel fuel: Biodiesel and other renewable diesel fuel or diesel fuel blending components derived from biomass, but excluding renewable diesel fuel coprocessed with petroleum feedstock.

Biomass gas (biogas): A medium-Btu gas containing methane and carbon dioxide, resulting from the action of microorganisms on organic materials such as a landfill.

Biomass waste: Organic non-fossil material of biological origin that is a byproduct or a discarded product. Biomass waste includes municipal solid waste from biogenic sources, landfill gas, sludge waste, agricultural crop byproducts, straw, and other biomass solids, liquids, and gases but excludes wood and wood-derived fuels (including black liquor), biofuels feedstock, biodiesel, and fuel ethanol. Biomass waste also includes energy crops grown specifically for energy production that would not normally constitute waste.

Biomaterials: Products derived from organic (as opposed to petroleum-based) products.

Bio-oil: Intermediate fuel derived from fast pyrolysis.

Biopower: The use of biomass feedstock to produce electric power to heat through direct combustion of the feedstock, through gasification and then combustion of the resultant gas, or through other thermal conversion processes. Power is generated with engines, turbines, fuel cells, or other equipment.

Biorefinery: A facility that processes and converts biomass into value-added products. These products can range from biomaterials to fuels such as ethanol or important feedstocks for the production of chemicals and other materials. Biorefineries can be based on a number of processing platforms using mechanical, thermal, chemical, and biochemical processes.

Biota: The plant and animal life of a region.

Black liquor (pulping liquor): The alkaline spent liquor removed from digesters in the process of chemically pulping wood. After evaporation, the liquor is burned as a fuel in a recovery furnace that permits the recovery of certain basic chemicals.

Blackbody: An ideal substance that absorbs all radiation falling on it and reflects nothing.

Bone dry: Having zero percent moisture content.

Borehole breakouts: Failure of the borehole wall resulting from stress in the rock surrounding the borehole. The breakout is generally located symmetrically in the wellbore perpendicular to the direction of greatest horizontal stress on a vertical wellbore.

Breakwater: A barrier protecting a harbor or shore from the impact of waves.

Breccia: A coarse-grained clastic rock composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix.

Breeding habitat: Habitat used by migratory birds or other animals during the breeding season.

Brine: A geothermal solution containing appreciable amounts of sodium chloride or other salts.

British thermal unit (Btu): A basic measure of thermal (heat) energy, the Btu is defined as the amount of energy required to increase the temperature of 1 pound of water by 1°F at normal atmospheric pressure; 1 Btu = 1055 joules.

Btu conversion factor: A factor for converting energy data between one unit of measurement and the British thermal unit (Btu). Btu conversion factors are generally used to convert energy data from physical units of measure (such as barrels, cubic feet, or short tons) into the energy-equivalent measure of Btu.

Btu per cubic foot: The total heating value, expressed in Btu, produced by the combustion, at constant pressure, of the amount of the gas that would occupy a volume of 1 cubic foot at a temperature of 60°F if saturated with water vapor and under a pressure equivalent to that of 30 inches of mercy at 32°F and under standard gravitational force (980.665 cm/sec^2) with air of the same temperature and pressure as the gas, when the products of combustion are cooled to the initial temperature of the gas and air when the water formed by combustion is condensed to the liquid state. (Sometimes called *gross heating value* or *total heating value*.)

Buffer zones: Land bordering and protecting critical habitats or water bodies by reducing runoff and non-point source pollution loading; areas created or sustained to lessen the negative effects of land development on animals, plants, and their habitats.

Bulk density: Weight per unit of volume, usually specified in pounds per cubic foot.

Bunker fuels: Fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft. The term *international bunker fuels* is used to denote the consumption of fuel for international transport activities. *Note:* For the purposes of greenhouse gas emissions inventories, data on emissions from the combustion of international bunker fuels are subtracted from national emissions totals. Historically, bunker fuels have meant only ship fuel.

Burnup: Amount of thermal energy generated per unit mass of fuel, expressed as gigawatt-days thermal per metric ton of initial heavy metal (GWDT/MTIHM), rounded to the nearest gigawatt day.

Butane (C_4H_{10}): A straight-chain or branch-chain hydrocarbon extracted from natural gas or refinery gas streams, which is gaseous at standard temperature and pressure. It includes isobutene and normal butane and is designated in ASTM Specification D1835 and Gas Processors Association specifications for commercial butane.

Butylene (C_4H_8): An olefinic hydrocarbon recovered from refinery or petrochemical processes, which is gaseous at standard temperature and pressure. Butylene is used in the production of gasoline and various petrochemical products.

C

Calcination: A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material is expelled.

Calcium sulfate: A white crystalline salt, insoluble in water. Used in Keene's cement, in pigments, as a paper filler, and as a drying agent.

Candidate species: Plants and animals for which the U.S. Fish and Wildlife Service (FWS) has sufficient information on their biological status and threats to propose them as endangered or threatened under the Endangered Species Act (ESA), but for which development of a proposed listing regulation is precluded by other higher priority listing activities.

Canopy: The layer of foliage formed by the crowns of trees in a stand. For stands with trees of different heights, foresters often distinguish among the upper, middle, and lower canopy layers. These represent foliage on tall, medium, and short trees. The uppermost layers are called the *overstory.*

Cap rocks: Rocks of low permeability that overlie a geothermal reservoir.

Capacity factor: The ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full-power operation during the same period.

Capacity, gross: The full-load continuous rating of a generator, prime mover, or other electric equipment under specified conditions as designated by the manufacturer. It is usually indicated on a nameplate attached to the equipment.

Capitol cost: The cost of field development and plant construction and the equipment required for the generation of electricity.

Carbon: A nonmetallic element (symbol C) found in all organic substances and in some inorganic substances such as coal and natural gas. The atomic weight of C is 12, and that of CO_2 is 44. Emissions expressed in units of C can be converted to emissions in CO_2 units by multiplying by 12/44.

Carbon accounting: In general, refers to processes undertaken to measure amounts of carbon dioxide equivalents emitted by an entity. It is used, for example, by nation states, corporations, and individuals.

Carbon budget: Balance of the exchanges (incomes and losses) of carbon between carbon sinks (e.g., atmosphere, biosphere) in the carbon cycle.

Carbon cycle: All carbon sinks and exchanges of carbon from one sink to another by various chemical, physical, geological, and biological processes (refer to Figure 9.1).

Carbon dioxide (CO_2): A product of combustion; the most common greenhouse gas.

Carbon dioxide equivalent (CDE): The amount of carbon dioxide by weight emitted into the atmosphere that would produce the same estimated radiative force as a given weight of another radiatively active gas. Carbon dioxide equivalents are computed by multiplying the weight of the gas being measured (e.g., methane) by its estimated global warming potential (21 for methane). *Carbon equivalent units* are defined as carbon dioxide equivalents multiplied by the carbon content of carbon dioxide (i.e., 12/44).

Carbon intensity: The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is the weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are identical. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels.

Carbon monoxide (CO): A colorless, odorless gas produced by incomplete combustion. Carbon monoxide is poisonous if inhaled.

Carbon output rate: The amount of carbon by weight per kilowatt-hour of electricity produced.

Carbon sequestration: Process through which carbon dioxide is removed from the atmosphere—for example, in forests through the process of photosynthesis. During this process, carbon dioxide is taken up through plants' leaves and incorporated into the plants' wood biomass.

Carbon sinks: Carbon reservoirs and conditions that take in and store more carbon (carbon sequestration) than they release. Carbon sinks can serve to partially offset greenhouse gas emissions. Forests and oceans are common carbon sinks.

Carnot cycle: An ideal heat engine (conceived by Sadi Carnot) in which the sequence of operations forming the working cycle consists of isothermal expansion, adiabatic expansion, isothermal compression, and adiabatic compression back to its initial state.

Cascading heat: A process that uses a stream of geothermal hot water or steam to perform successive tasks requiring lower and lower temperatures.

Casing: Pipe placed in a wellbore as a structural interface between the wellbore and the surrounding formation. It typically extends from the top of the well and is cemented in place to maintain the diameter of the wellbore and provide stability.

Cast silicon: Crystalline silicon obtained by pouring pure molten silicon into a vertical mold and adjusting the temperature gradient along the mold volume during cooling to obtain slow, vertically advancing crystallization of the silicon. The polycrystalline ingot thus formed is composed of large, relatively parallel, interlocking crystals. The cast ingots are sawed into wafers for further fabrication into photovoltaic cells. Cast-silicon wafers and ribbon-silicon sheets fabricated into cells are usually referred to as *polycrystalline photovoltaic cells.*

Cathode: The electrode at which reduction (a gain of electrons) occurs. For fuel cells and other galvanic cells, the cathode is the positive terminal; for electrolytic cells (where electrolysis occurs), the cathode is the negative terminal.

Cation: A positively charged ion.

Cells: Refers to the unencapsulated semiconductor compounds of a module that convert solar energy to electricity.

Cells to OEM (non-PV): Cells shipped to non-photovoltaic original equipment manufacturers such as boat manufacturers, car manufacturers, etc.

Cellulose: The main carbohydrate in living plants. Cellulose forms the skeletal structure of the plant cell wall.

Cellulosic ethanol: Ethanol produced from cellulosic and hemicellulosic biomass.

Chained dollars: A measure used to express real prices. Real prices are those that have been adjusted to remove the effect of changes in the purchasing power of the dollar; they usually reflect buying power relative to a reference year. Prior to 1996, real prices were expressed in constant dollars, a measure based on the weights of goods and services in a single year, usually a recent year. In

1996, the U.S. Department of Commerce introduced the chained-dollar measure. The new measure is based on the average weights of goods and services in successive pairs of years. It is "chained" because the second year in each pair, with its weights, becomes the first year of the next pair. The advantage of using the chained-dollar measure is that it is more closely related to any given period covered and is therefore subject to less distortion over time.

Characterization: Sampling, monitoring, and analysis activities to determine the extent and nature of contamination at a facility or site. Characterization provides the necessary technical information to develop, screen, analyze, and select appropriate clean-up techniques.

Chemical separation: A process for extracting uranium and plutonium from dissolved spent nuclear fuel and irradiated targets. The fission products that are left behind are high-level waste. Chemical separation is also known as *reprocessing*.

Chips: Woody material cut into short, thin wafers. Chips are used as a raw material for pulping and fiberboard or as biomass fuel.

Chlorofluorocarbon (CFC): Any of various compounds consisting of carbon, hydrogen, chlorine, and fluorine used as refrigerants. CFCs are now thought to be harmful to the Earth's atmosphere.

Christmas tree: The valves and fittings installed at the top of a gas or oil well to control and direct the flow of well fluids.

Climate: The average weather (usually taken over a 30-year time period) for a particular region and time period. Climate is not the same as weather; rather, it is the average pattern of weather for a particular region. Weather describes the short-term state of the atmosphere. Climatic elements include precipitation; temperature; humidity; sunshine; wind velocity; phenomena such as fog, frost, and hail storms; and other measures of the weather.

Climate change: Sometimes is used to refer to all forms of climatic inconsistency, but because the Earth's climate is never static the term is more properly used to imply a significant change from one climatic condition to another. In some cases, climate change has been used synonymously with the term *global warming*; however, scientists tend to use the term in the wider sense to also include natural changes in the climate.

Climate effects: Impact on residential space heating and cooling (kg CO_2/tree/year) from trees located greater than approximately 15 m (50 ft) from a building (far trees) due to associated reductions in wind speeds and summer air temperatures.

Closed-loop biomass: Crops grown in a sustainable manner for the purpose of optimizing their value for bioenergy and bioproduct uses. This includes annual crops such as maize and wheat and perennial crops such as trees, shrubs, and grasses such as switchgrass.

Cloud condensation nuclei: Aerosol particles that provide a platform for the condensation of water vapor, resulting in clouds with higher droplet concentrations and increased albedo.

Coarse materials: Wood residues suitable for chipping, such as slabs, edgings, and trimmings.

Co-firing: Practice of introducing biomass into the boilers of coal-fired power plants.

Cogeneration: The production of electrical energy and another form of useful energy (such as heat or steam) through the sequential use of energy.

Cogeneration system: A system using a common energy source to produce both electricity and steam for other uses, resulting in increased fuel efficiency.

Combined cycle: An electric generating technology in which electricity is produced from otherwise lost waste heat exiting from one or more gas (combustion) turbines. The exiting heat is routed to a conventional boiler or to a heat recovery steam generator for utilization by a steam turbine in the production of electricity. Such designs increase the efficiency of the electric generating unit.

Combined heat and power (CHP) plant: A plant designed to produce both heat and electricity from a single heat source. *Note:* This term is being used in place of the term *cogenerator*, which was used by the U.S. Energy Information Agency (EIA) in the past. CHP better describes the facilities because some of the plants included do not produce heat and power in a sequential fashion and, as a result, do not meet the legal definition of cogeneration specified in the Public Utility Regulatory Policies Act (PURPA).

Commercial sector: An energy-consuming sector that consists of service-providing facilities and equipment of businesses; federal, state, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. The commercial sector includes institutional living quarters. It also includes sewage treatment facilities. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a wide variety of other equipment. *Note:* This sector includes generators that produce electricity or useful thermal output primarily to support the activities of the above-mentioned commercial establishments.

Commercial species: Tree species suitable for industrial wood products.

Compressed natural gas (CNG): Mixtures of hydrocarbon gases and vapors, consisting principally of methane in gaseous form that has been compressed.

Concentrating solar power or solar thermal power system: A solar energy conversion system characterized by the optical concentration of solar rays through an arrangement of mirrors to generate a high-temperature working fluid. Concentrating solar power (but not solar thermal power) may also refer to a system that focuses solar rays on a photovoltaic cell to increase conversion efficiency.

Concentrator: A reflective or refractive device that focuses incident insolation onto an area smaller than the reflective or refractive surface, resulting in increased insolation at the point of focus.

Condensate: Water formed by condensation of steam.

Condenser: Equipment that condenses turbine exhaust steam into condensate.

Conifer: A tree or shrub in the phylum Gymnospermae whose seeds are borne in woody cones. There are 500 to 600 species of living conifers.

Conservation: Managing natural resources (including preservation, restoration, and enhancement) to prevent loss or waste.

Conservation corridor: Connections between suitable habitats that allow passage of plant or animal species.

Conservation easement: A voluntary agreement that allows a landowner to limit the type or amount of development on their property while retaining private ownership of the land. The easement is signed by the landowner, who is the easement donor, and by the Conservancy, who is the party receiving the easement. The Conservancy must enforce the terms of the easement in perpetuity.

Conservation feature: A feature in a building designed to reduce the usage of energy.

Conservation program: A program in which a utility company furnishes home weatherization services free or at reduced cost or provides free or low-cost devices for saving energy, such as energy-efficient light bulbs, flow restrictors, weather stripping, and water heater insulation.

Conservation Reserve Program (CRP): A program that provides farm owners or operators with an annual per-acre rental payment and half the cost of establishing a permanent land cover in exchange for retiring environmentally sensitive cropland from production for 10 to 15 years. In 1996, Congress reauthorized CRP for an additional round of contracts, limiting enrollment to 36.4 million acres at any time. The 2002 Farm Act increased the enrollment limit to 39 million acres. Producers can offer land for competitive bidding based on an Environmental Benefits Index (EBI) during periodic signups or can automatically enroll more limited acreages in processes such as riparian buffers, field windbreaks, and grass strips on a continuous basis. CRP is funded through the Commodity Credit Corporation (CCC).

Conservation status: Assessment of the status of ecological processes and of the viability of species or populations in an ecoregion.

Conventional hydroelectric (hydropower) plant: A plant in which all of the power is produced from natural streamflow as regulated by available storage.

Conventional oil and natural gas production: Crude oil and natural gas produced by a well drilled into a geologic formation in which the reservoir and fluid characteristics permit the oil and natural gas to readily flow to the wellbore.

Cooling tower: A structure in which heat is removed from hot condensate.

Core: A cylinder of rock recovered from the well by a special coring drill bit.

Correlation (statistical term): In its most general sense, correlation denotes the interdependence between quantitative or qualitative data. It would include the association of dichotomized attributes and the contingency of multiple classified attributes. The concept is quite general and may be extended to more than two variables. The word is most frequently used in a somewhat narrower sense to denote the relationship between measurable variates or ranks.

Criteria pollutant: A pollutant determined to be hazardous to human health and regulated under U.S. Environmental Protection Agency (USEPA) National Ambient Air Quality Standards. The 1970 amendments to the Clean Air Act required the USEPA to describe the health and welfare impacts of a pollutant as the criteria for inclusion in the regulatory regime.

Critical habitats: According to U.S. federal law, the ecosystems upon which endangered and threatened species depend; specific geographic areas, whether occupied by a listed species or not, that are essential for its conservation and that have been formally designated by a rule published in the *Federal Register*.

Crop failure: Consists mainly of the acreage on which crops failed because of weather, insects, and diseases but also includes some land not harvested due to lack of labor, low market prices, or other factors. The acreage planted to cover and soil improvement crops not intended for harvest is excluded from crop failure and is considered idle.

Crop residue: Organic residue remaining after the harvesting and processing of a crop.

Cropland: Total cropland includes five components: cropland harvested, crop failure, cultivated summer fallow, cropland used only for pasture, and idle cropland.

Cropland harvested: Includes row crops and closely sown crops; hay and silage crops; tree fruits, small fruits, berries, and tree nuts; vegetables and melons; and miscellaneous other minor crops. In recent years, farmers have double-cropped about 4% of the acreage.

Cropland pasture: Land used for long-term crop rotation; however, some cropland pasture is marginal for crop uses and may remain in pasture indefinitely. This category also includes land that was used for pasture before crops reached maturity and some land used for pasture that could have been cropped without additional improvement.

Cropland used for crops: Includes cropland harvested, crop failure, and cultivated summer fallow.

Crust: Earth's outer layer of rock; also called the *lithosphere*.

Cryogenic liquefaction: The process through which gases such as nitrogen, hydrogen, helium, and natural gas are liquefied under pressure at very low temperatures.

Cull tree: A live tree, 5.0 inches in diameter at breast height (d.b.h.) or larger, that is not merchantable for saw logs now or prospectively because of rot, roughness, or species.

Cull wood: Wood logs, chips, or wood products that are burned.

Cultivar: A horticulturally or agriculturally derived variety of a plant.

Cultural Resource Inventory: A professional study to locate and evaluate evidence of cultural resources within a defined geographic area.

Cultural Resources Overview: A comprehensive document prepared for a field office that discusses, among other things, project prehistory and cultural history, the nature and extent of known cultural resources, previous research, management objectives, resource management conflicts or issues, and a general statement of how program objectives should be met and conflicts resolved.

Cut-in speed: The speed at which a shaft must turn in order to generate electricity and send it over a wire.

D

Dam: A physical barrier constructed across a river or waterway to control the flow of or raise the level of water. The purpose of construction may be for flood control, irrigation needs, hydroelectric power production, or recreation usage.

Daylighting: The use of direct, diffuse, or reflected sunlight to provide supplemental lighting for building interiors.

Daylighting controls: A system of sensors that assesses the amount of daylight and controls lighting or shading devices to maintain a specified lighting level. The sensors are sometimes referred to as *photocells*.

d.b.h.: The diameter measured at approximately breast height (usually 4.5 feet above the ground), commonly used by foresters to describe tree size.

DC: Direct current.

Deadweight tons: The lifting capacity of a ship expressed in long tons (2.240 lb), including cargo, commodities, and crew.

Decatherm: Ten therms or 1,000,000 Btu.

Decontamination: Removal of unwanted radioactive or hazardous contamination by a chemical or mechanical process.

Deepest total depth: The deepest total depth of a given well is the distance from a surface reference point (usually the Kelly bushing; also called the *drive bushing*) to the point of deepest penetration measured along the wellbore. If a well is drilled from a platform or barge over water, the depth of the water is included in the total length of the wellbore.

Defoliator: An agent that damages trees by destroying leaves or needles.

Deforestation: The net removal of trees from forested land.

Degasification system: The methods employed for removing methane from a coal seam that could not otherwise be removed by standard ventilation fans and thus would pose a substantial hazard to coal miners. These systems may be used prior to mining or during mining activities.

Degradable organic carbon: The portion of organic carbon present in such solid waste as paper, food waste, and yard waste that is susceptible to biochemical decomposition.

Degradation: The loss of native species and processes due to human activities such that only certain components of the original biodiversity persist, often including significantly altered natural communities.

Demand indicator: A measure of the number of energy-consuming units, or the amount of service or output, for which energy inputs are required.

Demonstrated resources: Same qualifications as identified resources, but include measured and indicated degrees of geologic assurance and exclude the inferred.

Demurrage: The charge paid to a vessel owner or operator for detention of a vessel at a port beyond the time allowed, usually 72 hours, for loading and unloading.

Densification: A mechanical process to compress biomass (usually wood waste) into pellets, briquettes, cubes, or densified logs.

Dependable capacity: The load-carrying ability of a station or system under adverse conditions for a specified period of time.

Depleted resources: Resources that have been mined, including coal recovered, coal lost in mining, and coal reclassified as sub-economic because of mining.

Depletion factor: Annual percentage of depletion of the thermal resource.

Design head: The achieved river, pondage, or reservoir surface height (forebay elevation) that provides the water level to produce the full flow at the gate of the turbine in order to attain the manufacturer's installed nameplate rating for generation capacity.

Designated wilderness area: An area designated by Congress as part of the National Wilderness Preservation System.

Desired future condition: The qualities of an ecosystem or its components that an organization seeks to develop through its decisions and actions.

Desulfurization: The removal of sulfur, as from molten metals, petroleum oil, or flue gases.

Diesel fuel: A fuel composed of distillates obtained in petroleum refining operation or blends of such distillates with residual oil used in motor vehicles. The boiling point and specific gravity are higher for diesel fuels than for gasoline.

Diffusive transport: The process by which particles of liquids or gases move from an area of higher concentration to an area of lower concentration.

Digester gas: Biogas that is produced using a digester, which is an airtight vessel or enclosure in which bacteria decomposes biomass in water to produce biogas.

Diode: A solid-state device that acts as a one-way valve for electricity.

Direct methanol fuel cell (DMFC): A type of fuel cell in which the fuel is methanol (CH_3OH) in gaseous or liquid form. The methanol is oxidized directly at the anode instead of first being reformed to produce hydrogen. The electrolyte is typically polymer electrolyte membrane (PEM).

Direct use: Use of geothermal heat without first converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, etc.

Displacer: A body moved by the waves. It might be a buoyant vessel or, as in the case of oscillating water column (OWC) devices, a mass of water. If buoyant, the displacer may pierce the surface of the waves or be submerged.

Distillation unit (atmospheric): The primary distillation unit that processes crude oil (including mixtures of other hydrocarbons) at approximately atmospheric conditions. It includes a pipe still for vaporizing the crude oil and a fractionation tower for separating the vaporized hydrocarbon components in the crude oil into fractions with different boiling ranges. This is done by continuously vaporizing and condensing the components to separate higher boiling point material. The selected boiling ranges are set by the process scheme, the properties of the crude oil, and the product specifications.

Distributed generation (distributed energy resources): Refers to electricity provided by small, modular power generators (typically ranging in capacity from a few kilowatts to 50 megawatts) located at or near customer demand.

District heating: A type of direct use in which a utility system supplies multiple users with hot water or steam from a central plant or well field.

Disturbance: Any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment.

Diversity exchange: An exchange of capacity or energy, or both, between systems whose peak loads occur at different times.

Divestiture: The stripping off of one utility function from the others by selling (spinning-off) or in some other way changing the ownership of the assets related to that function. Stripping off is most commonly associated with spinning-off generation assets so they are no longer owned by the shareholders that own the transmission and distribution assets.

Downwind turbine: A turbine that does not face into the wind and whose direction is controlled directly by the wind.

Drag bit: Drilling bit that drills by scraping or shearing the rock with fixed hard surfaces, or *cutters*.

Drainage basin: The land drained by a river system.

Drawdown: The lowering of the water level of a reservoir as a result of withdrawing water.

Drilling: Boring into the Earth to access geothermal resources, usually with oil and gas drilling equipment that has been modified to meet geothermal requirements.

Dry natural gas: Natural gas that remains after (1) the liquefiable hydrocarbon portion has been removed from the gas stream (i.e., gas after lease, field, and/or plant separation), and (2) any volumes of non-hydrocarbon gases have been removed where they occur in sufficient quantity to render the gas unmarketable. *Note:* Dry natural gas is also known as consumer-grade natural gas. The parameters for measurement are cubic feet at 60°F and 14.73 pounds per square inch absolute.

Dry steam: Very hot steam that does not occur with liquid.

Dump load: A device that allows excess energy to be safely disposed of.

E

E-10: A mixture of 10% ethanol and 90% gasoline based on volume.

E-85: A mixture of 85% ethanol and 15% gasoline based on volume.

E-95: A fuel containing a mixture of 95% ethanol and 5% gasoline.

Ecological integrity: Refers to native species populations in their historic variety and numbers naturally interacting in naturally structured biotic communities. For communities, integrity is governed by demographics of component species, intactness of landscape-level ecological processes (e.g., natural fire regime), and intactness of internal community processes (e.g., pollination).

Ecological system: Dynamic assemblages of communities that occur together on the landscape at some spatial scale of resolution, are tied together by similar ecological processes, and form a cohesive, distinguishable unit on the ground. Examples are a spruce–fir forest, a Great Lakes dune and swale complex, and Mojave desert riparian shrublands.

Economy of scale: The principle that larger production facilities have lower unit costs than smaller facilities.

Ecoregion: A territory defined by a combination of biological, social, and geographic criteria rather than geopolitical considerations; generally, a system of related, interconnected ecosystems.

Ecosystem: A natural community of organisms interacting with its physical environment, regarded as a unit.

Ecosystem service: A benefit or service provided free by an ecosystem or by the environment, such as clean water, flood mitigation, or groundwater recharge.

Efficiency: The ratio of the useful energy output of a machine or other energy-converting plant to the energy input.

Electric energy: The ability of an electric current to produce work, heat, light, or other forms of energy. It is measured in kilowatt-hours.

Electric power sector: An energy-consuming sector that consists of electricity only and combined heat and power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public (i.e., North American Industry Classification System code 22 for plants).

Electric utility: A corporation, person, agency, authority, or other legal entity or instrumentality aligned with distribution facilities for delivery of electric energy for use primarily by the public. Included are investor-owned electric utilities, municipal and state utilities, federal electric utilities, and rural electric cooperatives. A few entities that are tariff based and corporately aligned with companies that own distribution facilities are also included.

Elution: The process of using a solvent (eluent) to remove select ions (e.g., uranium) from an adsorbent such as ion-exchange resins.

Embayment: A bay or baylike formation.

Emissions: Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).

Emissions coefficient: A unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (e.g., pounds of carbon dioxide emitted per Btu of fossil fuel consumed).

Emissions factor: A rate of carbon dioxide output resulting from the consumption of electricity, natural gas, or any other fuel source.

End user: A firm or individual that purchases products for its own consumption and not for resale (i.e., an ultimate consumer).

Endothermic: A chemical reaction that absorbs or requires energy (usually in the form of heat).

Energy: The ability to do work—that is, the capacity for doing work as measured by the capability of doing work (potential energy) or the conversion of this capability to motion (kinetic energy). Energy has several forms, some of which are easily convertible and can be changed to another form useful for work. Most of the world's convertible energy comes from fossil fuels that are burned to produce heat, which is then used as a transfer medium to mechanical or other means in order to accomplish tasks. Electrical energy is usually measured in kilowatt-hours, and heat energy is usually measured in British thermal units.

Energy crops: Crops grown specifically for their fuel value. They include food crops such as corn and sugarcane and non-food crops such as poplar trees and switchgrass. Currently, low-energy crops are under development: short-rotation woody crops, which are fast-growing hardwood trees harvested in 5 to 8 years, and herbaceous energy crops, such as perennial grasses, which are harvested annually after taking 2 to 3 years to reach full productivity.

Energy efficiency: A ratio of service provided to energy input (e.g., lumens to watts in the case of light bulbs). Services provided can include buildings-sector end uses such as lighting, refrigeration, and heating; industrial processes; or vehicle transportation. Unlike conservation, which involves some reduction of service, energy efficiency provides energy reductions without sacrifice of service.

Energy source: Any substance or natural phenomenon that can be consumed or transformed to supply heat or power. Examples include petroleum, coal, natural gas, nuclear, biomass, electricity, wind, sunlight, geothermal, water movement, and hydrogen in fuel cells.

Enhanced geothermal systems (EGSs): Engineered reservoirs that can extract economical amounts of heat from geothermal resources; rock fracturing, water injection, and water circulation technologies to sweep heat from the unproductive areas of existing geothermal fields or new fields lacking sufficient production capacity.

Enthalpy: A thermodynamic property of a substance, defined as the sum of its internal energy plus the pressure of the substance times its volume, divided by the mechanical equivalent of heat; the total heat content of air; the sum of enthalpies of dry air and water vapor per unit weight of dry air; measured in Btu per pound (or calories per kilogram).

Environment: The sum total of all biological, chemical, and physical factors to which organisms are exposed.

Environmental health (abiotic aspects): The composition, structure, and functioning of soil, water, air, and other abiotic features comparable with historic conditions, including the natural abiotic processes that shape the environment.

Environmental Impact Statement: A document created from a study of the expected environmental effects of a new development or installation.

Environmental restoration: Although usually described as "cleanup," this function encompasses a wide range of activities, such as stabilizing contaminated soil; treating groundwater; decommissioning process buildings, nuclear reactors, chemical separations plants, and many other facilities; and exhuming sludge and buried drums of waste.

Environmental restrictions: In reference to coal accessibility, land-use restrictions that constrain, postpone, or prohibit mining in order to protect environmental resources of an area—for example, surface- or ground water quality, air quality affected by mining, or plants or animals or their habitats.

Ethane (C_2H_6): A straight-chain saturated (paraffinic) hydrocarbon extracted predominately from the natural gas stream, which is gaseous at standard temperature and pressure. It is a colorless gas that boils at a temperate of –127°F.

Ethanol (ethyl alcohol or grain alcohol, CH_3-CH_2OH): A clear, colorless flammable oxygenated hydrocarbon with a boiling point of 173.5°F in the anhydrous state. However, it readily forms a binary azetrope with water, with a boiling point of 172.67°F at a composition of 9557% by weight ethanol. It is used in the United States as a gasoline octane enhancer and oxygenate (maximum 10% concentration). Ethanol can be used in higher concentrations (E85) in vehicles designed for its use. Ethanol is typically produced chemically from ethylene or biologically from fermentation of various sugars from carbohydrates found in agricultural crops and cellulosic residues from crops or wood. The lower heating value, equal to 76,000 Btu per gallon, is assumed for estimates in this text.

Ether: A generic term applied to a group of organic chemical compounds composed of carbon, hydrogen, and oxygen, characterized by an oxygen atom attached to two carbon atoms (e.g., methyl tertiary-butyl ether).

Ethylene (C_2H_4): An olefinic hydrocarbon recovered from refinery or petrochemical processes which is gaseous at standard temperature and pressure. Ethylene is used as petrochemical feedstock for many chemical applications and the production of consumer goods.

Ethylene dichloride: A colorless, oily liquid used as a solvent and fumigant for organic synthesis and for ore flotation.

Evacuated tube: In a solar thermal collector, an absorber tube, which is contained in an evacuated glass cylinder, through which collector fluids flows.

Evaluation: Examining how an organization's plans and actions have turned out and adjusting them for the future.

Evaporation pond: A containment pond (that preferably has an impermeable lining of clay or synthetic material such as hypalon) to hold liquid waste and to concentrate the waste through evaporation.

Evaporative cooler ("swamp cooler"): An air conditioner that uses evaporation from a centrally located pad; no refrigeration unit is involved.

Evapotranspiration (ET): The combined evaporation from the soil surface and transpiration from plants. Transpiration is the evaporation of water from internal surfaces of living plant organics and its subsequent diffusion into the atmosphere. Evaporation is the physical process by which liquid water is converted to vapor.

Exothermic: A chemical reaction that gives off heat.

Exotic species: A species that is not native to an area and has been introduced intentionally or unintentionally by humans; not all exotics become successfully established.

Expenditure: The incurrence of a liability to obtain an asset or service.

Externality: A cost or benefit not accounted for in the price of goods and services; often refers to the cost of pollution and other environmental impacts.

Extinction: The termination of any lineage of organisms, from subspecies to species and higher taxonomic categories from genera to phyla. Extinction can be local, in which one or more populations of a species or other unit vanish but others survive elsewhere, or total (global), in which all the populations vanish.

F

Fahrenheit: A temperature scale on which the boiling point of water is at 212° above 0 on the scale and the freezing point is at 32° above 0 at standard atmospheric pressure.

Failure or hazard (electrical power distribution): Any electric power supply equipment or facility failure or other event that, in the judgment of the reporting entity, constitutes a hazard to maintaining the continuity of the bulk electric power supply system such that load reduction action may become necessary and reportable outage may occur. Types of abnormal conditions that should be reported include the imposition of a special operating procedure, the extended purchase of emergency power, other bulk power system actions that may be caused by a natural disaster, a major equipment failure that would impact the bulk power supply, and an environmental or regulatory action requiring equipment outages.

Far trees: Trees located greater than 15 m (50 ft) from buildings so as to influence building energy use through their aggregate effect on air temperature and wind speed at the neighborhood scale.

Fast pyrolysis: Thermal conversion of biomass by rapid heating to 450 to 600°C in the absence of oxygen.

Fault: A fracture in rock exhibiting relative movement between the adjoining surfaces.

Fauna: All animal life associated with a given habitat, country, area, or period.

Federal land: Public land owned by the federal government, including national forests, national parks, and national wildlife refuges.

Federal listed species: A species listed as endangered or threatened, or a species at risk under the Endangered Species Act of 1973, as amended.

Federal Power Act: Enacted in 1920, and amended in 1935, the Act consists of three parts. The first part incorporated the Federal Water Power Act administered by the former Federal Power Commission, whose activities were confined almost entirely to licensing non-federal hydroelectric projects. The other two parts were added with the passage of the Public Utility Act. These parts extended the Act's jurisdiction to include regulating the interstate transmission of electrical energy and rates for its sale as wholesale in interstate commerce. The Federal Energy Regulatory Commission is now charged with administration of this law.

Feedstock: A product used as the basis for the manufacture of another product.

Feller–buncher: A self-propelled machine that cuts trees with giant shears near ground level and then stacks the trees into piles to await skidding.

Fenestration: The whole-building design approach determines what type of fenestration products (windows, doors, and skylights) should be used. Basically, such an approach involves selecting products with characteristics that accommodate a building's climate, including insulating, daylighting, heating and cooling, and natural ventilation needs.

Fermentation: Conversion of carbon-containing compounds by microorganisms for the production of fuels and chemicals such as alcohols, acids, or energy-rich gases.

Fiber products: Products derived from the fibers of herbaceous and woody plant materials. Examples include pulp, composition board products, and wood chips for export.

Fine materials: Wood residues not suitable for chipping, such as planer shavings and sawdust.

Fire management: All activities related to the management of wildland fires.

Fire regime: The characteristic frequency, intensity, and spatial distribution of natural fires within a given eco-region or habitat.

Fischer–Tropsch fuels: Liquid hydrocarbon fuels produced by a process that combines carbon monoxide and hydrogen. The process is used to convert coal, natural gas, and low-value refinery products into a high-value diesel substitute.

Fish passage project: Providing a safe passage for fish around a barrier in the upstream or downstream direction.

Fixing: Nearshore and offshore devices may be either bottom-mounted or floating, the former being fixed to the seabed by a static member and the latter moored to hold on station.

Flare: A tall stack equipped with burners used as a safety device at wellheads, refining facilities, gas processing plants, and chemical plants. Flares are used for the combustion and disposal of combustible gases. The gases are piped to a remote, usually elevated, location and burned in an open flame in the open air using a specially designed burner tip, auxiliary fuel, and steam or air. Combustible gases are flared most often due to emergency relief, overpressure, process upsets, startups, shutdowns, and other operational safety reasons. Natural gas that is not economical for sale is also flared. Often natural gas is flared as a result of the unavailability of a method for transporting such gas to markets.

Flash steam: Steam produced when the pressure on a geothermal liquid is reduced; also called *flashing*.

Flat plate pumped: A medium-temperature solar thermal collector that typically consists of a metal frame, glazing, absorbers (usually metal), and insulation and that uses a pump liquid as the heat-transfer medium; predominant use is in water heating applications.

Flexible-fuel vehicle: A vehicle with a single fuel tank designed to run on varying blends of unleaded gasoline with either ethanol or methanol.

Floodplain: Flat or nearly flat land that may be submerged by floodwaters; a plain built up or in the process of being built up by steam deposition.

Flora: All the plants found in a particular place.

Flow battery: An electrochemical energy storage device that utilizes tanks of rechargeable electrolyte to refresh the energy-producing reaction. Because its capacity is limited only by the size of its electrolyte tanks, it is useful for large-scale backup systems to supplement other forms of generation that may be intermittent in nature.

Fluidized-bed combustion: A method of burning particular fuel, such as coal, in which the amount of air required for combustion far exceeds that found in conventional burners. The fuel particles are continually fed into a bed of

mineral ash in the proportions of 1 part fuel to 200 parts ash, while a flow of air passes up through the bed, causing it to act like a turbulent fluid.

Fluorescent lamp: A glass enclosure in which light is produced when electricity is passed through mercury vapor inside the enclosure. The electricity creates a radiation discharge that strikes a coating on the inside surface of the enclosure, causing the coating to glow. *Note:* Traditional fluorescent lamps are usually straight or circular white glass tubes used in fixtures specially designed for them. A newer type of fluorescent lamp, the compact fluorescent lamp, takes up much less room, comes in many differently shaped configurations, and is designed to be used in some fixtures originally intended to house incandescent lamps.

Flux material: A substance used to promote fusion, such as of materials or minerals.

Fly ash: Particulate matter mainly from coal ash in which the particle diameter is less than 1×10^4 m. This ash is removed from the flue gas using flue gas particulate collectors such as fabric filters and electrostatic precipitators.

Flyway: Any one of several established migration routes of birds.

Focal species: A species that is indicative of particular conditions in a system (ranging from natural to degraded) and used as a surrogate measure for other species of particular conditions; an element of biodiversity selected as a focus for conservation planning or action. The two principal types of targets in conservancy planning projects are species and ecological communities.

Foliation period: Average period when a tree is in leaf.

Forest land: Land at least 10% stocked by forest trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between heavily forested and non-forested lands that are at least 10% stocked with forest trees and forest areas adjacent to urban and built-up lands. Also included are pinyon–juniper and chaparral areas in the West and afforested areas. The minimum area for classification of forest land is 1 acre. Roadside, streamside, and shelterbelt strips of trees much have a crown width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet wide or an acre in size.

Fossil fuels: A general term for combustible geologic deposits of carbon in reduced (organic) form and of biological origin, including coal, oil, natural gas, oil shales, and tar sands. A major concern is that they emit carbon dioxide into the atmosphere when burned, thus significantly contributing to the enhanced greenhouse effect.

Fractionation: The process by which saturated hydrocarbons are removed from natural gas and separated into distinct products, or "fractions," such as propane, butane, and ethane.

Fracture: Natural or induced break in rock.

Fracturing treatments: Treatments performed by pumping fluid into the subsurface at pressures above the fracture pressure of the reservoir formation to create a highly conductive flow path between the reservoir and the wellbore.

Fragmentation: The disruption of extensive habitats into isolated and small patches. Fragmentation has two negative components for biota: (1) the loss of total habitat area, and (2) the creation of smaller, more isolated patches of habitat remaining.

Fuel cell: One or more cells capable of generating an electrical current by converting the chemical energy of a fuel directly into electrical energy. Fuel cells differ from conventional electrical cells in that the active materials such as fuel and oxygen are not contained within the cell but are supplied from outside.

Fuel cell poisoning: The lowering of a fuel cell's efficiency due to impurities in the fuel binding to the catalyst.

Fuel cell stack: Individual fuel cells connected in a series. Fuel cells are stacked to increase voltage.

Fuel cycle: The entire set of sequential processes or stages involved in the utilization of fuel, including extraction, transformation, transportation, and combustion. Emissions generally occur at each stage of the fuel cycle.

Fuel ratio: The ratio of fixed carbon to volatile matter in coal.

Fuel treatment evaluator (FTE): A strategic assessment tool capable of aiding the identification, evaluation, and prioritization of fuel treatment opportunities.

Fuelwood: Wood and wood products, possibly including coppices, scrubs, branches, etc., bought or gathered, and used by direct combustion.

Fugitive emissions: Unintended leaks of gas from the processing, transmission, or transportation of fossil fuels.

Full sun: The amount of power density in sunlight received at the Earth's surface at noon on a clear day (about 1000 watts/square meter).

Fumarole: A vent or hole in the Earth's surface, usually in a volcanic region, from which steam, gaseous vapors, or hot gases issue.

G

Gallon: A volumetric measure equal to 4 quarts (231 cubic inches) used to measure fuel oil. One gallon equals 3785 liters; 1 barrel equals 42 gallons.

Gas: A non-solid, non-liquid combustible energy source that includes natural gas, coke-oven gas, blast-furnace gas, and refinery gas.

Gasification: A chemical or heat process to convert a solid fuel to a gaseous form.

Gasohol: A motor vehicle fuel that is a blend of 90% unleaded gasoline and 10% ethanol (by volume).

Gearbox: Device that increases the rpm of a low-speed shaft, transferring its energy to a high-speed shaft in order to provide enough speed to generate electricity.

Generally accepted accounting principles (GAAPs): Defined by the Financial Accounting Standards Board (FASB) as the conventions, rules, and procedures necessary to define accepted accounting practices at a particular time; includes both broad guidelines and relatively detailed practices and procedures.

Generation (electricity): The process of producing electric energy from other forms of energy; also, the amount of electric energy produced, expressed in watthours (Wh).

Geologic hazards: One of several types of adverse geologic conditions capable of causing damage or loss of property and life. These hazards include avalanches, earthquakes, forest fires, geomagnetic storms, ice jams, landslide, mudslide, rock falls, torrents, volcanic eruptions, alluvial fans, geyser deposits, liquefaction, sand dune migration, thermal springs, and stream erosion.

Geographic information system (GIS): A computerized system to compile, store, analyze, and display geographically referenced information.

Geologic sequestration: A type of engineered sequestration where captured carbon dioxide is injected for permanent storage into underground geologic reservoirs, such as oil and natural gas fields, saline aquifers, or abandoned coal mines.

Geothermal: Of or relating to the Earth's interior heat.

Geothermal energy: The Earth's interior heat made available for use by extracting it from hot water or rocks. As used at electric power plants, hot water or steam extracted from geothermal reservoirs in the Earth's crust is supplied to steam turbines at electric power plants that drive generators to produce electricity.

Geothermal gradient: The rate of temperature increase in the Earth as a function of depth. Temperature increases an average of 1°F for every 75 feet in descent.

Geothermal heat pumps: Devices that take advantage of the relatively constant temperature of the Earth's interior, using it as a source and sink of heat for both heating and cooling. For cooling, heat is extracted from the space and dissipated into the Earth; for heating, heat is extracted from the Earth and pumped into the space.

Geothermal plant: A plant in which a turbine is driven either from hot water or by natural steam that derives its energy from heat found in rocks or fluids at various depths beneath the surface of the Earth. The fluids are extracted by drilling or pumping.

Geothermal resources: The natural heat of the earth that can be used for beneficial purposes when the heat is collected and transported to the surface.

Geyser: A spring that shoots jets of hot water and steam into the air.

Gigawatt (GW): One billion watts or 1000 megawatts.

Gigawatt-electric (GWe): One billion watts of electric capacity.

Gigawatt-hour (GWh): One billion watt-hours.

Glazing: Transparent or translucent material (glass or plastic) used to admit light or to reduce heat loss; used for building windows, skylights, or greenhouses or for covering the aperture of a solar collector.

Global positioning system (GPS): A navigation system using satellite signals to fix the location of a radio receiver on or above the Earth's surface.

Global warming: An increase in the near-surface temperature of the Earth. Global warming has occurred in the distant past as a result of natural influence (it is a cyclical event that has occurred throughout Earth's history), but the term is most often used to refer to the warming predicted to occur as a result of increased emissions of greenhouse gases from commercial or industrial resources.

Global warming potential: Relative measure of how much heat a greenhouse gas traps in the atmosphere.

Grassland pasture and range: All open land used primarily for pasture and grazing, including shrub and brush land types of pasture; grazing land with sagebrush and scattered mesquite; and all tame and native grasses, legumes, and other forage used for pasture or grazing. Because of the diversity in vegetative composition, grassland pasture and range are not always clearly distinguishable from other types of pasture and range. At one extreme, permanent grassland may merge with cropland pasture, or grassland may often be found in transitional areas with forested grazing land.

Gravimetry: The use of precisely measured gravitational force to determine mass differences that can be correlated to subsurface geology.

Green pricing/marketing: In the case of renewable electricity, green pricing represents a market solution to the various problems associated with regulatory valuation of the non-market benefits of renewables. Green pricing programs allow electricity customers to express their willingness to pay for renewable energy development through direct payments on their monthly utility bills.

Greenhouse effect: The effect produced as greenhouse gases allow incoming solar radiation to pass through the Earth's atmosphere but prevent most of the outgoing infrared radiation from the surface and lower atmosphere from escaping into outer space.

Greenhouse gas: Gases that trap the heat of the sun in the Earth's atmosphere, producing the greenhouse effect. The two major greenhouse gases are water vapor and carbon dioxide. Other greenhouse gases include methane, ozone, chlorofluorocarbons, and nitrous oxide.

Grid: The layout of an electrical distribution system.

Gross domestic product (GDP): The total value of goods and services produced by labor and property located in the United States. As long as the labor and property are located in the United States, the supplier (that is, the workers and, for property, the owners) may be either U.S. residents or residents of foreign countries.

Gross generation: The total amount of electric energy produced by the generating units at a generation station or stations, measured at the generator terminals.

Gross head: A dam's maximum allowed vertical distance between the upstream's surface water (headwater) forebay elevation and the downstream's surface water (tailwater) elevation at the tail-race for reaction wheel dams or the elevation of the jet at impulse wheel dams during specified operation and water conditions.

Growing stock: A classification of timber inventory that includes live trees of commercial species meeting specified standards of quality or vigor. Cull tress are excluded. When associated with volume, classification includes only trees 5.0 inches d.b.h. and larger.

Groundwater: Water in the ground that is in the zone of saturation, from which wells and springs and groundwater runoff are supplied. Because groundwater is a major source of drinking water, concern is growing over areas where

leaching agricultural or industrial pollutants or substances from leaking underground storage tanks (USTs) are contaminating groundwater.

Groundwater hydrology: The branch of hydrology that deals with groundwater, its occurrence and movements, its replenishment and depletion, the properties of rocks that control groundwater movement and storage, and the methods of investigation and use of groundwater.

Groundwater recharge: The inflow to a groundwater reservoir.

Groundwater runoff: A portion of runoff that has passed into the ground, has become groundwater, and has been discharged into a stream channel as spring or seepage water.

H

Habitat: The place or type of site where species and species assemblages are typically found or successfully reproduce.

Habitat conservation: Protecting an animal or plant habitat to ensure that the use of that habitat by the animal or plant is not altered or reduced.

Habitat fragmentation: The breaking up of a specific habitat into smaller, unconnected areas.

Half-life: The time it takes for an isotope to lose half of its radioactivity.

Halogen lamp: A type of incandescent lamp that lasts much longer and is more efficient than the common incandescent lamp. The lamp uses a halogen gas, usually iodine or bromine, that causes the evaporating tungsten to be redeposited on the filament, thus prolonging its life.

Halogenated substances: A volatile compound containing halogens, such as chlorine, fluorine, or bromine.

Hardwoods: Usually broad-leaved and deciduous trees.

HDR (hot dry rock): Subsurface geologic formations of abnormally high heat content that contain little or no water.

Head: The product of the water's weight and a usable difference in elevation gives a measurement of the potential energy possessed by water.

Head-of-tide: The farthest point upstream where a river is affected by tidal fluctuations.

Heat content: The amount of heat energy available to be released by the transformation or use of a specified physical unit of an energy form (e.g., a ton of coal, a barrel of oil, a kilowatt-hour of electricity, a cubic foot of natural gas, a pound of steam). The amount of heat energy is commonly expressed in British thermal units (Btu). *Note:* Heat content of combustible energy forms can be expressed in terms of either gross heat content (higher or upper heating value) or net heat content (lower heating value), depending on whether or not the available heat energy includes or excludes the energy used to vaporize water (contained in the original energy form or created during the combustion process). The Energy Information Administration (EIA) typically uses gross heat content values.

Heat exchanger: A device for transferring thermal energy from one fluid to another.

Heat flow: Movement of heat from within the Earth to the surface, where it is dissipated into the atmosphere, surface water, and space by radiation.

Heat pump: A year-round heating and air-conditioning system employing a refrigeration cycle. In a refrigeration cycle, a refrigerant is compressed (as a liquid) and expanded (as a vapor) to absorb and reject heat. The heat pump transfers heat to a space to be heated during the winter period and by reversing the operation extracts (absorbs) heat from the same space to be cooled during the summer period. The refrigerant within the heat pump in the heating mode absorbs the heat to be supplied to the space to be heated from an outside medium (air, ground, or ground water) and in the cooling mode absorbs heat from the space to be cooled to be rejected to the outside medium.

Heat pump, air source: The most common type of heat pump. The heat pump absorbs heat from the outside air and transfers the heat to the space to be heated in the heating mode. In the cooling mode, the heat pump absorbs heat from the space to be cooled and rejects the heat to the outside air. In the heating mode, when the outside air approaches 32°F or less, air-source heat pumps lose efficiency and generally require a back-up (resistance) heating system.

Heat pump efficiency: The efficiency of a heat pump (that is, the electrical energy to operate it) is directly related to temperatures between which it operates. Geothermal heat pumps are more efficient than conventional heat pumps or air conditioners that use the outdoor air because the ground or groundwater a few feet below the Earth's surface remains relatively constant throughout the year. It is more efficient in the winter to draw heat from the relatively warm ground than from the atmosphere where the air temperature is much colder, and in summer transfer waste heat to the relatively cool ground than to the hotter air. Geothermal heat pumps are generally more expensive to install than outside air heat pumps. However, depending on the location, geothermal heat pumps can reduce energy consumption (operating cost) and, correspondingly, emissions by more than 20% compared to high-efficiency outside air heat pumps. Geothermal heat pumps also use the waste heat from air-conditioning to provide free hot water heating in the summer.

Heat pump, geothermal: A heat pump in which the refrigeration exchanges heat (in a heat exchanger) with a fluid circulating through an earth connection medium (ground or groundwater). The fluid is contained in a variety of loop (pipe) configurations depending on the temperature of the ground and the ground area available. Loops may be installed horizontally or vertically in the ground or submersed in a body of water.

Heat rate: A measure of generating station thermal efficiency commonly stated as Btu per kilowatt-hour. *Note:* Heat rates can be expressed as either gross or net heat rates, depending on whether the electricity output is gross or net generation. Heat rates are typically expressed as net heat rates.

Heating value: The maximum amount of energy available from burning a substance.

Heliostat: A mirror that reflects solar rays onto a central receiver. A heliostat automatically adjusts its position to track daily or seasonal changes in the sun's position. The arrangement of heliostats around a central receiver is also called a *solar collector field*.

Herbaceous: Non-woody type of vegetation, usually lacking permanent strong stems, such as grasses, cereals, and canola (rape).

High-speed shaft: Transmits force from the gearbox to the generator.

High-temperature collector: A solar thermal collector designed to operate at a temperature of 180°F or higher.

Historic conditions: The composition, structure, and functioning of ecosystems resulting from natural processes that we believe, based on sound professional judgment, were present prior to substantial human-related changes to the landscape.

Holding pond: A structure built to contain large volumes of liquid waste to ensure that it meets environmental requirements prior to release.

Horizontal axis wind turbine: The most common type of wind turbine where the axis of rotation is oriented horizontally.

Horsepower: A unit for measuring the rate of work (or power) equivalent to 33,000 foot-pounds per minute or 746 watts.

Hot dry rock (HDR): Subsurface geologic formations of abnormally high heat content that contain little or no water.

Hub: The center part of the rotor assembly, which connects the blades to the low-speed shaft.

Hub height: In a horizontal-axis wind turbine, the distance from the turbine platform to the rotor shaft.

Hydraulic fracturing: Fracturing of rock at depth with fluid pressure. Hydraulic fracturing at depth may be accomplished by pumping water into a well at very high pressures. Under natural conditions, vapor pressure may rise high enough to cause fracturing in a process known as hydrothermal brecciation.

Hydraulic head: The distance between the respective elevations of the upstream water surface (headwater) above and the downstream surface water (tailwater) below a hydroelectric power plant.

Hydraulic stimulation: A stimulation technique performed using fluid.

Hydrocarbon: An organic chemical compound of hydrogen and carbon in the gaseous, liquid, or solid phase. The molecular structure of hydrocarbon compounds varies from the simplest (methane, a constituent of natural gas) to the heavy and very complex.

Hydroelectric power: The use of flowing water to produce electrical energy.

Hydrogen: The lightest of all gases, occurring chiefly in combination with oxygen in water; exists also in acids, bases, alcohols, petroleum, and other hydrocarbons.

Hydrokinetic energy: The energy possessed by a body of water because of its motion (kinetic energy = 1/2 mass × velocity^2).

Hydrologic or flow regime: Characteristic fluctuations in river flows.

Hydrology: The science of waters of the Earth: their occurrences, distributions, and circulations; their physical and chemical properties; and their reactions with the environment, including living beings.

Hydrolysis: Decomposition of a chemical compound by reaction with water.

Hydrostatic energy: The energy possessed by a body because of its position or location at an elevation or height above a reference or datum (potential energy = mass × gravity × height).

Hydrothermal: Pertaining to hot water.

Hydrothermal reservoir: An aquifer, or subsurface water, that has sufficient heat, permeability, and water to be exploited without stimulation or enhancement.

I

Idle capacity: The component of operable capacity that is not in operation and not under active repair but is capable of being placed in operation within 30 days; also, capacity not in operation but under active repair that can be completed within 90 days.

Idle cropland: Land in cover and soil improvement crops and cropland on which no crops were planted. Some cropland is idle each year for various physical and economic reasons. Acreage diverted from corps to soil-conserving uses (if not eligible for and used as cropland pasture) under federal farm programs is included in this component. Cropland enrolled in the federal Conservation Reserve Program (CRP) is included in the idle cropland.

Impedance: The opposition to power flow in an AC circuit—that is, any device that introduces such opposition in the form of resistance, reactance, or both. The impedance of a circuit or device is measured as the ratio of voltage to current, where a sinusoidal voltage and current of the same frequency are used for the measurement; it is measured in ohms.

Impoundment: A body of water, such as a pond, confined by a dam, dike, floodgate, or other barrier, which is used to collect and store water for future use.

Incandescent lamp: A glass enclosure in which light is produced when a tungsten filament is electrically heated so that it glows. Much of the energy is converted into heat; therefore, this class of lamp is a relatively inefficient source of light. Included in this category are the familiar screw-in light bulbs, as well as somewhat more efficient lamps, such as tungsten halogen lamps, reflector or R-type lamps, parabolic aluminized reflector (PAR) lamps, and ellipsoidal reflector (ER) lamps.

Incident light: Light that shines onto the face of a solar cell or module.

Indicator species: A species used as a gauge for the condition of a particular habitat, community, or ecosystem. A characteristic or surrogate species for a community or ecosystem.

Indigenous: Native to an area.

Indigenous species: A species that, other than as a result of an introduction, historically occurred or currently occurs in a particular ecosystem.

Induced seismicity: Refers to typically minor earthquakes and tremors that are caused by human activity that alters the stresses and strains on the Earth's crust. Most induced seismicity is of an extremely low magnitude, and in many cases human activity is merely the trigger for an earthquake that would have occurred naturally in any case.

Industrial wood: All commercial roundwood products except fuelwood.

Injection: The process returning spent geothermal fluids to the subsurface. Sometimes referred to as *reinjection*.

Initial attack: An aggressive action to put a fire out consistent with firefighter and public safety and the valuables being protected.

Interferometric synthetic aperture radar (InSar): A remote sensing technique that uses radar satellite images to determine movement of the surface of the Earth.

Interjurisdictional fish: Populations of fish that are managed by two or more states or national or tribal governments because of the scope of their geographic distributions or migrations.

Internal collector storage: A solar thermal collector in which incident solar radiation is absorbed by the storage medium.

Interpretive facilities: Structures that provide information about an event, place, or thing by a variety of means, including printed, audiovisual, or multimedia materials (e.g., kiosks that offer printed materials and audiovisuals, signs, trail heads).

Introduced invasive species: Non-native species that have been introduced into an area and, because of their aggressive growth and lack of natural predators, displace native species.

Invasive species: An alien species whose introduction causes or is likely to cause economic or environmental harm or harm to human health.

Invertebrate: Any animal lacking a backbone or bony segment that encloses the central nerve cord.

Ion exchange: Reversible exchange of ions adsorbed on a mineral or synthetic polymer surface with ions in solution in contact with the surface. A chemical process used for recovery of uranium from solution by the interchange of ions between a solution and a solid, commonly a resin.

Irradiance: The direct, diffuse, and reflected solar radiation that strikes a surface.

Isobutane (C_4H_{10}): A branch-chain saturated (paraffinic) hydrocarbon extracted from both natural gas and refinery gas streams which is gaseous at standard temperature and pressure. It is a colorless gas that boils at a temperature of 11°F.

Isobutylene (C_4H_8): A branch-chain olefinic hydrocarbon recovered from refinery or petrochemical processes which is gaseous at standard temperature and pressure. Isobutylene is used in the production of gasoline and various petrochemical products.

Isohexane (C_6H_{14}): A saturated branch-chain hydrocarbon. It is a colorless liquid that boils at a temperature of 156.2°F.

Isomerization: A refining process that alters the fundamental arrangement of atoms in the molecule without adding or removing anything from the original material. Used to convert normal butane into isobutane (C_4), an alkylation process feedstock, and normal pentane and hexane into isopentane (C_5) and isohexane (C_6), high-octane gasoline components.

Isotopes: Forms of the same chemical element that differ only by the number of neutrons in their nucleus. Most elements have more than one naturally occurring isotope. Many isotopes have been produced in reactors and scientific laboratories.

J

Joule: The basic energy unit for the metric system or, in a later more comprehensive formulation, the International System of Units (SI). It is ultimately defined in terms of the meter, kilogram, and second.

K

Kaplan turbine: A type of turbine that has two blades whose pitch is adjustable. The turbine may have gates to control the angle of the fluid flow into the blades.
kBtu: A unit of work or energy, measured as 1000 British thermal units. One kBtu is equivalent to 0.293 kWh.
Kilowatt (kW): One thousand watts of electricity.
Kilowatt-hour (kWh): One thousand watt-hours.
Kinetic energy: Energy available as a result of motion that varies directly in proportion to an object's mass and the square of its velocity.

L

Lamp: A term generally used to describe artificial light. The term is often used when referring to a bulb or tube.
Land use: The ultimate uses to be permitted for currently contaminated lands, waters, and structures at each Department of Energy installation. Land-use decisions strongly influence the cost of environmental management.
Landfill gas: Gas that is generated by decomposition of organic material at landfill disposal sites. Landfill gas is approximately 50% methane.
Landform: The physical shape of the land reflecting geologic structures and processes of geomorphology that have sculpted the structures.
Landscape: A heterogeneous land area composed of a cluster of interacting ecosystems that are repeated in similar form throughout.
Langley (L): Unit of solar irradiance equal to 1 gram calorie per square centimeter of irradiated surface. One langley = 85.93 kWh/m^2.
Late-successional: Species, assemblages, structures, and processes associated with mature natural communities that have not experienced significant disturbance for a long time.
Leachate: The liquid that has percolated through the soil or other medium.
Leeward: Away from the direction of the wind; opposite of windward.
Life-cycle analysis: Analysis focused on the environmental impact of a product during the entirety of its life cycle, from resource extraction to post-consumer waste disposal. It is a comprehensive approach to examining the environmental impacts of a product or package.
Lignin: Structural constituent of wood and (to a lesser extent) other plant tissues that encrusts the cell walls and cements the cells together.
Limiting factor: An environmental limitation that prevents further population growth.
Line shaft pump: Fluid pump that has the pumping mechanism in the wellbore and that is driven by a shaft connected to a motor on the surface.

Liner: A casing string that does not extend to the top of wellbore but instead is anchored or suspended from inside the bottom of the previous casing string.

Liquid collector: A medium-temperature solar thermal collector, employed predominantly in water heating, which uses pumped liquid as the heat-transfer medium.

Lithology: The study and description of rocks, in terms of their color, texture, and mineral composition.

Live cull: A classification that includes live cull trees. When associated with volume, it is the net volume in live cull trees that are 5.0 inches in d.b.h. and larger.

Living shorelines: Restored shorelines that use nature-based techniques such as marsh plantings, beach nourishment, and low-profile oyster reefs, breakwaters, and sills. In addition to protecting property from erosion, living shorelines provide habitat for fish, birds, and other wildlife. Like undisturbed natural shorelines, they also protect water quality by trapping excess nutrients and sediment.

Load: The simultaneous demand of all customers required at any specified point in an electric power system.

Load balancing: Keeping the amount of electricity produced (the supply) equal to the consumption (the demand). This is one of the challenges of wind energy production, which produces energy on a less predicable schedule than other methods.

Local solar time: A system of astronomical time in which the sun crosses the true north–south meridian at 12 noon and which differs from local time according to longitude, time zone, and equation of time.

Logging residues: The unused portions of growing stock and non-growing stock trees cut or killed by logging and left in the woods.

Lost circulation: Zones in a well that imbibe drilling fluid from the wellbore, thus causing a reduction in the flow of fluid returning to the surface. This loss causes drilled rock particles to build up in the well and can cause problems in cementing casing in place.

Low-speed shaft: Connects the rotor to the gearbox.

Low-temperature collectors: Metallic or nonmetallic solar thermal collectors that generally operate at temperatures below 110°F and use pumped liquid or air as the heat-transfer medium. They usually contain no glazing and no insulation, and they are often made of plastic or rubber, although some are made of metal.

Lumen: An empirical measure of the quantity of light based on the spectral sensitivity of the photosensors in the human eye under high (daytime) light levels. Photometrically, it is the luminous flux emitted with a solid angle (1 steradian) by a point source having a uniform luminous intensity of 1 candela.

M

Macroinvertebrates: The emphasis on aquatic insect studies, which has expanded exponentially in the last three decades, has been largely ecological. With regard to freshwater macroinvertebrates, they are ubiquitous; even polluted waters contain some representative of this diverse and ecologically important

group of organisms. Benthic macroinvertebrates are aquatic organisms without backbones that spend at least a part of their life cycle on the stream bottom. Examples include aquatic insects (e.g., stoneflies, mayflies, caddisflies, midges, beetles), as well as crayfish, worms, clams, and snails. Most hatch from eggs and mature from larvae to adults. The majority of the insects spend their larval phase on the river bottom and, after a few weeks to several years, emerge as winged adults. The aquatic beetles, true bugs, and other groups remain in the water as adults. Macroinvertebrates typically collected from the stream substrate are either aquatic larvae or adults.

Macrophyte: An aquatic plant that grows in or near water.

Magma: Molten rock within the Earth from which igneous rock is formed by cooling.

Magnetic survey: Measurements of the Earth's magnetic field that are then mapped and used to determine subsurface geology.

Magnetotellurics: An electromagnetic method of determining structures below the Earth's surface using electrical currents and the magnetic field.

Mantle: The Earth's inner layer of molten rock lying beneath the Earth's crust and above the Earth's core of liquid iron and nickel.

Marshlands: Areas interspersed with open water, emergent vegetation (hydrophytes), and terrestrial vegetation (phreatophytes).

Matrix treatments: Treatments used to restore or improve the natural permeability of a reservoir following damage to the near-wellbore area. Matrix treatments typically use hydrochloric or hydrofluoric acid to remove mineral material reducing flow into the well.

Mature tree size: The approximate tree size 40 years after being planted.

Mean power output (of wind turbine): The average power output of a wind energy conversion system at a given mean wind speed based on a Raleigh frequency distribution.

Median: The middle number of a dataset when the measurements are arranged in ascending (or descending) order.

Medium pressure: For valves and fittings, implies that they are suitable for working pressures between 125 to 175 pounds per square inch.

Medium-temperature collectors: Solar thermal collectors designed to operate in the temperature range of 140 to 180°F but that can also operate at a temperature as low as 110°F. The collector typically consists of a metal frame, metal absorption panel with integral flow channels (attached tubing for liquid collectors or integral ducting for air collectors), and glazing and insulation on the sides and back.

Megavoltamperes (MVA): Millions of voltamperes, which are a measure of apparent power.

Megawatt (WM): One million watts of electricity.

Megawatt-hour (MWh): One thousand kilowatt-hours or 1 million watt-hours.

Mercaptan: An organic chemical compound with a sulfur-like odor that is added to natural gas before distribution to the consumer to give the natural gas a distinct, unpleasant odor (like rotten eggs). This serves as a safety device by allowing the gas to be detected when leaks occur.

Methane: A colorless, flammable, odorless hydrocarbon gas (CH_4) that is the major component of natural gas. It is also an important source of hydrogen in various industrial processes. Methane is a greenhouse gas.

Methanogens: Bacteria that synthesize methane, requiring completely anaerobic conditions for growth.

Methanol: Also known as methyl alcohol or wood alcohol and having the chemical formula CH_3OH. Methanol is usually produced by chemical conversion at high temperature and pressure. Although usually produced from natural gas, methanol can be produced from gasified biomass.

Microseismicity: Small movements of the Earth causing fracturing and movement of rocks. Such seismic activity does not release sufficient energy for the events to be recognized except with sensitive instrumentation.

Migratory nongame birds of management concern: Species of nongame birds that (1) are believed to have undergone significant population declines, (2) have small or restricted populations, or (3) are dependent upon restricted or vulnerable habitats.

Mineral: Any of the various naturally occurring inorganic substances, such as metals, salt, sand, stone sulfur, and water, usually obtained from the Earth. *Note:* For reporting on the Financial Reporting System the term also includes organic nonrenewable substances that are extracted from the Earth such as coal, crude oil, and natural gas.

Mineral rights: Ownership of the minerals beneath the Earth's surface with the right to remove them. Mineral rights may be conveyed separately from surface rights.

Mini-frac: A small fracturing treatment performed before the main hydraulic fracturing treatment to acquire stress data and to test prestimulation permeability.

Minimum streamflow: The lowest rate of flow of water past a given point during a specified period.

Mitigation: Actions to compensate for the negative effects of a particular project.

Moisture content: The water content of a substance (a solid fuel) as measured under specified conditions: (1) "dry basis," which equals the weight of the wet sample minus the weight of a (bone) dry sample divided by the weight of the dry sample times 100 (to get percent); or (2) "wet basis," which is equal to the weight of the wet sample minus the weight of the dry sample divided by the weight of the wet sample times 100.

Mole: The quantity of a compound or element that has a weight in grams numerically equal to its molecular weight. Also referred to as *gram molecule* or *gram molecular weight.*

MSW (municipal solid waste): Residential solid waste and some nonhazardous commercial, institutional, and industrial wastes.

MTBE (methyl tertiary-butyl ether): A fuel oxygenate produced by reacting methanol with isobutylene.

Multiplier effect: Sometimes called the *ripple effect*, term refers to a single expenditure in an economy can have repercussions throughout the entire economy. The multiplier is a measure of how much additional economic activity is generated from an initial expenditure.

Municipal waste: Defined in the Energy Security Act (P.L. 96-294; 1960) as "any organic matter, including sewage, sewage sludge, and industrial or commercial waste, and mixtures of such matter and inorganic refuse from any publicly or privately operated municipal waste collection or similar disposal system, or from similar waste flows (other than such flows which constitute agricultural wastes or residues, or wood wastes or residues from wood harvesting activities or production of forest products)."

N

Nacelle (or cowling): Contains and protects the gearbox and generator; sometimes it is large enough for an engineer or technician to stand in while doing maintenance.

Naphtha: Generic term applied to a petroleum fraction with an approximate boiling range between 122 and 400°F.

Native: A species that, other than as a result of an introduction, historically occurred or currently occurs in a particular ecosystem.

Native gas: A gaseous mixture of hydrocarbon compounds, the primary one being methane.

Native plant: A plant that has grown in the region since the last glaciation and occurred before European settlement.

Natural gas: A gaseous mixture of hydrocarbon compounds, the primary one being methane.

Natural processes: A complex mix of interactions among animals, plants, and their environment that ensures maintenance of an ecosystem's full range of biodiversity. Examples include population and predator–prey dynamics, pollination and seed dispersal, nutrient cycling, migration, and dispersal.

Natural sinks: In reference to greenhouse gases, any natural process in which these gases are absorbed from the atmosphere.

Near tree: Trees located within approximately 15 m (50 ft) of a building so as to directly influence irradiance and air flow on the building envelope.

Net head: The gross head minus all hydraulic losses except those chargeable to the turbine.

Net metering: Arrangement that permits a facility (using a meter that reads inflows and outflows of electricity) to sell any excess power it generates over its load requirement back to the electrical grid to offset consumption.

Net photovoltaic cell shipment: The difference between photovoltaic cell shipments and photovoltaic cell purchases.

Net photovoltaic module shipment: The difference between photovoltaic module shipments and photovoltaic module purchases.

Net summer capacity: The maximum output, commonly expressed in megawatts (MW), that generating equipment can supply to system load, as demonstrated by a multiple-hour test at the time of summer peak demand. This output reflects a reduction in capacity due to electricity used for station service or auxiliaries.

Niche: The specific part or smallest unit of a habitat occupied by an organism.

Nitrogen dioxide: A compound of nitrogen and oxygen formed by the oxidation of nitric oxide (NO) which is produced by the combustion of solids fuels.

Nitrogen oxides (NO_x): Compounds of nitrogen and oxygen produced by the burning of fossil fuels.

Nitrous oxide (N_2O): A colorless gas, naturally occurring in the atmosphere. Nitrous oxide has a 100-year global warming potential of 310.

Nocturnal cooling: The effect of cooling by the radiation of heat from a building to the night sky.

Non-biomass waste: Material of non-biological origin that is a byproduct or a discarded product; includes municipal solid waste from non-biogenic sources, such as plastics, and tire-derived fuels.

Nonforest land: Land that has never supported forests and lands formerly forested where use of time management is precluded by development for other uses. *Note:* This category includes areas used for crops, improved pasture, residential areas, city parks, improved roads of any width and adjoining clearings, powerline clearings of any width, and 1- to 4.5-acre areas of water classified by the Bureau of the Census as land. If intermingled in forest areas, unimproved roads and nonforest strips must be more than 120 feet wide, and clearings, etc., must be more than 1 acre in area to qualify as nonforest land.

Non-industrial private: An ownership class of private lands where the owner does not operate wood-using processing plants.

Non-point source: A diffuse form of water quality degradation produced by erosion of land that causes sedimentation of streams, eutrophication from nutrients and pesticide used in agricultural and silvicultural practices, and acid rain resulting from burning fuels that contain sulfur.

Non-renewable fuels: Fuels that cannot be easily made or renewed, such as oil, natural gas, and coal.

Non-utility generation: Electric generation by end-users, or small power producers under the Public Utility Regulatory Policies Act, to supply electric power for industrial, commercial, and military operations, or sales to electric utilities.

Non-utility power producer: A corporation, person, agency, authority, or other legal entity or instrumentality that owns electric generating capacity and is not an electrical utility. Non-utility power producers include qualifying cogenerators, qualifying small power producers, and other non-utility generators without a designated, franchised service area that do not file forms listed in the Code of Federal regulations, Title 18, Part 141.

O

Occupied space: The space within a building or structure that is normally occupied by people and that may be conditioned (heated, cooled, and/or ventilated).

Ocean energy systems: Energy conversion technologies that harness the energy in tides, waves, and thermal gradient in the oceans.

Ocean thermal energy conversion (OTEC): The process or technologies for producing energy by harnessing the temperature differences (thermal gradients) between ocean surface waters and the ocean depths. Warm surface water

is pumped through an evaporator containing a working fluid in a closed Rankine-cycle system. The vaporized fluid drives a turbine/generator.

Oligohaline: Low salinity (0.5 to 5 parts per thousand).

Oscillating water column (OWC): A partly submerged structure (collector) that is open to the sea below the water surface so that it contains a column of water. Air is trapped above the surface of the water column. As waves enter and exit the collector, the water column moves up and down and acts like a piston on the air, pushing it back and forth. The air is channeled toward a turbine and forces it to turn. The turbine is coupled to a generator to produce electricity.

Other biomass: A category of biomass energy that includes agricultural byproducts/crops (agricultural byproducts, straw); other biomass gas (digester waste alcohol); other biomass liquids (fish oil, liquid acetonitrite waste, tall oil, waste alcohol); and other biomass solids (medical waste, solid byproducts, sludge waste, tires).

Other forest land: Forest land other than timberland and reserved forest land. It includes available forest land that is incapable of annually producing 20 cubic feet per acre of industrial wood under natural conditions because of adverse site conditions such as sterile soils, dry climate, poor drainage, high elevation, steepness, or rockiness.

Other removals: Unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as precommercial thinnings, or from timberland clearing. Does not include volume removed from inventory through reclassification of timberland to productive reserved forest land.

Other sources: Sources of roundwood products that are not growing stock. These include available dead, rough, and rotten trees; trees of non-commercial species; trees less the 5.0 inches d.b.h.; tops; and roundwood harvested from non-forest land (e.g., fence rows).

Overtopping terminator: A floating reservoir structure with a ramp over which the waves topple and hydroturbines through which the water returns to the sea. The head of collected water turns the turbines as it flows back out to sea and the turbines are coupled to generators to produce electricity.

P

Packer: Device that can be placed in the wellbore to block vertical fluid flow so as to isolate zones.

Palustrine forested wetlands: Riparian wetlands found next to rivers and lakes and those isolated from any surface watercourse that are dominated by trees, including wooded swamps and low-lying hardwood forests near rivers. Sixty-eight percent of the wetlands in the Chesapeake Bay watershed are forested.

Palustrine wetlands: Nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all tidal wetlands where salinity due to ocean-derived salts is below 0.5 ppt.

Paper pellets: Paper compressed and bound into uniform diameter pellets to be burned in a heating stove.

Parabolic dish: A high-temperature (above 180°F) solar thermal concentrator, generally bow-shaped and with two-axis tracking.

Parabolic trough: A high-temperature (above 180°F) solar thermal concentrator with the capacity for tracking the sun using one axis of rotation.

Particulate: A small, discrete mass of solid or liquid matter that remains individually dispersed in gas or liquid emissions. Particulates take the form of aerosol, dust, fume, mist, smoke, or spray. Each of these forms has different properties.

Passive solar: A system in which solar energy alone is used for the transfer of thermal energy. Pumps, blowers, or other heat-transfer devices that use energy other than solar are not used.

Peak demand: The maximum load during a specified period of time.

Peak watt: A manufacturer's unit indicating the amount of power a photovoltaic cell or module will produce at standard test conditions (normally 1000 watts per square meter at 25°C).

Peaking plants: Electricity generators that are operated to meet the peak or maximum load on the system. The cost of energy from such plants is usually higher than from baseload plants.

Peat: Consisting of partially decomposed plant debris, peat is considered an early stage in the development of coal. Peat is distinguished from lignite by the presence of free cellulose and a high moisture content (exceeding 70%). The heat content of air-dried peat (about 50% moisture) is about 9 million Btu per ton. Most U.S. peat is used as a soil conditioner.

Permeability: The ability of a rock to transmit fluid through its pores or fractures when subjected to a difference in pressure; typically measured in darcies or millidarcies.

Petrochemical feedstocks: Chemical feedstocks delivered from petroleum principally for the manufacture of chemicals, synthetic rubber, and a variety of plastics.

Phenology: The study of periodic plant and animal life-cycle events and how these are influenced by seasonal and interannual variations in climate.

Photosynthesis: The manufacture by plants of carbohydrates and oxygen for carbon dioxide and water in the presence of chlorophyll, with sunlight as the energy source. Carbon is sequestered, and oxygen and water vapor are release in the process.

Photovoltaic (PV) cell: An electronic device consisting of layers of semiconductor materials fabricated to form a junction (adjacent layers of materials with different electronic characteristics) and electrical contacts and being capable of converting incident light directly into electricity (direct current).

Photovoltaic (PV) module: An integrated assembly of interconnected photovoltaic cells designed to deliver a selected level of working voltage and current at its output terminals, packaged for protection against environmental degradation, and suited for incorporation in photovoltaic power systems.

Planetary albedo: The fraction of incident solar radiation that is reflected by the Earth–atmosphere system and returned to space, mostly by backscatter from clouds in the atmosphere.

Plate tectonics: A theory of global-scale dynamics involving the movement of many rigid plates of the Earth's crust. Tectonic activity is evident along the margins of the plates where buckling, grinding, faulting, and vulcanism occur as the plates are propelled by the forces of deep-seated mantle convection current. Geothermal resources are often associated with tectonic activity, as it allows groundwater to come in contact with deep subsurface heat sources.

Point absorber: A floating structure that absorbs energy in all direction by virtue of its movements at or near the water surface. It may be designed so as to resonate (i.e., move with larger amplitudes than the waves themselves). This feature is useful for maximizing the amount of power that is available for capture. The power take-off system may take a number of forms, depending on the configuration of displaces and reactors.

Point source: A source of pollution that involves discharge of waste from an identifiable point, such as a drainage pipe, smokestack or water-treatment plant.

Poletimber trees: Live trees that are at least 5.0 inches d.b.h. but smaller than sawtimber trees.

Polycrystalline diamond compact (PDC) drilling bit: A drilling bit that uses polycrystalline diamond compact inserts on the drill bit to drill by means of rotational shear of the rock face.

Pondage: The amount of water stored behind a hydroelectric dam of relatively small storage capacity; the dam is usually used for daily or weekly control of the flow of the river.

Population: An interbreeding group of plants or animals; the entire group of organisms of one species.

Porosity: The ratio of the aggregate volume of pore spaces in rock or soil to its total volume, usually stated as a percent.

Power factor: The ratio of real power (kilowatt) to apparent power kilovolt-ampere for any given load and time.

Powerhouse: A structure at a hydroelectric plant site that contains the turbine and generator.

Prescribed fire: The application of fire to wildland fuels, either by natural or intentional ignition, to achieve identified land use objectives.

Primary wood-using mill: A mill that converts roundwood products into other wood products. Common examples are sawmills that convert sawlogs into lumber and pulp mills that convert pulpwood roundwood into wood pulp.

Process heating: The direct process end use in which energy is used to raise the temperature of substances involved in the manufacturing process.

Program tree: A tree planted within a site area as a result of a shade tree program.

Propane (C_3H_8): A straight-chain saturated (paraffinic) hydrocarbon extracted from natural gas or refinery gas streams which is gaseous at standard temperature and pressure.

Proppant: Sized particles mixed with fracturing fluid to hold fractures open after a hydraulic stimulation.

Propylene (C_3H_6): An olefinic hydrocarbon recovered from refinery or petrochemical processes which is gaseous at standard temperature and pressure. Propylene is an important petrochemical feedstock.

Public land: Land owned by the local, state, or federal government.

Public Utility Regulatory Policies Act of 1978 (PURPA): Contains measures designed to encourage the conservation of energy, more efficient use of resources, and equitable rates. Principal among these were suggested retail rate reforms and new incentives for production of electricity by cogenerators and uses of renewable resources.

Pulpwood: Roundwood, whole tree chips, or wood residues that are used for the production of wood pulp.

Pumped-storage hydroelectric plant: A plant that usually generates electric energy during peak load periods by using water previously pumped into an elevated storage reservoir during off-peak periods when excess generating capacity is available to do so. When additional generating capacity is needed, the water can be released from the reservoir through a conduit to turbine generators located in a power plant at a lower level.

Pyrolysis: The thermal decomposition of biomass at high temperatures (greater than 400°F, or 200°C) in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, carbon monoxide, and carbon dioxide), with the proportions determined by operating temperature, pressure, oxygen content, and other conditions.

Q

Quadrillion Btu (quad): Equivalent to 10^{15} Btu.

Qualifying facility (QF): A cogeneration or small power production facility that meets certain ownership, operating, and efficiency criteria established by the Federal Energy Regulatory Commission (FERC) pursuant to the Public Utility Regulatory Policies Act of 1978 (PURPA).

R

Radiant energy: Energy that transmits away from its source in all directions.

Rankine cycle: The thermodynamic cycle that is an ideal standard for comparing the performance of heat engines, steam power plants, steam turbines, and heat pump systems that use a condensate vapor as the working fluid; efficiency is measured as work done divided by sensible heat supplied.

Ratoon crop: A crop cultivated from the shoots of a perennial plant.

Rayleigh frequency distribution: A mathematical representation of the frequency or ratio that specific wind speeds occur within a specified time interval.

Reactance: A phenomenon associated with AC power characterized by the existence of a time difference between volt and current variations.

Reactor: The body that provides the reaction to the displacer. It could be a body fixed to the seabed, or the seabed itself. It could also be another structure or mass that is not fixed but moves in such a way that reaction forces are created (e.g., by moving by a different amount or at different times). A degree of control over the forces acting on each body and/or acting between the bodies (particularly stiffness and damping characteristics) is often required to optimize the amount of energy captured. In some designs, the reactor is actually inside the displacer, whereas in others it is an external body.

Reclamation: Process of restoring surface environment to acceptable pre-existing conditions. Includes surface contouring, equipment removal, well plugging, revegetation, etc.

Recovery factor: Fraction of total resources that can be extracted for productive uses.

Recycling: The process of converting materials that are no longer useful as designed or intended into a new product.

Reflectivity: The ratio of the energy carried by a wave after reflection from a surface to its energy before reflection.

Refuge lands: Lands in which the National Forest Service holds full interest in fee title, such as an easement.

Renewable energy: Energy that is produced using resources that regenerate quickly or are inexhaustible. Wind energy is considered inexhaustible, because although it may blow intermittently it will never stop.

Renewable energy resources: Energy resources that are naturally replenishing but flow limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include biomass, hydropower, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

Renewable Portfolio Standard (RPS): A mandate requiring that renewable energy provide a certain percentage of total energy generation or consumption.

Reservoir: A natural underground container of liquids, such as water or steam (or, in the petroleum context, oil or gas).

Residues: Bark and woody materials that are generated in primary wood-using mills when roundwood products are converted to other products. Examples are slabs, edgings, trimmings, sawdust, shavings, veneer cores and clippings, and pulp screenings. Includes bark residues and wood residues (both coarse and fine materials) but excludes logging residues.

Resistivity survey: The measurement of the ability of a material to resist or inhibit the flow of an electrical current, measured in ohm-meters. Resistivity is measured by the voltage between two electrodes while an electrical current is generated between two other electrodes. Resistivity surveys can be used to delineate the boundaries of geothermal fields.

Resource base: All of a given material in the Earth's crust, whether its existence is known or unknown, and regardless of cost considerations.

Ribbon silicon: Single-crystal silicon derived by means of fabricating processes that produce sheets or ribbons of single-crystal silicon. These processes include edge-defined film-fed growth, dendritic web growth, and ribbon-to-ribbon growth.

Riparian: Refers to the interface between freshwater habitats and the terrestrial landscape.

River in-stream energy systems: These systems tend to be smaller than their tidal counterparts; however, many possess similar designs. Unlike tidal facilities, river systems produce electricity only from flows in one direction.

Roller cone bit: Drill bit that drills by crushing the rock with studded rotating cones attached to the bit.

Rotten tree: A live tree of commercial species that does not contain a saw log now or prospectively primarily because of rot (that is, when rot accounts for more than 50% of the total cull volume).

Rough tree: (1) A live tree of commercial species that does not contain a saw log now or prospectively primarily because of roughness (that is, when sound cull, due to such factors as poor form, splits, or cracks, accounts for more than 50% of the total cull volume). (2) A live tree of noncommercial species.

Roundwood: Wood cut specifically for use as a fuel.

Roundwood products: Logs and other round timber generated from harvesting trees for industrial or consumer use.

Run-of-river hydroelectric plant: A low-head plant using the flow of a stream as it occurs and having little or no reservoir capacity for storage.

Runoff: Water from rain, melted snow, or agricultural or landscape irrigation that flows over a land surface into a water body.

S

Salinity: A measure of the quantity or concentration of dissolved salts in water.

Salvable dead tree: A downed or standing dead tree that is considered currently or potentially merchantable by regional standards.

Saplings: Live trees 1.0 inch through 4.9 inches d.b.h.

Secondary wood processing mills: Mills that use primary wood products in the manufacture of finished wood products, such as cabinets, moldings, and furniture.

Seismic: Pertaining to, of the nature of, or caused by an earthquake or earth vibration, natural or man-made.

Seismicity: Refers to the phenomenon of earth movement. Also, the frequency, distribution, and intensity of earthquakes.

Seismometer: Electrical device that is used on the surface and within wellbores to measure the magnitude and direction of seismic events.

Self-potential: In geothermal systems, a measure of currents induced in the subsurface because of the flow of fluids.

Septic tank: A tank in which the solid matter of continuously flowing sewage is disintegrated by bacteria.

Sequestration: Annual net rate at which a tree removes carbon dioxide from the atmosphere through the processes of photosynthesis and respiration (kgCO_2/tree/year).

Shade effects: Impact on residential space heating and cooling (kgCO_2/tree/year) from trees located within approximately 15 m (50 ft) of a building (near trees) so as to directly shade the building.

Shale gas: Natural gas produced from wells that are open to shale formations. Shale is a fine-grained, sedimentary rock composed of mud from flakes of clay minerals and tiny fragments (silt-sized particles) of other materials. The shale acts as both source and reservoir for the natural gas.

Short ton: A measure of weight equal to 2000 pounds or 0.9072 metric tons.

Silicon: A semiconductor material made from silica, purified for photovoltaic applications.

Silviculture: Tending and regenerating forest stands to realize sought-after benefits and to sustain them over time.

Single-crystal silicon (Czochralski): An extremely pure form of crystalline silicon produced by the Czochralski method of dipping a single crystal seed into a pool of molten silicon under high vacuum conditions and slowly withdrawing a solidifying single crystal boule rod of silicon. The boule is sawed into thin wafers and fabricated into single-crystal photovoltaic cells.

Skylight: A window located on the roof of a structure to provide interior building spaces with natural daylight, warmth, and ventilation.

Slim hole: Drill holes that have a nominal inside diameter of less than about 6 inches.

Slotted liner: Liner that has slots or holes in it to let fluid pass between the wellbore and surrounding rock.

Sludge: A dense, slushy, liquid-to-semifluid product that accumulates as an end result of an industrial or technological process designed to purify a substance. Industrial sludges are produced from the processing of energy-related raw materials, chemical products, water, mined ores, sewerage, and other natural and man-made products. Sludges can also form from natural processes, such as the runoff produced by rain fall, and accumulate on the bottom of bogs, streams, lakes, and tidelands.

Smart tracer: Tracer that is useful in determining the flow path between a well injecting fluid into the subsurface and a well producing fluid from an adjacent well and can also be used to the determine temperature along the flow path, surface area contacted by the tracer, volume of rock that the tracer interacts with, and relative velocities of separate phases (gas, oil, and water in petroleum fields; steam and liquid water in geothermal systems).

Solar energy: The radiant energy of the sun which can be converted into other forms of energy, such as heat or electricity.

Solar heat gain coefficient (SHGC): Measures how well a product blocks heat caused by sunlight. The SHGC is expressed as a number between 0 and 1. The lower the SHGC, the less solar heat the product transmits.

Solar thermal collector: Device that receives solar radiation and converts it into thermal energy. Normally, a solar thermal collector includes a frame, glazing, and an absorber, together with the appropriate insulation. The heat collected by the solar thermal collector may be used immediately or stored for later use.

Solar thermal collector, special: An evacuated tube collector or a concentrating (focusing) collector. Special collectors operate in the temperature range from just above ambient temperature (low concentration for pool heating) to several hundred degrees Fahrenheit (high concentration for air-conditioning and specialized industrial processes).

Species: The basic category of biological classification intended to designate a single kind of animal or plant. Any variation among the individuals may be regarded as not affecting the essential sameness that distinguishes them from all other organisms.

Spent liquor: The liquid residue left after an industrial process; it can be a component of waste materials used as fuel.

Spent sulfite liquor: End-product of pulp and paper manufacturing processes that contains lignins and has a high moisture content; it is often reused in recovery boilers and is similar to black liquor.

Spinner survey: The use of a device with a small propeller that spins when fluid passes in order to measure fluid flow in a wellbore. The device is passed up and down the well, continuously measuring flow to establish where and how much fluid enters or leaves the wellbore at various depths.

Spinning reserve: A reserve of generation capacity, where generators are kept online, but at idle, in anticipation of an unexpected increase in demand or decrease in supply.

Start-up speed: The windspeed at which a rotor begins to rotate.

Stimulation: A treatment performed to restore or enhance the productivity of a well. Stimulation treatments fall into two main groups: hydraulic fracturing treatments and matrix treatments.

Stormwater: A term used to describe water runoff generated when precipitation from rain and snowmelt events flows over land or imperious surfaces.

Stress: The forces acting on rock. In the subsurface, the greatest force or stress is generally vertical caused by the weight of overlying rock.

Structural discontinuity: A discontinuity of the rock fabric that can be a fracture, fault, intrusion, or differing adjacent rock type.

Submersible sump: Pump with both the pumping mechanism and a driving electric motor suspended together at depth in the well.

Subsidence: The sinking of an area of the Earth's crust due to fluid withdrawal and pressure decline.

Succession: The natural, sequential change in species composition of a community in a given area.

Sulfur dioxide (SO_2): A toxic, irritating, colorless gas soluble in water, alcohol, and ether. Used as a chemical intermediate, in paper pulping and ore refining, and as a solvent.

Surface water: All waters whose surface is naturally exposed to the atmosphere, or wells or other collectors directly influenced by surface water.

Swell direction (SwD): The direction that the swells are coming from. Swells are waves not produced by the local wind and come in at a higher period (longer wavelength) than waves produced by the local wind. Direction is given on a 16-point compass scale.

Swell height (SwH): The estimated average height of the highest one-third of the swells. It is estimated by determining how the wave energy is distributed among various periods (frequencies) and if a separate swell energy peak exists, and then picking a frequency to separate swell and wind-waves. The swell height is calculated from the wave energies below the separation frequency.

Swell period (SwP): The peak period in seconds of the swells. If more than one swell is present, this is the period of the swell containing the maximum energy.

Syngas: A synthesis gas produced through gasification of biomass. Syngas is similar to natural gas and can be cleaned and conditioned to form a feedstock for production of methanol.

T

Tall oil: The oily mixture of rosin acids, fatty acids, and other materials obtained by acid treatment of the alkaline liquors from the digesting (pulping) of pine wood.

Terminator: A floating structure that moves at or near the water surface and absorbs energy in only a single direction. The device extends in the direction normal to the predominant wave direction, so that as waves arrive the device restrains them. Again, resonance may be employed and the power take-off system may take a variety of forms.

Terrestrial sequestration: Basic sequestration of carbon in above- and below-ground biomass and soils.

Thermal drawdown: Decline in formation temperature due to geothermal production.

Thermal gradient: The rate of increase in temperature as a function of depth into the Earth's crust.

Thermosiphon system: A solar collector system for water heating in which circulation of the collection fluid through a storage loop is provided solely by the temperature and density difference between the hot and cold fluids.

Thin-film silicon: A technology in which amorphous or polycrystalline material is used to make photovoltaic (PV) cells.

Tiltmeter: Device able to measure extremely small changes in its rotation from horizontal. The tilt measured by an array of tiltmeters emplaced over a stimulation allows delineation of inflation and fracturing caused by the stimulation.

Tipping fee: A fee for disposal of waste.

Total dissolved solids (TDS): The amount of solid materials in water.

Tower: Steel structures that support a turbine assembly. Higher towers allow for longer blades and the capture of faster moving air at higher altitudes.

Tracer: A chemical injected into the flow stream of a production or injection well to determine fluid path and velocity.

Transformer: Used to step up or step down AC voltage or AC current.

Transmission line: Structures and conductors that carry bulk supplies of electrical energy from power-generating units.

Transmission system, electric: An interconnected group of electric transmission lines and associated equipment for moving or transferring electric energy in bulk between points of supply and points at which it is transformed for delivery over the distribution system lines to consumers, or is delivered to other electric systems.

Transportation sector: An energy-consuming sector that consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. Included are automobiles; trucks; buses; motorcycles; trains, subways, and other rail vehicles; aircraft; and ships, barges, and other waterborne vehicles. Vehicles whose primary purpose is not transportation (e.g., construction cranes and bulldozers, farming vehicles, warehouse tractors and forklifts) are classified in the sector of their primary use.

Turbidity: Refers to the extent to which light penetrates a body of water. Turbid waters are those that do not generally support net growth of photosynthetic organisms.

Turbine: A machine for generating rotary mechanical power from the energy of a stream of fluid (such as water, steam, or hot gas). Turbines convert the kinetic energy of fluids to mechanical energy through the principles of impulse and reaction, or a mixture of the two.

U

U-factor: A measure the rate of heat loss or how well a product prevents heat from escaping. It includes the thermal properties of the frame as well as the glazing. The insulating value is indicated by the R-value, which is the inverse of the U-factor. U-factor ratings generally fall between 0.20 and 1.20. The lower the U-factor, the greater a product's resistance to heat flow and the better its insulating value.

Under reamer: A drilling device that can enlarge a drill hole. The device is placed about the drill bit and can be opened to drill and then closed to be brought back up through a smaller diameter hole or casing.

Upwind turbine: A turbine that faces into the wind; it requires a wind vane and yaw drive in order to maintain proper orientation in relation to the wind.

Useful heat: Heat stored above room temperature (in a solar heating system).

Useful thermal output: The thermal energy made available for use in any industrial or commercial process or used in any heating or cooling application (i.e., total thermal energy made available for processes and applications other than electrical generation).

V

Vapor dominated: A geothermal reservoir system in which subsurface pressures are controlled by vapor rather than by liquid. Sometimes referred to as a *dry-steam reservoir.*

Variable-speed wind turbine: Turbines in which the rotor speed increases and decreases with changing wind speed, producing electricity with a variable frequency.

Vernal pool: A type of seasonal wetland formed by isolated depressions in the landscape that hold water in the winter and spring and are usually dry by midsummer or fall.

Viewshed: The scenic characteristics of an area, when referred to as a resource.

Visible light transmittance: The amount of visible light that passes through the glazing material of a window, expressed as a percentage.

Voltage: The measure of electrical potential difference.

W

Watt, electric: The electrical unit of power; the rate of energy transfer equivalent to 1 ampere of electric current flowing under a pressure of 1 volt at unity power factor.

Watt-hour (Wh): The electrical energy unit of measure equal to 1 watt of power supplied to, or taken from, an electric circuit steadily for 1 hour.

Watt, thermal: A unit of power in the metric system, expressed in terms of energy per second; equal to the work done at a rate of 1 joule per second.

Well log: Includes measurements of the diameter of the well and various electrical, mass, and nuclear properties of the rock which can be correlated with physical properties of the rock. The well log is a chart of measurements relative to depth in the well.

Wind energy: Energy present in wind motion that can be converted to mechanical energy for driving pumps, mills, and electric power generators. Wind pushes against sails, vanes, or blades radiating from a central rotating shaft.

Wind power plant: A group of wind turbines interconnected to a common utility system through a system of transformers, distribution lines, and (usually) one substation. Operation, control, and maintenance functions are often centralized through a network of computer monitoring systems, supplemented by visual inspection. This is a term commonly used in the United States; in Europe, it is called a *generating station*.

Wind rose: A diagram that indicates the average percentage of time that the wind blows from different directions on a monthly or annual basis.

Wind turbine or windmill: A device for harnessing the kinetic energy of the wind and using it to do work, or generate electricity.

Wind vane: Wind direction measurement device, used to send data to the yaw drive.

Wind-wave direction (WWD): The direction that the wind waves are coming from. Wind waves are produced by the local wind. If a swell is present, these waves arrive at a lower period (more frequently) than do the swells. Direction is given on a 16-point compass scale.

Wind-wave height (WWH): The average height of the highest one-third of the wind waves. It is estimated by the process mentioned under "Swell height," except that it is calculated from the energies above the separation frequency.

Wind-wave period (WWP): The peak period in seconds of the wind waves.

Windward: Into or facing the direction of the wind; opposite of leeward.

Wood energy: Wood and wood products used as fuel, including roundwood (cordwood), limb wood, wood chips, bark, sawdust, forest residues, charcoal, pulp waste, and spent pulping liquor.

Wood pellets: Sawdust compressed into uniform-diameter pellets to be burned in a heating stove.

Wood/wood waste: A category of biomass energy that includes black liquor; wood/wood waste liquids (red liquor, sludge wood, spent sulfite liquor); and wood/wood waste solids (peat, paper pellets, railroad ties, utility poles, wood/wood waste).

Y

Yaw: The rotation of a horizontal axis wind turbine around its tower or vertical axis.
Yaw drive: Motor that keeps an upwind turbine facing into the wind.

Z

Zonal isolation: Various methods to selectively partition portions of the wellbore for stimulation, testing, flow restriction, or other purpose.
Zone: An area within the interior space of a building, such as individual rooms, to be cooled, heated, or ventilated. A zone has its own thermostat to control the flow of conditioned air into the space.

Appendix 1. Conversion Factors

Conversion factors are used to change measurements or calculated values from one unit of measurement to another. In making the conversion from one unit to another, you must know two things:

1. The exact number that relates the two units
2. Whether to multiply or divide by that number

Most environmental professionals memorize some heat content conversion because of actually using the conversions, not because of attempting to memorize them (see Table A1.1).

TABLE A1.1
Heat Contents

Fuel	Units	Approximate Heat Content
Coal		
Production	Million Btu per short ton	20.136
Consumption	Million Btu per short ton	19.810
Coke plants	Million Btu per short ton	26.304
Industrial	Million Btu per short ton	23.651
Residential and commercial	Million Btu per short ton	20.698
Electric power sector	Million Btu per short ton	19.370
Imports	Million Btu per short ton	25.394
Exports	Million Btu per short ton	25.639
Coal coke	Million Btu per short ton	24.800
Crude oil		
Production	Million Btu per barrel	5.800
Imports	Million Btu per barrel	5.967
Petroleum products and other liquids		
Consumption[a]	Million Btu per barrel	5.353
Motor gasoline[a]	Million Btu per barrel	5.048
Jet fuel	Million Btu per barrel	5.670
Distillate fuel oil[a]	Million Btu per barrel	5.762
Diesel fuel[a]	Million Btu per barrel	5.759
Residual fuel oil	Million Btu per barrel	6.287
Liquefied petroleum gases[a]	Million Btu per barrel	3.577
Kerosene	Million Btu per barrel	5.670

TABLE A1.1 (continued)
Heat Contents

Fuel	Units	Approximate Heat Content
Petrochemical feedstocks[a]	Million Btu per barrel	5.114
Unfinished oils	Million Btu per barrel	6.039
Imports[a]	Million Btu per barrel	5.580
Exports[a]	Million Btu per barrel	5.619
Ethanol	Million Btu per barrel	3.580
Biodiesel	Million Btu per barrel	5.359
Natural gas plant liquids		
Production[a]	Million Btu per barrel	3.566
Natural gas[a]		
Production, dry	Btu per cubic foot	1.022
Consumption	Btu per cubic foot	1.022
End-use sectors	Btu per cubic foot	1.023
Electric power sector	Btu per cubic foot	1.021
Imports	Btu per cubic foot	1.025
Exports	Btu per cubic foot	1.009
Electricity consumption	Btu per kilowatt-hour	3412

Sources: EIA, *Annual Energy Review 2011*, DOE/EIA-0384(2011), U.S. Energy Information Administration, Washington, DC, 2012; EIA, *AEO2013 National Energy Modeling System*, run REF2013. D102312A, U.S. Energy Information Administration, Washington, DC, 2013.

[a] The conversion factor varies from year to year; the value shown is for 2011.

Appendix 2. Definitions of Terrorism-Related Terms

Abu Sayyaf: Meaning "bearer of the sword," Abu Sayyaf is the smaller of the two Islamist groups whose goal is to establish an Iranian-style Islamic state in Mindanao in the Southern Philippines. In 1991, the group split from the Maro National Liberation Front with ties to numerous Islamic fundamentalist groups. They finance their operations through kidnapping for ransom, extortion, piracy, and other criminal acts. It is also thought that they receive funding from al Qaeda. It is estimated that there are between 200 and 500 Abu Sayyaf terrorists, mostly recruited from high schools and colleges.

Acid bomb: A crude bomb made by combining muriatic acid with aluminum strips in a 2-liter soda bottle.

Aerosol: A fine mist or spray that contains minute particles.

Afghanistan: At the time of 9/11, Afghanistan was governed by the Taliban, and Osama bin Laden called it home. Amid U.S. air strikes, which began on October 7, 2001, the United States sent more than $300 million in humanitarian aid. In December 2001, Afghanistan reopened their embassy for the first time in more than 20 years.

Aflatoxin: A toxin created by bacteria that grow on stored foods, especially on rice, peanuts, and cotton seeds.

Agency: A division of government with a specific function or a non-governmental organization (e.g., private contractor, business) that offers a particular kind of assistance. Under the Incident Command System (a systematic tool used for the command, control, and coordination of emergency responses), agencies are defined as jurisdictional (having statutory responsibility for incident mitigation) or assisting and/or cooperating (providing resources and/or assistance).

Air marshal: A federal marshal whose purpose is to ride commercial flights dressed in plainclothes and armed to prevent hijackings. Israel's use of air marshals on El Al is credited as the reason Israel has had a single hijacking in 31 years. The United States started using air marshals after 9/11. Despite President Bush's urging, there are not enough air marshals to go around, so many flights do not have them.

Airborne: Carried by or through the air.

al-Gama'a al-Islamiyya (Islamic Group, IG): Islamic terrorist group that emerged spontaneously during the 1970s in Egyptian jails and later in Egyptian universities. After President Sadat released most of the Islamic prisoners from prisons in 1971, groups of militants organized themselves in groups and cells, and al-Gama'a al-Islamiyya was one of them.

al Jazeera: Satellite television station based in Qatar and broadcast throughout the world. al Jazeera has often been called the CNN of the Arab world.

al Qaeda ("the base"): al Qaeda is an international terrorist group founded in approximately 1989 and dedicated to opposing non-Islamic governments with force and violence. One of the principal goals of al Qaeda was to drive the U.S armed forces out of the Saudi Arabian peninsula and Somalia by violence. Members of al Qaeda are currently wanted for several terrorist attacks, including those on the U.S. embassy in Kenya and Tanzania, as well as the first and second World Trade Center bombings and the attack on the Pentagon.

al Tahwid: A Palestinian group based in London that professes a desire to destroy both Israel and the Jewish people throughout Europe. Eleven al Tahwid members were arrested in Germany allegedly as they were about to initiate an attack on that country.

Alpha radiation: The least penetrating type of nuclear radiation; not considered dangerous unless particles enter the body.

American Airlines Flight 11: The Boeing 767 carrying 81 passengers, 9 flight attendants, and 2 pilots which was highjacked and crashed into the North Tower of the World Trade Center at 8:45 a.m. Eastern time on September 11, 2001. Flight 11 was en route to Los Angeles from Boston.

American Airlines Flight 77: The Boeing 757 carrying 58 passengers, 4 flight attendants, and 2 pilots, which was highjacked and crashed into the Pentagon at 9:40 a.m. Eastern time on September 11, 2001. Flight 77 was en route to Los Angeles from Dulles International Airport in Virginia.

Ammonium nitrate–fuel oil (ANFO): A powerful explosive made by mixing fertilizer and fuel oil. This is the type of bomb that was used in the first World Trade Center attack as well as in the Oklahoma City bombing.

Analyte: The name assigned to a substance or feature that is subject to an analytical procedure designed to describe it in terms of its molecular composition, taxonomic nomenclature, or other characteristic.

Anthrax: An often fatal infectious disease contracted from animals. Anthrax spores have a long survival period, and the incubation period is short. Disability is severe, making anthrax a bioweapon of choice by several nations.

Antidote: A remedy to counteract the effects of poison.

Antigen: Substance that stimulates an immune response by the body. The immune system recognizes antigens as foreign and produces antibodies to fight them.

Antitoxin: An antibody that neutralizes a biological toxin.

Armed Islamic Group (GIA): An Algerian Islamic extremist group which aims to overthrow the secular regime in Algeria and replace it with an Islamic state. The GIA began its violent activities in early 1992 after Algiers voided the victory of the largest Islamic party, Islamic Salvation Front (FIS), in the December 1991 elections.

Asymmetric threat: The use of crude or low-tech methods to attack a superior or more high-tech enemy.

Axis of Evil: Iran, Iraq, and North Korea, which were mentioned by President George W. Bush during his State of the Union speech in 2002 as nations that were a threat to U.S. security due to harboring terrorism.

Baath Party: The official political party in Iraq until the U.S. "de-baathified" Iraq in May 2003, after a war that lasted a little over a month. Saddam Hussein, the former ruler of the Baath party, was targeted by American-led coalition forces and fled. Baath party members have been officially banned from participating in any new government in Iraq.

Beltway Sniper: For nearly a month in October 2002, Washington, DC; Maryland; and Virginia were the hunting grounds for 41-year-old John Allen Muhammad and 17-year-old Lee Boyd Malvo. Dubbed the "Beltway Sniper" by the media, they shot people at seemingly random places such as schools, restaurants, and gas stations.

Bioaccumulative: Substances that concentrate in living organisms rather than being eliminated through natural processes; occurs in those who breathe contaminated air, drink or live in contaminated water, or eat contaminated food.

Biochemical warfare: Collective term for the use of both chemical warfare and biological warfare weapons.

Biochemterroism: Terrorism using biological or chemical agents as weapons.

Biological ammunition: Ammunition designed specifically to release a biological agent used as the warhead for biological weapons. Biological ammunition may take many forms, such as a missile warhead or bomb.

Biological attacks: The deliberate release of germs or other biological substances that cause illness.

Biosafety Level 1: Considered suitable for work involving well-characterized biological agents not known to consistently cause disease in healthy adult humans, and of minimal potential hazard to lab personnel and the environment. Work is generally conducted on open bench tops using standard microbiological practices.

Biosafety Level 2: Considered suitable for work involving biological agents of moderate potential hazard to personnel and the environment. Lab personnel should have specific training in handling pathogenic agents and be directed by competent scientists. Access to the lab should be limited when work is being conducted, extreme precautions should be taken with contaminated sharp items, and certain procedures should be conducted in biological safety cabinets or other physical containment equipment if there is a risk of creating infectious aerosols or splashes.

Biosafety Level 3: Considered suitable for work done with indigenous or exotic biological agents that may cause serious or potentially lethal disease as a result of exposure by inhalation. Lab personnel must have specific training in handling pathogenic and potentially lethal agents and be supervised by competent scientists who are experienced in working with these agents. All procedures involving the manipulation of infectious material are conducted within biological safety cabinets or other physical containment devices, or by personnel wearing appropriate personal protective clothing and equipment. The lab must have special engineering and design features.

Biosafety Level 4: Considered suitable for work with the most infectious biological agents. Access to the two Biosafety Level 4 labs in the United States is highly restricted.

Bioterrorism: The use of biological agents in a terrorist operation. Biological toxins would include anthrax, ricin, botulism, the plague, smallpox, and tularemia.

Bioterrorism Act: The Public Health Security and Bioterrorism Preparedness and Response Act of 2002.

Biowarfare: The use of biological agents to cause harm to targeted people either directly, by bringing the people into contact with the agents, or indirectly, by infecting other animals and plants which would in turn cause harm to the people.

Blister agents: Agents that cause pain and incapacitation instead of death and might be used to injure many people at once, thereby overloading medical facilities and causing fear in the population. Mustard gas is the best known blister agent.

Blood agents: Agents based on cyanide compounds; more likely to be used for assassination than for terrorism.

Botulism: An illness caused by the botulinum toxin, which is exceedingly lethal and quite simple to produce. It takes just a small amount of the toxin to destroy the central nervous system. Botulism may be contracted by the ingestion of contaminated food or through breaks or cuts in the skin. Food supply contamination or aerosol dissemination of the botulinum toxin are the two ways most likely to be used by terrorists.

Bush Doctrine: The policy that holds responsible nations that harbor or support terrorist organizations and says that such countries are considered hostile to the United States. From President Bush's speech: "A country that harbors terrorists will either deliver the terrorist or share in their fate. … People have to choose sides. They are either with the terrorists, or they're with us."

BWC: Officially known as the Convention on the Prohibition of Development, Production, and Stockpiling of Bacteriological (Biological) and Toxin Weapons and Destruction, the BWC works toward general and complete disarmament, including the prohibition and elimination of all types of weapons of mass destruction.

Camp X-Ray: Guantanamo Bay, Cuba, which houses al Qaeda and Taliban prisoners.

Carrier: A person or animal that is potentially a source of infection by carrying on infectious agent without visible symptoms of the disease.

Cascading event: The occurrence of one event that causes another event.

Causative agent: The pathogen, chemical, or other substance that is the cause of disease or death in an individual.

Cell: The smallest unit within a guerrilla or terrorist group. A cell generally consists of two to five people dedicated to a terrorist cause. The formation of cells is born of the concept that an apparent "leaderless resistance" makes it difficult for counterterrorists to penetrate.

Chain of custody: Tracking and documenting the physical control of evidence.

Chemical agent: A toxic substance intended to be used for operations to debilitate, immobilize, or kill military or civilian personnel.

Chemical ammunition: A munition, commonly a missile, bomb, rocket, or artillery shell, designed to deliver chemical agents.

Chemical attack: The intentional release of toxic liquid, gas, or solid in order to poison the environment or people.

Chemical warfare: The use of toxic chemicals as weapons, not including herbicides used to defoliate battlegrounds or riot control agents such as gas or mace.

Chemical weapons: Weapons that produce effects on living targets via toxic chemical properties. Examples would be sarin, VX nerve gas, or mustard gas.

Chemterrorism: The use of chemical agents in a terrorist operation. Well-known chemical agents include sarin and VX nerve gas.

Choking agent: Compounds that cause injury primarily in the respiratory tract (i.e., nose, throat, and lungs). In extreme cases, membranes swell up, lungs become filled with liquid, and death results from a lack of oxygen.

Cipro® (ciprofloxacin): A Bayer® antibiotic that combats inhalation anthrax.

Confirmed: During a threat evaluation process, a water contamination incident is confirmed if there is definitive evidence that the water has been contaminated.

Counterterrorism: Measures to prevent preempt, or retaliate against terrorist attacks.

Credible: During a threat evaluation process, a water contamination threat is characterized as credible if information collected during the threat evaluation process corroborates information from the threat warning.

Cutaneous: Related to or entering through the skin.

Cutaneous anthrax: Anthrax that is contracted via broken skin. The infection spreads through the bloodstream causing cyanosis, shock, sweating, and finally death.

Cyanide agent: Used by Iraq in the Iran war against the Kurds in the 1980s and by the Nazis in the gas chambers of concentration camps, cyanide agents are a colorless liquid that is inhaled in its gaseous form. Liquid cyanide and cyanide salts are absorbed by the skin. Symptoms are headache, palpitations, dizziness, and respiratory problems followed later by vomiting, convulsions, respiratory failure, unconsciousness, and eventually by death.

Cyberterrorism: Attacks on computer networks or systems, generally by hackers working with or for terrorist groups. Some forms of cyberterrorism include denial-of-service attacks, inserting viruses, or stealing data.

Department of Homeland Security: An agency organized after 9/11, with former Pennsylvania Governor Tom Ridge originally heading it up. The Office of Homeland Security is at the top of approximately 40 federal agencies charged with protecting the U.S. against terrorism.

Dirty bomb: A makeshift nuclear device created from radioactive nuclear waste material. Although it is not a nuclear blast, the explosion of a dirty bomb causes localized radioactive contamination as the nuclear waste material is carried into the atmosphere where it is dispersed by the wind.

Ebola: Ebola virus disease (EVD) is a severe, often fatal disease in nonhuman primates such as monkeys, chimpanzees, and gorillas, as well as in humans. Ebola has appeared sporadically since 1976 when it was first recognized.

eBomb: Electromagnetic bomb that produces a brief pulse of energy which affects electronic circuitry. At low levels, the pulse temporarily disables electronics systems, including computers, radios, and transportation systems. High levels completely destroy circuitry, causing mass disruption of infrastructure while sparing life and property.

Ecotage: Used to describe illegal acts of vandalism and violence committed in the name of environmental protection.

Ecoterrorism: A neologism for terrorism that includes sabotage intended to hinder activities that are considered damaging to the environment.

Euroterrorism: Associated with left-wing terrorism of the 1960s, 1970s, and 1980s involving the Red Brigade, Red Army Faction, and November 17th Group, among other groups targeting American interests in Europe and NATO. Other groups include Orange Volunteers, Red Hand Defenders, Continuity IRA, Loyalist Volunteer Force, Ulster Defense Association, and First of October Anti-Fascist Resistance Group.

Fallout: The descent to the Earth's surface of particles contaminated with radioactive material from a radioactive cloud. The term can also be applied to the contaminated particulate matter itself.

Fatah: Meaning "conquest by means of jihad," Fatah is a political organization created in the 1960s and led by Yasser Arafat. With both a military and intelligence wing, it has carried out terrorist attacks on Israel since 1965. It joined the Palestine Liberation Organization (PLO) in 1968. Since 9/11, Fatah has been blamed for attempting to smuggle 50 tons of weapons into Israel.

Fatwa: A legal ruling regarding Islamic law.

Fedayeen Saddam: Iraq's paramilitary organization, which is said to be equivalent to the Nazi SS, The militia is loyal to Saddam Hussein and is responsible for using brutality on civilians who are not loyal to the policies of Saddam. They do not dress in uniform.

Filtrate: In ultrafiltration, the water that passes through the membrane and contains particles smaller than the molecular weight cutoff of the membrane.

Frustration–aggression hypothesis: A hypothesis that every frustration leads to some form of aggression and every aggressive act results from some prior frustration. According to Ted Robert Gurr, an authority on political conflict and instability, "The necessary precondition for violent civil conflict is relative deprivation, defined as actors' perception of discrepancy between their value expectations and their environment's apparent value capabilities. This deprivation may be individual or collective."

Fundamentalism: Conservative religious authoritarianism. Fundamentalism is not specific to Islam; it exists in all faiths. Characteristics include literal interpretation of scriptures and a strict adherence to traditional doctrines and practices.

Geneva Protocol 1925: The 1925 Geneva Protocol for the Prohibition of the Use in War of Asphyxiating, Poisonous or Other Gases and Bacteriological Methods of Warfare, the first treaty to prohibit the use of biological weapons.

Germ warfare: The use of biological agents to harm targeted people either directly, by bringing the people into contact with the agents, or indirectly, by infecting other animals and plants which would in turn cause harm to the people.

Glanders: An infectious bacterial disease known to cause inflammation in horses, donkeys, mules, goats, dogs, and cats. Human infection has not been seen since 1945, but because so few organisms are required to cause disease, it is considered a potential agent for biological warfare.

Grab sample: A single sample that is collected at a particular time and place and represents the composition of the water, air, or soil only at that time and location.

Ground zero: From 1946 until 9/11, ground zero was the point directly above, below, or at which a nuclear explosion occurs or the center or origin of rapid, intense, or violent activity or change. After 9/11, the term, when used with initial capital letters, refers to the ground at the epicenter of the World Trade Center attacks.

Guerrilla warfare: The term was invented to describe the tactics Spain used to resist Napoleon, although the tactic itself has been around much longer. Literally, it means "little war." Guerilla warfare features cells and utilizes no front line. The oldest form of asymmetric warfare, guerilla warfare is based on sabotage and ambush with the objective of destabilizing the government through lengthy and low-intensity confrontation.

Hamas: A radical Islamic organization that operates primarily in the West Bank and Gaza Strip and whose goal is to establish an Islamic Palestinian state in place of Israel. On the one hand, Hamas operates overtly in their capacity as social services deliverers, but its activists have also conducted many attacks, including suicide bombings, against Israeli civilians and military targets.

Hazard: An inherent physical or chemical characteristic that has the potential for causing harm to people, the environment, or property.

Hazard assessment: The process of evaluating available information about the site to identify potential hazards that might pose a risk to the site characterization team. The hazard assessment results in assigning one of four levels to risk: lower hazard, radiological hazard, high chemical hazard, or high biological hazard.

Hemorrhagic fevers: In general, the term *viral hemorrhagic fever* is used to describe a severe multisystem syndrome wherein the overall vascular system is damaged and the body becomes unable to regulate itself. These symptoms are often accompanied by hemorrhage; however, the bleeding itself is not usually life threatening. Some types of hemorrhagic fever viruses can cause relatively mild illnesses.

Hizbollah (Hezbollah): Meaning "the party of God," Hizbollah is one of many terrorist organizations seeking the destruction of Israel and the United States. They have taken credit for numerous bombings against civilians and have declared that civilian targets are warranted. Hizbollah claims it sees no legitimacy for the existence of Israel, and that their conflict is one of legitimacy that is based on religious ideals.

Homicide bombings: A term the White House coined to replace "suicide bombings."

Incident: A confirmed occurrence that requires response actions to prevent or minimize loss of life or damage to property and/or natural resources. A drinking water contamination incident occurs when the presence of a harmful contaminant has been confirmed.

Inhalation anthrax: A form of anthrax that is contracted by inhaling anthrax spores. This results in pneumonia, sometimes meningitis, and finally death.

Intifada (intifadah): From the Arabic for "shaking off," the two intifadas (uprisings) that have occurred are similar in that both were originally characterized by civil disobedience by the Palestinians which escalated into the use of terror. In 1987, following the killing of several Arabs in the Gaza Strip, the first intifada began and continued until 1993. The second intifada began in September 2000, following Ariel Sharon's visit to the Temple Mount.

Islam: Meaning "submit," Islam is the faith practiced by followers of Muhammad. Islam claims more than a billion believers worldwide.

Jihad: Meaning "struggle," jihad is not easily defined, and doing so is a subject of vast debate. There are two definitions generally accepted. The first is a struggle against oppression, whether political or religious. The second is the struggle within oneself, or a spiritual struggle.

Kneecapping: A malicious wounding by a firearm to damage the knee joint; it was a common punishment used by Northern Ireland's Irish Republican Army (IRA) on those who collaborated with the British.

Koran (Qu'ran): The holy book of Islam, considered by Muslims to contain the revelations of God to Mohammed.

Laboratory Response Network (LRN): A network of labs developed by the Centers for Disease Control and Prevention (CDC), Association of Public Health Laboratories (APHL), and Federal Bureau of Investigation (FBI) for the express purpose of dealing with bioterrorism threats, including pathogens and some biotoxins.

Lassa fever: An acute, often fatal, viral disease characterized by high fever, ulcers of the mucous membranes, headaches, and disturbances of the gastrointestinal system.

LD_{50}: The dose of a substance that kills 50% of those infected.

Links: The means (road, rail, barge, or pipeline) by which a chemical is transported from one node to another.

Mindset: (1) A fixed mental attitude or disposition that predetermines a person's response to an interpretation of situations; or (2) an inclination or a habit (*American Heritage Dictionary*). Alternatively, (1) a mental attitude or inclination, or (2) a fixed state of mind (*Merriam Webster's Collegiate Dictionary*, 10th ed.). The term dates from 1926 but apparently is not included in dictionaries of psychology.

Molotov cocktail: A crude incendiary bomb made of a bottle filled with flammable liquid and fitted with a rag wick.

Monkeypox: The Russian bioweapon program worked with this virus, which is in the same family as smallpox. In June 2003, a spate of human monkeypox cases was reported in the U.S. Midwest. This was the first time that monkeypox was seen in North America, and it was the first time that monkeypox was transferred from animal to human. There was some speculation that it was a bioattack.

Mullah: A Muslim, usually holding an official post, who is trained in traditional religious doctrine and law and doctrine.

Muslim (Moslem): Followers of the teachings of Mohammed, or Islam.

Mustard gas: Blistering agents that cause severe damage to the eyes, internal organs, and respiratory system. Produced for the first time in 1822, mustard gas was not used until World War 1. Victims suffered the effects of mustard gas 30 to 40 years after exposure.

Narcoterrorism: The view of many counterterrorist experts that there exists an alliance between drug traffickers and political terrorists.

National Pharmaceutical Stockpile: A stock of vaccines and antidotes stored at the CDC in Atlanta to be used against biological warfare.

Nerve agent: The Nazis used the first nerve agents: insecticides developed into chemical weapons. Some of the better known nerve agents include VX, sarin, soman, and tabun. These agents are used because only a small quantity is necessary to inflict substantial damage. Nerve agents can be inhaled or can be absorbed through intact skin.

Nodes: A facility at which a chemical is produced, store, or consumed.

Nuclear blast: An explosion of any nuclear material that is accompanied by a pressure wave, intense light and heat, and widespread radioactive fallout which can contaminate the air, water, and ground surface for miles around the blast.

Opportunity contaminant: A contaminant that might be readily available in a particular area, even though it may not be highly toxic or infectious or easily dispersed and stable in treated drinking water.

Osama (Usama) bin Laden: A native of Saudi Arabia, bin Laden was born the 17th of 24 sons of Saudi Arabian builder Mohammed bin Oud bin Laden, a Yemeni immigrant. Early in his career, he helped the mujahedeen fight the Soviet Union by recruiting Arabs and building facilities. He hated the United States, apparently because he viewed the United States as having desecrated holy ground in Saudi Arabia with their presence during the first Gulf War. Expelled from Saudi Arabia in 1991 and from Sudan in 1996, he operated terrorist training camps in Afghanistan. His global network al Qaeda is credited with the attacks on the United States on September 11, 2001, the attack on the USS *Cole* in 2000, and a number of other terrorist attacks. bin Laden was killed in Pakistan on May 2, 2011, by a U.S. special forces military unit.

Pathogen: Any agent that can cause disease.

Pathways: The sequence of nodes and links by which a chemical is produced, transported, and transformed from its initial source to its ultimate consumer.

Plague: The pneumonic plague, which is more likely to be used in connection with terrorism, is naturally carried by rodents and fleas but can be aerosolized and sprayed from crop dusters. A 1970 World Health Organization assessment asserted that, in a worst-case scenario, a dissemination of 50 kg in an aerosol over a city of 5 million could result in 150,000 cases of pneumonic plague, 80,000 to 100,000 of which would require hospitalization and 36,000 of which would be expected to die.

Political terrorism: Terrorist acts directed at governments and their agents and motivated by political goals (i.e., national liberation).

Possible: In the context of the threat evaluation process, a water contamination threat is characterized as possible if the circumstances of the threat warning appear to have provided an opportunity for contamination.

Potassium iodide: A U.S. Food and Drug Administration (FDA)-approved nonprescription drug for use as a blocking agent to prevent the thyroid gland from absorbing radioactive iodine.

Presumptive results: Results of chemical and/or biological field testing that need to be confirmed by further lab analysis. Typically used in reference to the analysis of pathogens.

Psychopath: A person suffering from chronic mental disorder with abnormal or violent social behavior; an unstable and aggressive person.

Psychopathology: The study of psychological and behavioral dysfunction occurring in mental disorder or in social disorganization.

Psychopathy: A mental disorder, especially an extreme mental disorder marked usually by egocentric and antisocial activity.

Psychotic: Of, relating to, or affected with psychosis, which is a fundamental mental derangement (e.g., schizophrenia) characterized by defective or lost contact with reality.

Rapid field testing: Technology used for analysis of water during site characterization in an attempt to tentatively identify contaminants or unusual water quality.

Red teaming: A group exercise to imagine all possible terrorist attack scenarios against the chemical infrastructure and their consequences.

Retentate: In ultrafiltration, the retentate is the solution that contains the particles that do not pass through the membrane filter. The retentate is also called the *concentrate*.

Ricin: A stable toxin easily made from the mash that remains after processing castor beans. At one time, it was used as an oral laxative (castor oil). Castor oil causes diarrhea, nausea, vomiting, abdominal cramps, internal bleeding, liver and kidney failure, and circulatory failure. There is no antidote.

***Salmonella*:** A Gram-negative bacillus, a germ of the *Salmonella* genus. Infection with this bacteria may involve only the intestinal tract or may be spread from the intestines to the bloodstream and then to other sites in the body. Symptoms of *Salmonella* enteritis include diarrhea, nausea, fever, abdominal pain, and fever. Dehydration resulting from the diarrhea can cause death, and the disease could cause meningitis or septicemia. The incubation period is between 8 and 48 hours, while the acute period of the illness can continue for 1 to 2 weeks.

Sarin: A colorless, odorless gas. With a lethal dose of 0.5 mg (a pinprick-sized droplet), it is 26 times more deadly than cyanide gas. Because the vapor is heavier than air, it hovers close to the ground. Sarin degrades quickly in humid weather, but its life expectancy increases as the temperature rises, regardless of how humid it is.

Sentinel laboratory: A Laboratory Response Network (LRN) lab that reports unusual results that might indicate a possible outbreak and refers specimens that may contain select biological agents in reference labs within the LRN.

Site characterization: The process of collecting information from an investigation site in order to support the evaluation of a drinking water contamination threat. Site characterization activities include the site investigation, field safety screening, rapid field testing of the water, and sample collection.

Sleeper cell: A small cell that keeps itself undetected until such time as they can "awaken" and cause havoc.

Smallpox: The first biological weapon, smallpox was used during the 18th century, and it killed 300 million people in the 19th century. There is no specific treatment for smallpox disease, and the only prevention is vaccination. This currently poses a problem, because the vaccine was discontinued in 1970 and the World Health Organization (WHO) declared smallpox eradicated. Incubation is 7 to 17 days, during which the carrier is not contagious. Thirty percent of people exposed become infected, and smallpox has a 30% mortality rate.

Sociopath: Basically synonymous with psychopath. Sociopathic symptoms in the adult sociopath include an inability to tolerate delay or frustration, a lack of guilt feelings, a relative lack of anxiety, a lack of compassion for others, a hypersensitivity to personal ills, and a lack of responsibility. Many authors prefer use of the term sociopath rather than psychopath because this type of person has had defective socialization and a deficient childhood.

Sociopathic: Of, relating to, or characterized by asocial or antisocial behavior or a psychopathic personality.

Spore: An asexual, usually single-celled reproductive body of plants such as fungi, mosses, or ferns; a microorganism, such as a bacterium, in a resting or dormant state.

Terrorist group: A group that practices or has significant elements involved in terrorism.

Threat: An indication that a harmful incident, such as contamination of the drinking water supply, may have occurred. The threat may be direct, such as a verbal or written threat, or circumstantial, such as a security breach or unusual water quality.

Toxin: A poisonous substance produced by living organisms that is capable of causing disease when introduced into body tissues.

Transponder: A device on an airliner that sends out a signal allowing air traffic controllers to track the airplane. Transponders were disabled in some of the planes highjacked on 9/11.

Transportation Security Administration (TSA): An agency created by the Patriot Act of 2001 for the purpose of overseeing technology and security in American airports.

Tularemia: An infectious disease caused by a hardy bacterium, *Francisella tularensis*, found in animals, especially rabbits, hares, and rodents. Symptoms depend on how the person was exposed to tularemia but can include difficulty breathing, chest pain, bloody sputum, swollen and painful lymph glands, ulcers on the mouth or skin, swollen and painful eyes, and sore throat. Symptoms usually appear from 3 to 5 days after exposures but sometimes will take up to 2 weeks. Tularemia is not spread from person to person, so people who have it need not be isolated.

Ultrafiltration: A filtration process for water that uses membranes to preferentially separate very small particles that are larger than the membrane's molecular weight cutoff, typically greater than 10,000 Daltons. A Dalton is a unit of mass, defined as 1/12 the mass of a carbon-12 nucleus. It is also called an *atomic mass unit*, abbreviated as either amu or u.

Vector: An organism that carries germs from one host to another.

Vesicle: A blister filled with fluid.

Weapons of mass destruction (WMD): According to the National Defense Authorization Act, WMDs are any weapons or devices that are intended, or have the capability, to cause death or serious bodily injury to a significant number of people through the release, dissemination, or impact of toxic or poisonous chemicals or their precursors, a disease organism, or radiation or radioactivity.

Xenophobia: Irrational fear of strangers or those who are different from oneself.

Zyklon B: A form of hydrogen cyanide. Symptoms of inhalation include increased respiratory rate, restlessness, headache, and giddiness followed later by convulsions, vomiting, respiratory failure, and unconsciousness. It was used in the Nazi gas chambers in World War 2.

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