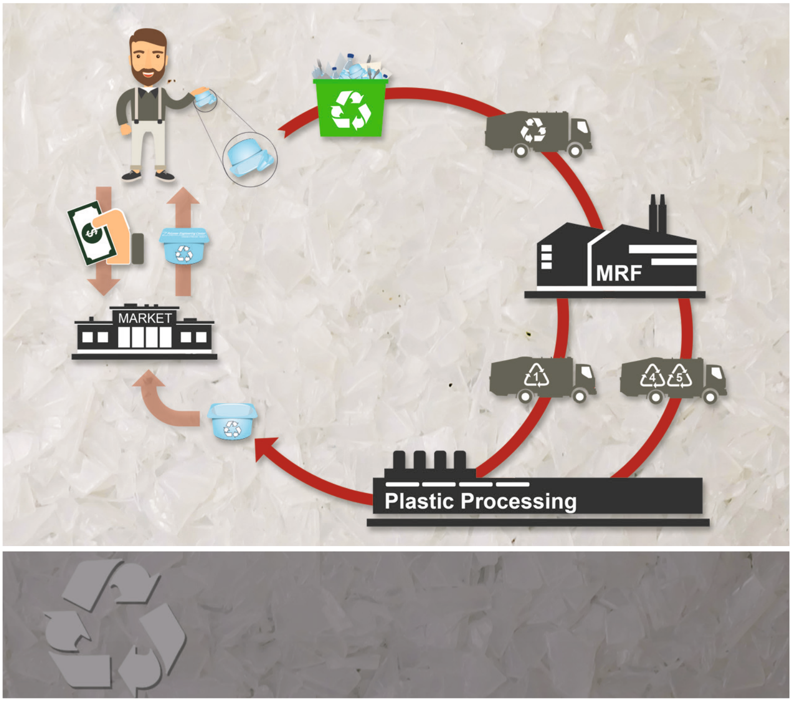
Natalie Rudolph
Raphael Kiesel
Chuanchom Aumnate

Understanding Plastics Recycling

Economic, Ecological, and Technical Aspects of Plastic Waste Handling



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Preface

Thank you for taking the time to read this book on plastic recycling. We hope you benefit from reading our summary and research regarding this topic. With different backgrounds and states in our scientific careers, we are united by the interest in using our knowledge to educate and make the world a little better—one topic and one word at a time.

It all began when I had started as an assistant professor at the University of Wisconsin-Madison and a new potential graduate student was sitting in front of me to discuss our collaboration. With many topics in my head and finally a position where I could explore topics close to my heart, Chuanchom Aumnate wanted to work on recycling of plastics. I thought to myself that I should probably still wait some more years with such a topic, get more established first, and then start working on it.

But in reality, I could not resist and we started formulating a project. Our aim was to focus on a topic that would make an impact and could solve problems around the globe. We decided to start with plastic packaging, due to its huge worldwide market share, and wanted to investigate the necessity of sorting, a process which is still immature for typical packaging materials and therefore limits the amount of recycled plastic.

Thus we worked on blending of typical packaging materials like polypropylene and polyethylene as an alternative for the sorting process to increase the amount of recycled plastic waste. We used scientific as well as industrial tests to analyze the resulting material properties. Our goal was to identify promising combinations as well as practical test methods for their analysis.

Very early on we realized that in addition to our technical study, we needed to understand the cost benefit of eliminating the sorting process and compare it to both conventional recycling and other waste management strategies. We could expand our work when Raphael Kiesel, on a scholarship from Germany, came to UW-Madison and decided to work on this topic. He combines the solid technical and business background needed to look at all of those aspects in combination. Soon after Raphael started on the topic, we realized that all of us were driven by understand-

ing recycling holistically—including the technical, economic, and ecological advantages and disadvantages.

The idea for the book was born from my colleague and mentor, Prof. Tim A. Osswald, when he attended Raphael's Master defense and suggested that we should publish our very interesting analysis in a book to reach a broader audience. And this is what we did.

We compiled our own analysis results together with data from other research groups and summarized it in the present book.

The book starts with a general overview of waste handling strategies and their shares of the U.S. market are presented (Chapters 1 and 2). In Chapter 3 special focus is placed on the technical aspects of recycling for various applications and specific polymers.

In separate chapters their economic (Chapter 4) and ecological value and costs (Chapter 5) are evaluated and compared. The analysis shows the advantages of plastic recycling as well as the necessary boundary conditions for future growth. In Chapter 6 different scenarios to increase the profitability of recycling are analyzed and blending of plastic materials is identified as a suitable strategy.

Last but not least, the findings for the U.S. are put into context to the worldwide potential for waste handling and in particular plastic recycling using Europe and China as examples in Chapter 7. All the data and calculations presented in the book and summarized in the tables in the Appendix in Chapter 8 can be downloaded as spreadsheets for the reader's own analysis and updates in a fast changing economy.

Thus, the book is an entry level book for decision makers in the plastics industry as well as students, researchers, and industry experts new to the field of plastic recycling.

True to our mission, this book is printed on recycled paper. We hope you enjoy reading it.

Madison, March 2017 *Natalie Rudolph*

Contents

Acronyms and Other Abbreviations

Abbreviation	Description
ABS	acrylonitrile butadiene styrene
ARR	average rate of return
ASTM	American Society for Testing and Materials
CCM	cost comparison method
CLF	closed loop fund
DSC	differential scanning calorimetry
EPA	U. S. Environmental Protection Agency
EPS	expanded polystyrene
GHG	greenhouse gas
HDPE	high-density polyethylene
HIPS	high-impact polystyrene
LDPE	low-density polyethylene
LFG	landfill gas
LLDPE	linear low-density polyethylene
MFI	melt flow index
MFR	melt flow rate
MRF	materials recovery facility
MSW	municipal solid waste
OCC	old corrugated cardboard
PA	polyamide
PBT	polybutylene terephthalate
PC	polycarbonate
PCM	profit comparison method
PE	polyethylene
PEEK	polyether ether ketone (or polyarylether etherketone)
PET	polyethylene terephthalate
PLA	polylactide
PMMA	polymethyl methacrylate
POM	polyoxymethylene (polyacetals)

Abbreviation	Description
PP	polypropylene
PPE	polyphenylene ether
PPP	purchasing power parity
PRF	plastics recycling facility
PS	polystyrene
PTFE	polytetrafluoroethylene
PU	polyurethane
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RCRA	Resource Conservation and Recovery Act
rLDPE	recycled low-density polyethylene
RoM	rule of mixtures
rPP	recycled polypropylene
SAN	styrene acrylonitrile
SNCR	selective noncatalytic reduction
SPP	static payback period
UV	ultraviolet
WARM	EPA Waste Reduction Model
WTE	waste-to-energy
XPS	extruded polystyrene

1 All About the Waste

Empty plastic bottles, yesterday's newspapers, eggshells, or used tea bags—all of these have one thing in common: they belong to *municipal solid waste (MSW)*, ordinarily called "trash" or "garbage". MSW refers to household, office, or retail waste and is part of everyone's daily life. Each person in the United States generates 2 kg of MSW every day, which resulted in a total waste creation of 254 million tons (t)[1] in 2013, and the trend is rising. As the volume of waste produced in the United States continues to increase, the handling and disposal of MSW are growing concerns of society. [1, 2, 3] In order to understand the impact of plastics and their recycling in the waste stream, it is important to understand the composition of MSW and current strategies for handling it.

1.1 Municipal Solid Waste—A Daily Companion

Municipal solid waste (MSW) is generally defined as nonhazardous waste. The United States Environmental Protection Agency (EPA) characterizes MSW as *"waste consisting of everyday items, used and then thrown away, such as product packaging, bottles, food scraps and newspapers which comes from homes, schools, hospitals and businesses."* MSW is classified in three broad categories according to where it is generated: household waste, commercial waste, and institutional waste. [4, 5] Household waste includes that from single- and multiple-family homes, hotels and motels, and day-use recreation areas. This category accounts for 55 to 65% of the total MSW generated and is also referred to as postconsumer waste. Thus, households are the primary source of MSW in the United States. Commercial waste includes solid waste from stores, offices, restaurants, warehouses, and other non-manufacturing activities. Waste from schools, colleges, and similar public or quasi-public buildings is listed as institutional waste. The waste generated by the

[1] Unless otherwise stated, "ton" in this book always refers to a metric ton (1000 kg).

industrial sector is negligible. Manufacturing companies manage their solid residues or preconsumer waste by recycling, direct reuse, or self-disposal in industrial waste landfills. [1, 4, 5]

The total MSW generation in the United States increased steadily between 1960 and 2013, from 88 t/year (tons per year) to 254 t/year, due to economic expansion. The generation per capita per year has risen from 1.2 kg to 2 kg. However, it is important to note that after a peak in 2000, the MSW produced per capita per year has decreased slightly since then (2.15 kg to 2 kg). [2] Factors affecting the quantity of MSW generated include changes in population, individual purchasing power, product packaging, and technology, which again affect disposal habits as well as the nature of materials disposed. Hence, an analysis of the MSW composition over time is necessary to explain and also forecast future MSW generation in the United States. [4] The EPA uses two methods to characterize MSW, by material and by major products. In order to understand the studies presented in this book, knowledge of the proportion and quantity of different materials in MSW (Figure 1.1) is important and reflects the changes described in MSW generated in the United States.

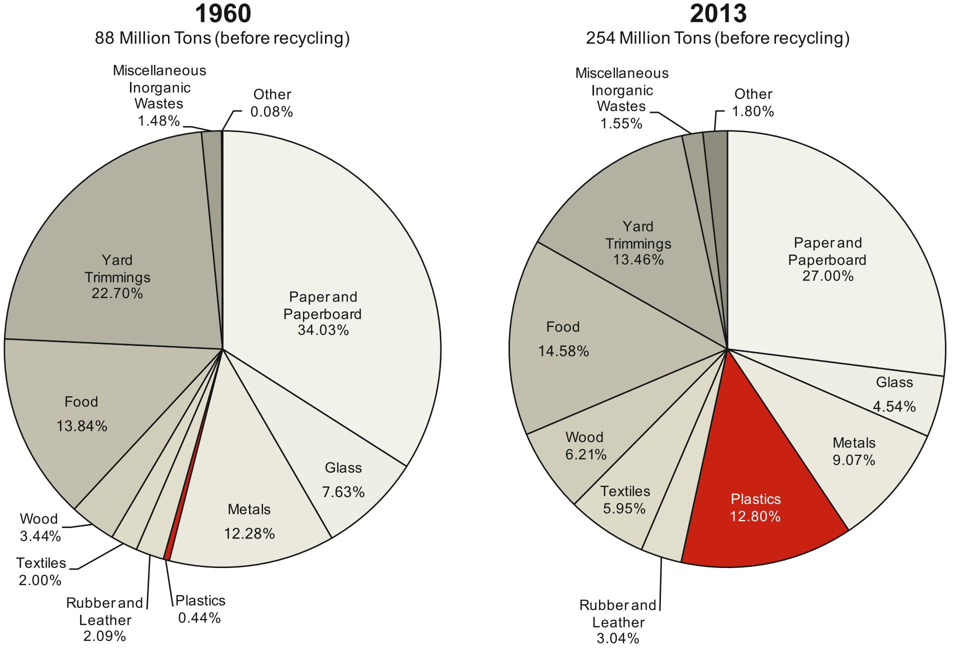

Figure 1.1 Comparison of the types and amounts of plastic waste generated in the United States in 1960 and 2013[2]

[2] The waste composition of 2013 is the basis for further calculations in this book.

Figure 1.1 provides information about the trends in consumer behavior and production of waste as seen, for example, in the significant change in the proportion of plastics in MSW between 1960 and 2013, which will be further discussed in Chapter 2. In this chapter we will discuss how the composition of MSW is of particular relevance for waste handling.

1.2 Management Methods for Municipal Solid Waste

The United States manages wastes in three different ways:

- Landfilling
- Incineration with energy recovery [waste-to-energy (WTE)]
- Recycling

Figure 1.2 shows a flowchart of this waste management system. Due to a growing awareness of environmental pollution, the EPA has strived to recycle as much MSW as possible or at least to burn it for energy, which will be further discussed in Chapter 3. It can be seen that residues from all waste treatment processes end up in landfill (dashed lines), which make disposal sites the final destination of MSW. [6, 7]

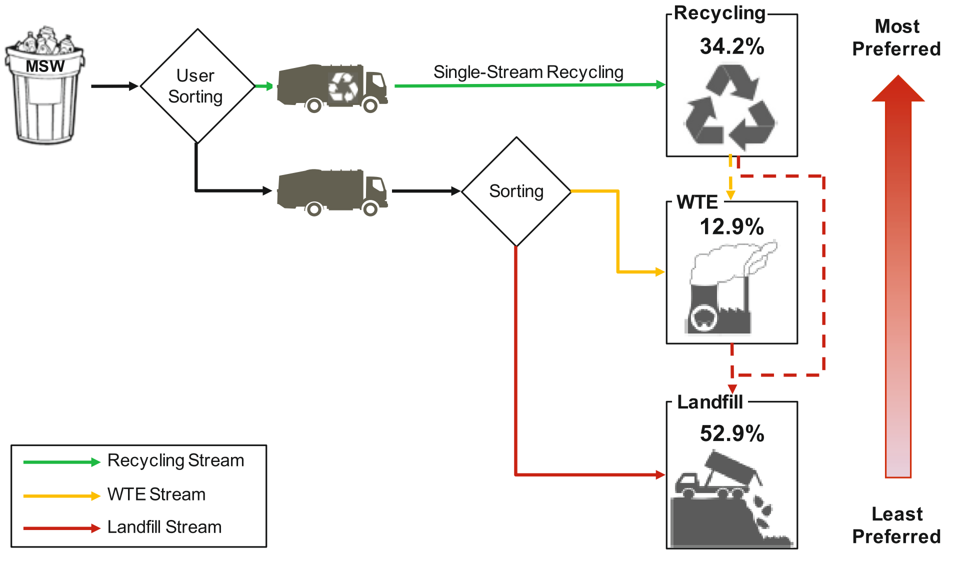

Figure 1.2 Flowchart of the waste management stream in the United States in 2013. WTE, waste-to-energy plants

Changing technologies, waste compositions (Section 1.1), and regulations, together with this growing environmental awareness, has induced a change in MSW treatment in recent decades. In 1960, 94 % of the MSW generated in the United States was disposed of in landfills and afterwards open burned for volume reduction, which refers to burning garbage in outdoor pits. The remaining 6 % was recycled and the amount of energy recovered was insignificant. Since then, the amount of waste that is burned for energy recovery or recycled has increased steadily. In 2013, the majority of waste was still disposed of in U.S. landfills, but compared to the 1960s, it was only 52.9 %; 12.9% of MSW was burned with energy recovery and 34.2 % was recycled (Figure 1.2). [1, 2, 4, 8]

1.2.1 Landfilling

Landfill describes engineered areas of land used for the controlled deposit of solid waste onto or into land. The EPA distinguishes between three sizes of landfill, which are listed in Table 1.1. [9]

Table 1.1 Classification of Landfill Sizes in the United States

	Weight [t]	Size [m^3]
Small Landfills	< 26,000	<52,000
Medium Landfills	26,000 – 130,000	52,000 – 200,000
Large Landfills	> 130,000	> 200,000

United States MSW landfills are required to comply with federal regulations contained in subtitle D of the *Resource Conservation and Recovery Act (RCRA)*. The RCRA D requirements include siting restrictions in floodplains, surface and groundwater protection, disease and vector control, open-burning prohibitions, explosive gas (methane) control, fire prevention through the use of cover materials, and prevention of bird hazards to aircraft. [10, 11]

The United States mainly uses two different methods for active disposal of waste into landfills: the *area fill method* and the *trench method*. In the area fill method the waste is placed, spread out, and finally compacted in uniform layers using heavy equipment in large open sections of lined landfills. In the trench method, the waste is placed and compacted in a trench using material from the trench excavation as daily cover. The most appropriate method for a specific landfill is often determined by local conditions; a combination of both methods is possible. At the end of each day, cover materials are applied on top of the waste mass to prevent odors and fires, and to reduce litter, insects, and rodents. The daily cover material includes soil, compost, incinerator ash, foam, and tarps. If a landfill has reached its permitted height, the cell has to be closed. The required postclosure care period is

30 years, but it can be shortened or extended with changing state regulations and approvals. [4, 11, 12, 13, 14, 15]

Due to the described regulations, regularly amended by the EPA, opening a new or expanding an existing landfill plant has become increasingly difficult. After adoption of the first RCRA in 1968, the total number of landfills in the United States has steadily declined, especially small and private landfills. [1, 13]

Despite a decreasing number of landfills and a diminishing percentage of total MSW disposed of in landfills, the total waste capacity of landfills is still increasing due to the increasing amount of waste in general. The focus in the United States is on large and modern landfill plants. The fact that the combined capacity of the two largest landfill plants in the United States in 2014 was close to 10 billion t underlines this trend. [1, 13]

1.2.2 Incineration with Energy Recovery (Waste-to-Energy)

Incineration with energy recovery is the only *waste-to-energy (WTE)* technology that is commercially used in the United States. The heat generated by burning waste can be used directly for heating, to produce steam, or to produce electricity. In 2013, 12.9 % of the total MSW in the United States was burned with energy recovery. [16, 17]

The main motivation for burning waste was and still is the reduction of the volume and weight of solid waste. Nowadays, combustion decreases the volume of waste by about 90 % and its weight by about 70 %. [17]

The first garbage incinerator in the United States was built in 1885 by the U.S. Army. It only served to reduce the volume and weight of MSW and did not generate energy. At the beginning of the twentieth century, incineration became a convenient method to dispose of waste. Due to air emission problems, technical limitations, and the increasing popularity of landfills, the amount of waste being burned was negligible in the 1960s. Europe, however, constantly improved and built waste-to-energy technologies mainly because these countries had less land available for landfilling. Increasing oil prices in the 1970s, caused by the OAPEC oil embargo, as well as federal laws and policies finally forced the United States to build their own waste-to-energy incineration plants. [2, 17]

The facilities tended to be built near landfills of urban centers. On average, 1 ton of solid waste produces 525 kWh of electricity, which is equivalent to the energy produced by a $^1/_4$ ton of coal or 1 barrel of oil. [1, 17]

The most common type of incineration plant is the *mass-burn facility* (64 out of 84 of the facilities in the United States [18]). Therefore, this type of facility will be further considered in the analysis. Mass-burn facilities use solid waste directly out of the garbage truck, without shredding or processing of the material. A plant diagram of a mass-burn facility is shown in Figure 1.3.

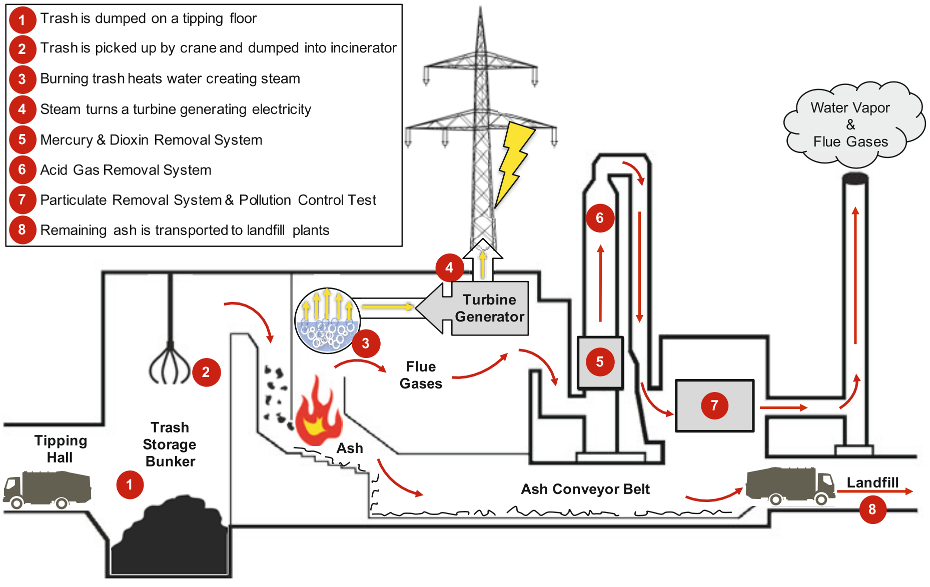

Figure 1.3 Waste-to-energy plant diagram of a mass-burn facility

After the trash is dumped on the tipping floor (1), it is picked up by a crane and dropped into an incinerator (2). Burning the trash in the incinerator generates three different "products": ash, flue gases, and heat. While both ash and flue gases are waste products, the generated heat is really valuable. The heat is used to boil water in a big tank to thereby create steam (3). The steam is used to run a turbine generator, which produces energy, mostly in form of electricity (4). The flue gases pass a pollution control system before they are mixed with water vapor and blown into the air. This control system includes a nitrogen oxide removal system, a mercury and dioxin removal system (5), an acid gas removal system (6), a particulate removal system (7), and the final pollution control test (7). The remaining ash is conveyed to a waste truck and transported to the closest landfill plant (8), where it is mixed with the untreated landfill waste. [17]

In 2014, 84 waste-to-energy facilities were in operation in the United States, with a combined capacity to generate 2,769 MWh of energy daily. [1, 18]

A fairly new process among the WTE technologies that converts plastics such as PE, PP, and PS into light crude oil is *pyrolysis*, or *thermochemical decomposition*. Also known as plastic-to-oil processing, it is able to produce 1 L of oil out of 1 kg of plastic, for which 1 kWh of electricity is required to operate the processing machinery. In the process, plastic flakes are heated to around 400 °C to decompose the plastic material into inactive carbon char and gas. The gas is then condensed and liquefied into oil. The remaining gas is filtered and released as carbon dioxide and steam. Although the technology is promising and commercially available, it is

not yet economically viable due to the initial investment in most settings today. However, some successful prototype facilities exist in the United States and Canada. [19]

1.2.3 Recycling

Recycling converts materials and products that would otherwise become waste into valuable resources. Paper and cardboard, yard trimmings, metals, glass, and plastics are the most important recyclables in the United States. The main characteristic of the U.S. recycling process is single-stream recycling. Single-stream recycling means that all recyclables are picked up unsorted and are not separated until they get to the processing facility. [2]

The general cyclic recycling process involves three main steps:

1. Collecting the recyclables
2. Processing the recyclables and turning them into new products
3. Purchasing recycled products

After collecting the recyclables via curbside collection, drop-off programs, buyback operations, and container-deposit systems, they are transported to material recovery facilities (MRFs), mixed-waste processing facilities, or mixed-waste composting facilities. Since MRFs are the most common of these facilities in the United States and are more and more high tech, the analysis in this book will focus on this type of facilities (more details can be found in Chapter 4). [2, 5]

High-tech MRFs are characterized by the automated separation of unsorted recyclables using eddy currents, magnetic pulleys, optical sensors, and air classifiers, reducing manual sorting. Automatic sorting supports and simplifies single-stream recycling and enhances its economic profitability (more details can be found in Chapter 4). [2]

In 2013, 34.2 % of the total MSW was recycled. Items with the highest recycling rates include lead-acid batteries (96 %), steel cans (70.8 %), paper and cardboard (70%), yard waste (57 %), and aluminum cans (54.6 %). Only 9.2 % of the total plastic waste, which is 12.8 % of the total MSW, was recovered in 2013. Thus, the potential and motivation for improving the recycling of this widely used material is very high. [1, 20]

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2 Plastics—Increasing Value, Decreasing Lifetime

"For the last 150 years, plastic materials have been key enablers for innovation and have contributed to the development and progress of society." [1] This quote from PlasticsEurope portrays the importance of plastics in today's industrialized society. Imagining today's world without plastics is virtually impossible. Compared to every other engineered material in the world, plastics have the highest growth rate. This is related to their outstanding properties: they are lightweight and easy and economical to manufacture into complex products. Plastics have become the most important raw material for a variety of products and applications from automotive components, mobile phones, pipes, and foams to packaging. Their versatility, durability, and high strength-to-weight ratio have led to a twentyfold exponential growth in their production in the past half-century. They constitute about 15 % of the weight of a car and 50 % of the Boeing Dreamliner. By 2030, their production is expected to double and by 2050, to quadruple. [2, 3, 4, 5, 6, 7]

Plastics' largest application is in packaging, representing 34 % of total sales of plastics in the United States in 2012. Their low cost, light weight, and high performance make them suitable for packaging materials. In addition, plastic packaging benefits the environment in some ways: its low weight reduces fuel consumption for transportation and its barrier properties keep various foods fresh longer, thus leading to a reduction in food waste. As a result, plastics are progressively replacing other packaging materials. [5, 7]

This growth in plastics production and replacement of other materials in many industry sectors is leading to an increasing amount of plastic waste, as can be seen in Figure 2.1. Between 1960 and 2013, the total amount of plastic waste in the United States increased by a factor of 80. In parallel, the percentage of plastic waste in municipal solid waste (MSW) grew as well, which demonstrates the rising significance of plastics in our daily life. [3, 8] However, it should be noted that the rate of increase in the amount of plastic waste has slowed down slightly since 2005 in comparison to the steep increase between 1980 and 2005.

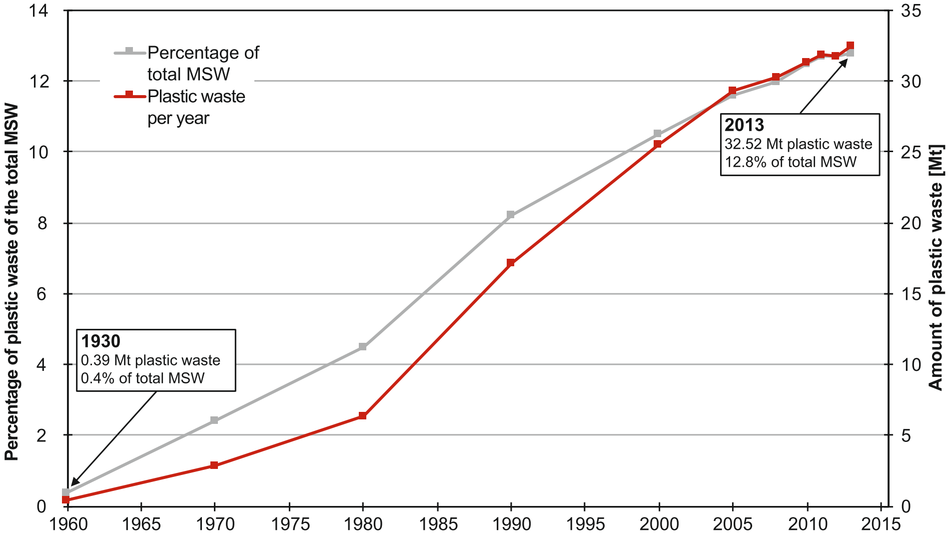

Figure 2.1 Changes in the amount of plastic waste in the U. S. between 1960 and 2013. MSW, municipal solid waste; Mt, megatons.

Comparing the amount of plastic waste to the total amount of plastic produced in the United States between 2005 and 2012, the ratio of waste to production increased from 26.8 % in 2005 to 30 % in 2012. The reason for this change is the reduced lifetime of plastic products caused by the increasing use of plastics for *single-use products*, such as plastic bags, packaging, and containers, which are immediately thrown away after unpacking the product they hold or contain. [3, 7, 8]

Polypropylene (PP), *low-density polyethylene (LDPE)*, and *high-density polyethylene (HDPE)* are the three most common polymers found in the packaging waste stream, especially in the form of plastic films. Table 2.1 shows the breakdown of plastic waste by polymer. PP, LDPE, and HDPE add up to a total weight percentage of more than 60 %. However, the recycling levels of plastic films from postconsumer waste are very small. [3, 9, 10]

Table 2.1 Plastic Waste by Polymer in the United States in 2013

Polymer	Generated		Recycled	
	Amount [kt]	Percentage of Plastic Waste [%]	Amount [kt]	Percentage of Plastic Waste [%]
PET	4,680	14.39	930	19.87
HDPE	5,580	17.16	570	10.22
PP	7,400	22.76	40	0.54
LDPE/LLDPE	7,460	22.94	470	6.30
PS	2,270	6.98	30	1.32
PVC	900	2.77	Negligible	–
Other resins	4,230	13.00	960	22.70
Total	**32,520**	**100.00**	**3,000**	**100.00**

Regardless of the positive aspects of the increasing use of plastics, the increasing plastic waste from single-use products generates significant negative consequences. The production of plastics consumes a large amount of the scarce resource, oil: the processing and raw materials for producing 1 kg of plastics requires about 2 kg of crude oil. If the current plastic waste handling does not change, the ratio of plastic waste to fish (by weight) in the ocean in 2050 will be 1 : 1. Additionally, plastics' share of global oil consumption would increase from 6 % (2012) to 20 % (2050) and plastics' share of the carbon budget would rise from 1 % (2012) to 15 % (2050). Therefore, the emerging challenge of these developments from both an economic and an environmental point of view is to improve plastic waste handling and, in the best case, to recycle and reuse these resources. [5, 11]

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3 Plastics Recycling—Conservation of Valuable Resources

Plastics recycling is the term used for reprocessing postconsumer and preconsumer plastic waste (manufacturing scrap) into useable products. The idea behind recycling is to break down finished products into their component materials and then use those materials as feedstock to manufacture new products. Based on the plastics waste source, the recycling process and the finished product differ. In general, plastics can only be reused a limited number of times before they are too degraded for further use. Currently, all preconsumer plastic waste is fed back into the plastic production stream, but only a little portion of postconsumer plastic waste is reclaimed for its original use. However, every bit of plastic that is recycled reduces the need for new plastic feedstock and thus decreases the amount of resources and energy used for its production.

Recycling of plastics for use in creating new high-quality plastic products requires that the recycled materials are clean and consist of only a single type of plastic. In such cases, the recycled plastic substitutes for virgin plastic. The big challenge in recycling postconsumer plastics, especially those from mixed (co-mingled and/or single) stream collection is that they are often contaminated. Recycling of mixed plastics is much more complicated. If the recycled plastics are contaminated and/or are a mixture of different types of plastic, the quality of the recycled plastic is lower; for example, the plastic may have lower strength. The challenge in managing the recycling of large quantities of a mixture of miscellaneous types of contaminated plastics needs to be considered using an integrated approach to source reduction, reuse, and recycling. [1]

Plastics recycling is more complex than metal or glass recycling because of the many different types of plastic. Thus, recyclability and environmental compatibility need to be criteria considered at the beginning of the design process of plastic products instead of as an afterthought, particularly in many products where several kinds of plastic and sometimes non-plastic components are integrated. The separation, recovery, and purification of the plastic components in such a product require several steps, which consume additional energy. Unfortunately, the recycling rate, the amount of any type of plastic that is recycled in a period of time, is

directly related to the price of virgin resins for that type of plastic, which is related to the price of oil (see Section 4.4.5). Low oil prices result in low costs for the virgin resins. In these times, recycled resins are too expensive to be used by comparison, and the recycling rates drop. Therefore, the goal of any sustainable growth in recycling should be the maximization of efficiency of energy utilization in every step of the process, from the initial production of plastic goods to the disposal or recovery of plastic wastes. [2]

3.1 Plastics Recycling Methods

There are three common methods for plastics recycling: *mechanical recycling* (primary and secondary recycling) and *chemical recycling* (tertiary recycling). Based on the degree of contamination of the plastics (Section 3.5) with organic or inorganic substances (other polymers or impurities), one of these three recycling methods is chosen. The molecular structure of the plastics as well as existing cross-links, such as in thermosets or rubbers, also influence the decision process. [3, 4]

3.1.1 Mechanical Recycling

Amongst the recycling methods, mechanical recycling is the most desirable approach because of its low cost and high reliability. In general, mechanical recycling keeps the molecular structure of the polymer molecule basically intact. After grinding of the plastics waste material, the main processing step is remelting of the regrind material, which limits the use of mechanical recycling to thermoplastic polymers. Since remelting causes a degradation of the polymer chain, virgin material is often mixed with recycled material to reduce the effects of degradation on the product properties. The mixing leads to a dilution of the virgin material, which is described in Section 3.2.1.2. [5]

Mechanical recycling is divided into primary and secondary mechanical recycling, depending on whether the source of the waste is preconsumer or postconsumer, respectively. Preconsumer manufacturing scrap plastic is usually clean and of a single type or at least of a known composition and requires no further treatment, whereas postconsumer waste is highly contaminated and requires additional steps like collecting, sorting, and cleaning.

3.1.2 Chemical Recycling

Chemical recycling is used for *cross-linked polymers* or for thermoplastic polymers if no sufficient quality can be achieved using mechanical recycling. Chemical processes are used to convert the polymer chains to *low molecular weight* compounds or, in some cases, the original plastic monomer (feedstock). The monomers can be used for polymerization to generate the original polymer again, whereas the low molecular weight compounds are used as feedstock for the petrochemical industry. Common processes for this recycling method are hydrolysis, hydrocracking, and depolymerization. Because of the large amounts of energy and chemicals consumed by these processes, chemical recycling is only economically and ecologically reasonable for a very limited number of polymers such as polymethyl methacrylate (PMMA) and polyether ether ketone (PEEK). Chemical recycling of polyethylene terephthalate (PET) has been successfully developed. However, it is hindered by the processing cost. Furthermore, the chemical processing has been proven to be technically possible for polyolefins but is still in the laboratory stage of development. [3, 4, 6, 7, 8]

3.2 Recycling Different Types of Plastic Waste

As mentioned before, plastic waste can be divided into *preconsumer waste* (manufacturing scrap) and *postconsumer waste* (recovered waste). These different plastic waste types are recycled differently.

3.2.1 Preconsumer Waste

3.2.1.1 Manufacturing Scrap

Preconsumer waste, such as runners, gates, sprues, and trimming, is normally recycled using primary mechanical recycling. It is ground and remelted in-house.

3.2.1.2 Dilution Effect

Manufacturing scrap is often mixed into virgin material to reduce material cost while at the same time minimizing the effects of degradation on part performance. Depending on the mixing ratio, either the virgin material is diluted with regrind or the regrind is refreshed with virgin material. By using a constant mixing ratio during continuous processing, the regrind waste itself is diluted by material that

has been reprocessed once, twice, three times, etc. The composition of a material with a proportion of recyclate q after n processing cycles can be calculated using Equation (3.1).

$$\sum_{i=1}^{n} q^{n-i}(1-q) = 1 \tag{3.1}$$

For small proportions of recyclate, the regrind material contains only minimal amounts of material that has passed through a large number of processing cycles and therefore is highly degraded.

Figure 3.1 shows the composition of material with different mixing ratios of recycled and virgin material. The first column shows 30 % recycled and 70 % virgin material. Under these conditions, the regrind material contains less than 0.8 % of material that has been reprocessed five times or more. Seventy percent of the material is virgin material, 21 % has been processed once, 6.3 % twice, and 1.9 % three times. As proportions of material smaller than 1 % do not have a significant influence on the material properties and can be neglected [9], the properties will be dominated by fractions that have been processed four times or less. Thus, it can be concluded that the properties of a material with small amounts of recyclate will not fall below a certain level. [10]

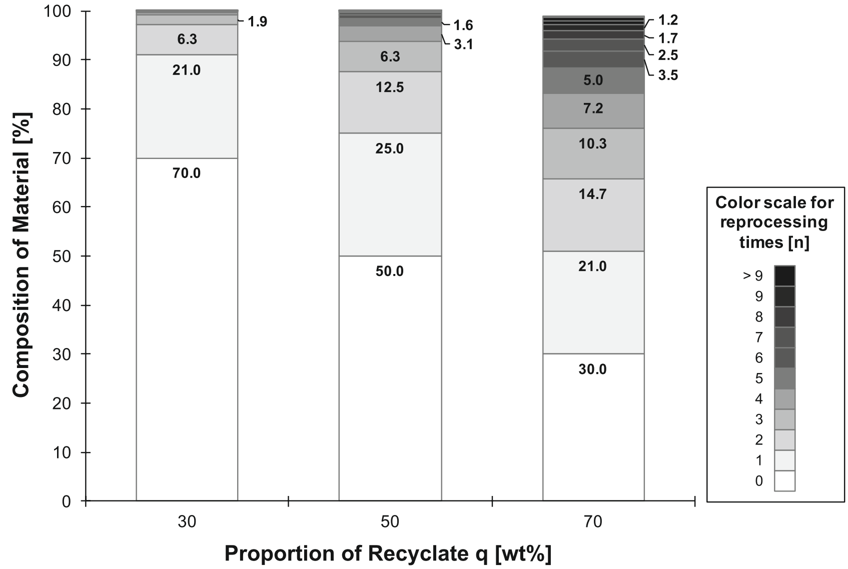

Figure 3.1 Composition of recycled plastics material after n reprocessing steps for 30 %, 50 %, and 70 % recycled material

However, regrind material with high proportions of recyclate contains significant amounts of highly degraded material, as can be seen in the right column in Figure 3.1, in which 70 % of the regrind is recycled and 30 % is virgin material. This regrind material contains 5.0 % material that has been reprocessed five times, as well as 30 % that is virgin material, 21 % that has been processed once, 14.7 % twice, 10.3 % three times, and 7.2 % four times. After nine processing cycles, the material still contains 1.2 % of the initial material. Although this mix contains significant portions of highly degraded material, after 10 reprocessing cycles the material reaches a steady state in which performance properties are not affected any further by further processing. Therefore, this mixing ratio is used quite frequently for packaging products.

3.2.2 Postconsumer Waste

Consumer plastics are largely made from six different polymer resins, which are indicated by a number, or *resin code*, from 1 to 7 molded or embossed onto the surface of the plastic product. The number 7 indicates any polymer other than those numbered 1 to 6. Table 3.1 lists the polymer resins, their resin codes, and the general applications for virgin and recycled plastics made from these resins. The percentages of the different types of postconsumer plastic waste in municipal solid waste (MSW) in the United States in 2013 are given in Table 2.1. [11]

Table 3.1 Plastic Types and Products from Virgin and Recycled Materials

Resin Symbol and Plastic Type	Products Created from Virgin Plastics	Products Created from Recycled Plastics
01 PET Polyethylene terephthalate	Bottles for water, soft drinks, salad dressing, peanut butter, and vegetable oil	Egg cartons, carpet, and fabric for T-shirts, fleeces, tote bags, etc.
02 HDPE High-density polyethylene	Milk and juice cartons, detergent containers, shower gel bottles, and shipping containers	Toys, pails, drums, traffic barrier cones, fencing, and trash cans
03 PVC Polyvinyl chloride	Packaging materials, plastic pipes, decking, wire and cable products, blood bags, and medical tubing	Shoe soles, construction material, and boating and docking bumpers

Table 3.1 Plastic Types and Products from Virgin and Recycled Materials *(continued)*

Resin Symbol and Plastic Type	Products Created from Virgin Plastics	Products Created from Recycled Plastics
04 LDPE Low-density polyethylene	Disposable diaper liners, cable sheathing, shrink-wrap, and film	Timbers, trash can liners, shopping envelopes, lumber, and floor tiles
05 PP Polypropylene	Medicine bottles, drinking straws, yogurt containers, butter and margarine tubs, automotive parts, and carpeting	Signal lights, bicycle racks, trays, battery cables, and ice scrapers
06 PS Polystyrene	Egg cartons, cups, food containers, plastic forks, and foam packaging	Egg cartons, foam packing, and light-switch plates
07 O All other resins or mixtures of resins	Mixed plastics or multilayer plastics packaging	–

The chemical composition and function of each resin controls where the resin can be recycled as well as the recycling rate. The latter is attributed to the difficulty of separating mixed plastic during the recycling process. For example, PET, or resin code 1, only accounts for 14.39 % of the total plastic waste but it has the highest recycling rate of all resins. Because of its widespread use in transparent drinking bottles, PET is easy to identify and sort by transmission detectors.

Some resins are not compatible with others, because their molecular structures repel each other if mixed. This leads to deterioration of the mechanical performance of plastic products made from them if they are not engineered properly. Most plastics have additives incorporated to achieve certain additional properties such as flame retardancy, flexibility, or resistance to ultraviolet (UV) damage. This makes it nearly impossible to obtain a homogeneous plastic mixture with uniform behavior. Therefore, it is important that the sorting process is well regulated to ensure the integrity and overall performance of recycled plastic products.

Depending on their properties, different plastics are used for different applications. Currently, packaging, consumer and institutional products, and building and construction materials are the top three uses for plastics. The share of U.S. plastics demand by use in 2015 is shown in Figure 3.2. These different applications are again represented in the plastic waste. [12]

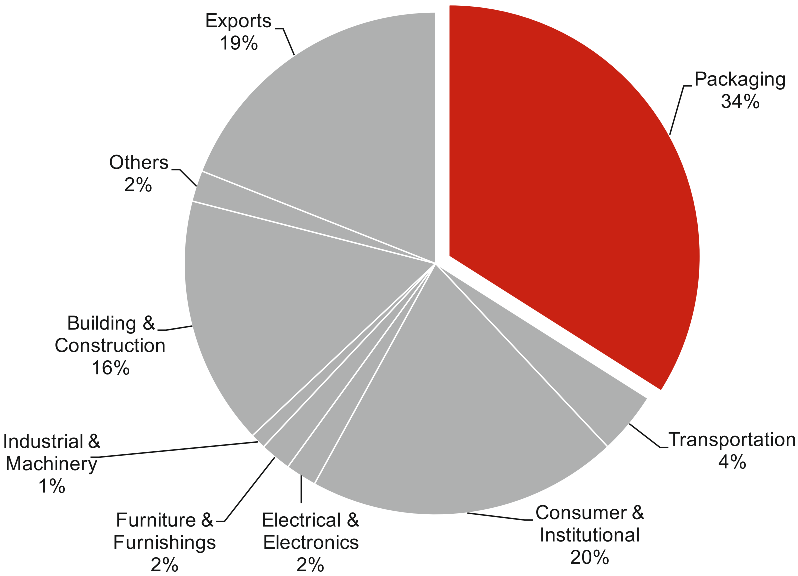

Figure 3.2 United States plastics demand by use in 2015 [11]

3.2.2.1 Packaging Plastic Waste

As a result of the demand for plastics, a large share of MSW plastics consists of packaging items in which high-density polyethylene (HDPE, 17.16 %), low-density polyethylene (LDPE, 22.94 %), and polypropylene (PP, 22.76 %) together account for about 63 % of the waste (see Table 2.1). The continuing increase in the use of disposable packaging has led to increasing amounts of plastics ending up in the waste stream. In Europe, where the proportion of plastic waste in the waste stream is similar to that in the United States, packaging waste amounts to nearly two-thirds of all the plastic waste, as shown in Figure 7.6. [13] The difference in the demand for packaging (34 %) and the generation of packaging waste (63 %) is based on the different service life of the products. About 60 % of all plastic products were designed for a long service life (years), while about 40 % were designed for a shorter service life or even for a single use.

Due to their similar density, packaging wastes, especially LDPE, HDPE, and PP, are difficult to separate (Section 3.3.2). Unfortunately, waste management strategies are not developing at the same rate as the increasing levels of plastic waste. In 2013, only 3 million tons (9.23 %) out of the total 32.5 million tons of plastic waste in America's MSW stream were recycled (see Table 2.1). [11, 14] The recovered plastics were mainly PET and HDPE bottles. The main polymers used for packaging applications are summarized in Table 3.2. [13]

Table 3.2 Most Common Polymers Used in Packaging Applications

Application	Most Common Polymers Used
Bottles, flasks	PET (66 %), HDPE (28 %), PP (3 %), LDPE (0.4 %), PVC (3 %)
Closure items, bottle caps	PP (73 %), HDPE (20 %), LDPE (5 %), PVC (2 %)
Films	LDPE (76 %), PP (20 %), PVC (3 %), PET (1 %)
Bags, sacks	LDPE (61 %), HDPE (31 %), PP (8 %)
Jars, boxes, tubs	PP (73 %), HDPE (20 %), LDPE (5 %), PVC (2 %)

Abbreviations: HDPE, high-density polyethylene; LDPE, low-density polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PVC, polyvinyl chloride

3.2.2.2 Building and Construction Plastic Waste

In the building and construction industry, plastics play an important role due to their durability, aesthetics, easy handling, and high performance. Normally, they are designed to be durable for 30 to 40 years before disposal. They are used, for example, in pipework, insulation, wall coverings and flooring, interior fittings and window frames. Common plastics used in construction include HDPE, polyvinyl chloride (PVC), and polyurethane (PU) (see Table 3.3). [13]

Table 3.3 Most Common Polymers Used in Building and Construction Applications

Application	Most Common Polymers Used
Pipes and ducts	PVC, PP, HDPE, LDPE, ABS
Insulation	PU, EPS, XPS
Windows and other frames, flooring, and wall coverings	PVC
Lining	PE, PVC
Interior fittings	PS, PMMA, PC, POM, PA

Abbreviations: ABS, acrylonitrile butadiene styrene; EPS, expanded polystyrene; HDPE, high-density polyethylene; LDPE, low-density polyethylene; PA, polyamide; PC, polycarbonate; PE, polyethylene; PMMA, polymethyl methacrylate; POM, polyoxymethylene; PP, polypropylene; PS, polystyrene; PU, polyurethane; PVC, polyvinyl chloride; XPS, extruded polystyrene

Rigid PU foam is known for its high thermal resistance, which promotes temperature maintenance. It is also popular because it is lightweight, chemically resistant, and flame retardant. Moreover, acrylonitrile butadiene styrene (ABS) and polycarbonate (PC) are used in the construction industry as well.

The variety of material grades and properties used in the building and construction industry leads to a small recycling rate for these materials. [15] Nevertheless, the building and construction industry can be counted as a secondary market for recycled plastic. There it can be used in many applications including as a filler, in packaging, in landscaping for walkways, bridges, fences, and signs, and in traffic management and industrial strapping products. [16]

3.2.2.3 Automotive Plastic Waste

In automotive applications, plastics are used for a wide variety of parts and functions, mainly because of their low weight and cost. Furthermore, they have advantages due to their impact and corrosion resistance. The largest share of plastics used in vehicles is for the passenger cell, followed by the body. PP, PE, PU, and PVC are the most common plastics by volume used in a typical car. Table 3.4 lists the common plastics used in various automotive parts.

Table 3.4 Most Common Polymers Used in Automotive Applications

Application	Most Common Polymers Used
Bumper	PP, ABS, PC/PBT
Seats	PU, PP, PVC, ABS, PA
Dashboard	PP, ABS, PPE, PC
Fuel system	HDPE, POM, PA, PP, PBT
Body	PP, PPE
Interior trim	ABS, PP, PBT, POM, PP
Lighting	PC, PBT, ABS, PMMA

Abbreviations: ABS, acrylonitrile butadiene styrene; HDPE, high-density polyethylene; PA, polyamide; PBT, polybutylene terephthalate; (PC), polycarbonate; PMMA, polymethyl methacrylate; POM, polyoxymethylene; PP, polypropylene; PPE, polyphenylene ether; PU, polyurethane; PVC, polyvinyl chloride

3.2.2.4 Agricultural Plastic Waste

Plastics are everywhere on a typical farm and substitute for traditional materials due to their low price and light weight. Nowadays, hay bales are often wrapped in plastic or grain is stored in plastic bags instead of silos. Furthermore, plastic has become essential for widespread applications in modern farm operations. For example, large plastic sheets are used for everything from heating the soil and suppressing weeds to roofing greenhouses. A lot of agricultural products are plastic films, which is reflected in the types of polymers used in agricultural applications as shown in Table 3.5. Currently only 10 % of agricultural plastic waste is recycled. [13, 17, 18, 19]

Table 3.5 Most Common Polymers Used in Agricultural Applications

Application	Most Common Polymers Used
Bale bags, seed bags	LDPE, LLDPE, PP
Greenhouse covers, silo covers, mulch film	LDPE, LLDPE
Nets and mesh	LDPE, HDPE
Rope, strings	PP
Pipes and fittings	PVC, LDPE
Pesticide containers, nursery pots	HDPE, PS, PP

Abbreviations: HDPE, high-density polyethylene; LDPE, low-density polyethylene; LLDPE, linear low-density polyethylene; PP, polypropylene; PS, polystyrene; PVC, polyvinyl chloride

3.2.2.5 Waste from Electrical and Electronic Equipment (WEEE)

In general, the plastic waste from electrical and electronic equipment (WEEE) and in particular the metals in them are recovered by metal recyclers. The remaining plastics and nonmetals are known as electronics shredder residue (ESR). The principal polymers found in WEEE include ABS, high-impact polystyrene (HIPS), PP, polyamide (PA), polycarbonate (PC), blends of PC with ABS (PC/ABS), and some others as shown in Table 3.6. So far only half of a typical ESR mixture is recovered and the rest goes into landfill. [13, 20]

Table 3.6 Most Common Polymers Used in Electrical and Electronics Equipment

Application	Most Common Polymers Used
Printers/faxes	PS, HIPS, SAN, ABS, PP
Telecommunications equipment	ABS, PC/ABS, HIPS, POM
Televisions	PPE/PS, PC/ABS, PET
Monitors	PC/ABS, ABS, HIPS
Computers	ABS, PC/ABS, HIPS
Refrigeration	PS, ABS, PU, PVC
Dishwashers	PP, PS, ABS, PVC

Abbreviations: ABS, acrylonitrile butadiene styrene; HIPS, high-impact polystyrene; PC, polycarbonate; PET, polyethylene terephthalate; POM, polyoxymethylene; PP, polypropylene; PPE, polyphenylene ether; PS, polystyrene; PU, polyurethane; PVC, polyvinyl chloride

3.3 Sorting Processes for Plastic Waste

After postconsumer plastic waste is collected, it is transported to material recovery factories (MRF) and, in a first step, sorted by plastic type. Depending on the type of plastic, sorting methods vary. Although sorting currently is the step in the recycling process that has the largest impact on integrity, it is still very difficult to execute well. Sorting can be done manually or it can be automated. In the following discussion, the main methods used in the MRF in the United States for the different plastics are identified.

3.3.1 Manual Sorting

A simple sorting method is *manual sorting*. It involves visual identification of the plastic type by operators using the resin identification code, shape, color, appearance, and trademark of the plastic. It is very labor intensive and has a possibility of human error. Furthermore, it is still difficult to manually differentiate between the resin types by just visual means.

3.3.2 Automated Sorting

3.3.2.1 Float-and-Sink Sorting

The *float-and-sink* process, or sorting by flotation, in which plastics are sorted by density is one of the most common *automated sorting* processes. The washed and chipped plastics are sent into tubs of water and the pieces that float or sink are separated. This process is fast, inexpensive, and can be considered as a first stage washing of plastic waste. However, as pointed out earlier, most plastics are very similar in density and thus cannot be separated using this process. An overview of the densities of various polymers is given in Table 3.7. [9, 21, 22]

Table 3.7 Polymer Density Ranges (densities of <1 g/cm^3 will float)

Polymer	Density Range [g/cm^3]
Polyethylene terephthalate (PET)	1.330 – 1.400
High-density polyethylene (HDPE)	0.956 – 0.980
Polyvinyl chloride (PVC)	1.304 – 1.388
Low-density polyethylene (LDPE)	0.910 – 0.955
Polypropylene (PP)	0.861 – 0.925
Polystyrene (PS)	1.050 – 1.220

3.3.2.2 Froth-Flotation Sorting

The *froth-flotation* process works similarly to the float-and-sink process. In froth-flotation, the materials to be separated are first treated with a surfactant and then suspended in water. Plastics that would normally sink in water are suspended in the water-surfactant mixture. Then, air is pumped into the system. The air bubbles adhere to some plastics pieces based on their resin type but others are not affected by the air bubbles and so sink to the bottom. The key advantage of this method is to be able to separate PET from PVC.

3.3.2.3 Near-Infrared Sorting

Another promising technology, which was recently developed for high-speed sorting machines, is *near-infrared (NIR) sorting*, which uses a well-established technique for characterizing the type of plastic, infrared light transmission. Plastics absorb light of specific wavelengths unique to their chemical composition, allowing for the identification and separation of different types of plastic.

This technology is used for the automated identification of PET bottles. However, this sorting method is not suitable for identification of dark-colored plastics, adhesives, residues, and plastics with additives. [23, 24]

3.3.2.4 X-Ray Fluorescence

Some plastics, like PET and PVC, have similar densities, and so sorting them must be based on another property in which they differ significantly. The molecular structure of PVC includes chlorine atoms, unlike PET, which does not. *X-ray fluorescence* generates a spectral fingerprint based on a plastic's chemical composition, and, from this, it can be sorted into its resin type. For example, this technology can be applied to the sorting of PVC; X-ray fluorescence detects the chlorine atoms in PVC, and thus provides a basis to separate PVC from other plastics. [25]

3.3.2.5 Laser-Aided Identification

Laser-aided systems identify plastics by shining a laser beam onto the material surface to determine various material properties including absorption coefficient, thermal conductivity, thermal capacity, and surface temperature distribution, which can be used to identify the plastic type. It is not yet being used in recycling facilities.

3.3.2.6 Marker Systems

Marker systems involve marking either the plastic container or the resin itself with something readily detectable. One marker system, developed by Continental Container Corporation, allows for sorting by resin type, color, resin additive package, and package contents. This method is costly since every packaging production line

would need to install a marking system and the recycler would need to install a machine for scanning the marker. An alternative method developed by the Eastman Chemical Company uses a molecular marker to identify the resin type. The cost increase for the addition of the marker system would be relatively low since it would only require recyclers and resin manufacturers to contribute to the costs. However, all of these methods are still, at most, at the proof-of-concept stage in development.

3.4 Plastic Degradation Mechanisms

In general, polymers are stabilized only for processing and a first lifetime of use and not for reprocessing and a second lifetime of use. This is particularly true for plastic film packaging material made out of polyolefins, such as PP and PE, which usually has a short lifetime.

Degradation of a polymer results from exposure to factors like heat, mechanical stress, oxygen, and UV light. For example, polyethylene films used in commercial packaging suffer from oxidative and photo-oxidative degradation due both to processing and to use. Reprocessing can induce mechanical, thermal, and thermal oxidative degradation.

The degradation process leads to changes in the polymer's structure, typically characterized by fragmentation, or scission, of the macromolecular chain, which results in changes in the properties of the polymer. Radical chain reactions, such as formation of hydroperoxides and cross-linking, also occur during degradation and also result in changes in the polymer's structure. During processing, both chain scission and cross-linking reactions take place, which lead to increased fractions of lower molecular weight polymer chains and increased chain branching, respectively. Thus, fragmentation, self-termination, and chain-transfer reactions of the polymer radicals are occurring during degradation. [26] Polyolefins often undergo oxidative degradation.

During processing and lifetime use, the material is exposed to heat, mechanical stresses, oxygen, and UV radiation. Depending on the polymer structure and the processing conditions, these stresses lead to more or less degradation. In general, the effects of the degradation processes can be categorized as:

- Change in molecular weight and molecular weight distribution, leading to a change in viscosity
- Formation of cross-links and branched chains
- Formation of oxygenated compounds and unsaturated compounds

A knowledge of the degradation kinetics of polymers is important for designing the recycling process and the processes for creating new products out of recycled material. During the recycling process, the *melt viscosity* and *flow behavior* of materials change, leading to a change in the processing settings and sometimes difficulty in reprocessing. The recycled products can further have inferior mechanical properties compared to virgin material. The thermal stability is not affected for most polymers.

The mechanism of degradation, which can be classified as *mechanical degradation*, *thermal degradation*, *thermal oxidative degradation*, or *photo degradation*, depends on the method used for polymerization. Furthermore, the degree and type of degradation depend on the processing conditions and on the nature of the polymer.

3.4.1 Mechanical Degradation

The chemical bonds of the carbon-carbon polymer backbone break when shear and tensile stresses (mechanical stresses), induced by shearing and stretching in the extrusion process, exceed the intramolecular bonding forces leading to mechanical degradation. The mechanical stresses increase with increasing chain length and decreasing distance to the center of the chain. As a result, chain scission increases for longer polymer chains and is most likely to occur in the chain center. In addition, a reduction in temperature decreases the flexibility of the chain segments, which also leads to an increase of these mechanical stresses. [27, 28]

3.4.2 Thermal Degradation

Thermal degradation is induced by heat. Heating of a polymer results in an increase of its internal energy causing the following effects: First, the rate of rotation of any freely moving group in the polymer increases, weakening the intermolecular forces. Second, the vibrational energy of the polymer bonds increases, leading to bond breaking along the chain according to a statistical pattern and the formation of two radicals for each end of the broken bond. Finally, the mobility of absorbed species increases, enabling their migration through the polymer and hence their reaction with energetic sites. [29, 30]

3.4.3 Thermal Oxidative Degradation

Thermal oxidative degradation of polymers is caused by autoxidation. The reaction follows the same steps known for polymerization: initiation, propagation, and termination. Depending on the dominating reactions during autoxidation, both a decrease or an increase of the average molecular weight of the polymer can occur. While β-scission and fragmentation cause a decrease of the molecular weight, an increase can be observed for recombination. [31, 32, 33]

3.4.4 Effect of Degradation on Processing and Service-Life Properties

It is important to analyze the effect of degradation on the processing parameters as well as the service-life properties of the desired product. Based on the product requirements, the number of reprocessing events has to be limited or the amount of virgin material mixed into the recyclate has to be adjusted to reduce the dilution effect. In the following, data for these property changes is presented for some common plastic materials.

As already mentioned, PET is the most widely recycled polymer due to the ease of its separation in the recycling stream. The degradation mechanism of PET is chain scission, which can be seen from the reduction of molecular weight from virgin PET to recycled PET over three extrusion cycles (Figure 3.3 *left*). Even though the chain length is reduced significantly, the mechanical properties are only slightly affected as can be seen in Figure 3.3 *middle* and *right*. Both tensile strength and impact strength show a small reduction over the three extrusion cycles.

In industrial practice, virgin PET is often used to refresh the recyclate. The mixing ratio and resulting dilution (Figure 3.1) depends on the desired product properties. Figure 3.4 shows the change of the molecular weight and impact strength for different mixing ratios. The graph in Figure 3.3 *left* shows that the molecular weight of 100 % recycled PET (same as reprocessing step 2 in Figure 3.3) is about 20 % lower than virgin PET (same as reprocessing step 1 in Figure 3.3). The blended materials follow the linear trend based on the mixing ratio of virgin to recycled PET. Both data sets show the feasibility of reprocessing and the ability of refreshing with virgin material to slow down the degradation process significantly.

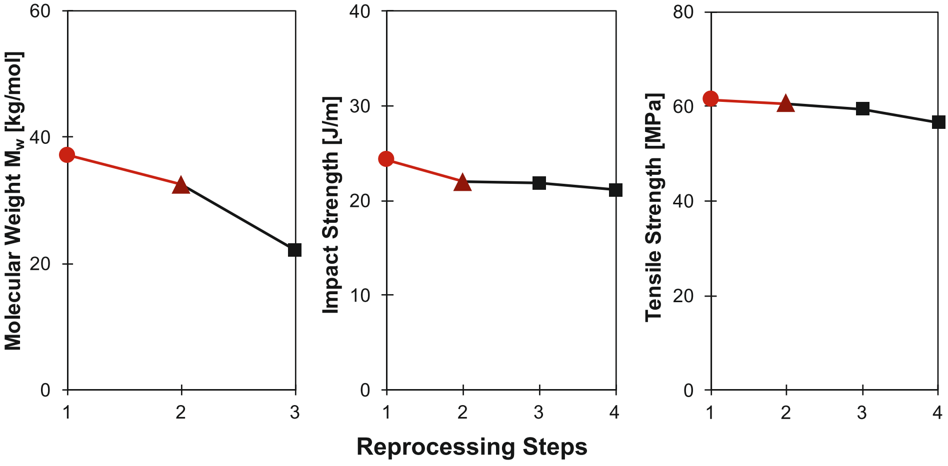

Figure 3.3 Weight-averaged molecular weight and mechanical properties of virgin polyethylene terephthalate (PET) and recycled PET as a function of the number of reprocessing steps (extrusion) [34]

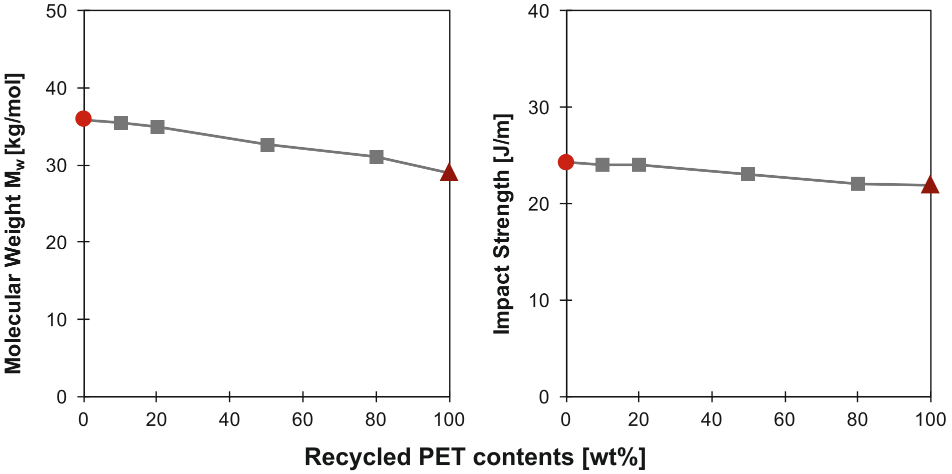

Figure 3.4 Weight-averaged molecular weight and impact strength of virgin PET (polyethylene terephthalate)/recycled PET blends during the first extrusion step [34]

A decrease in molecular weight leads to a reduction in melt viscosity, which is a measure of the resistance to flow, and thus affects the processing behavior. Therefore, the process settings have to be adjusted accordingly. For example, the injection pressure can be lower. However, if the mixing ratio is kept constant, the material is in a steady state and adjustments are very minimal. Nevertheless, in certain cases the processibility of materials is affected so strongly that the material cannot

be processed with the same process. The stretch-blow molding process is an example of such a sensitive process.

High-impact polystyrene (HIPS) is among the promising materials for recycling since it shows only a small variation in melt viscosity. Figure 3.5 shows the change in viscosity with melt flow index (MFI), which indicates how much material in grams flows through a small capillary within 10 min. The larger the MFI values, the lower the viscosity. The MFI increases slightly with an increasing number of reprocessing steps. The increase in MFI during this continued reprocessing without refreshing is caused by chain scission degradation due to thermal and mechanical degradation.

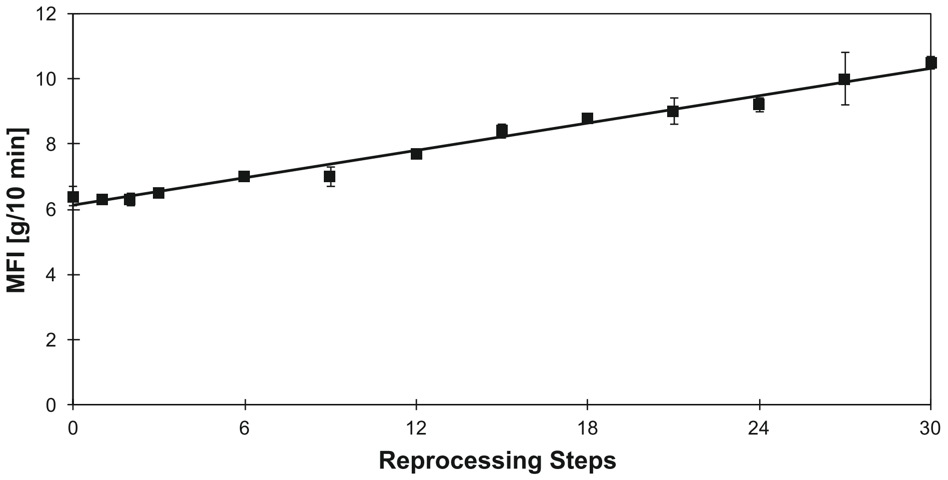

Figure 3.5 Melt flow index (MFI) of high-impact polystyrene (HIPS) as a function of the number of reprocessing steps (injection molding) [35]

Figure 3.6 shows the discoloration of HIPS due to degradation during the various reprocessing steps. Furthermore, it illustrates the resulting changes in the tensile properties of HIPS. The degradation leads to an increase of tensile stress at break and a reduction of elongation at break over multiple reprocessing steps. Thus, the material behavior changes from more ductile to brittle, which needs to be known for product design. [35, 36]

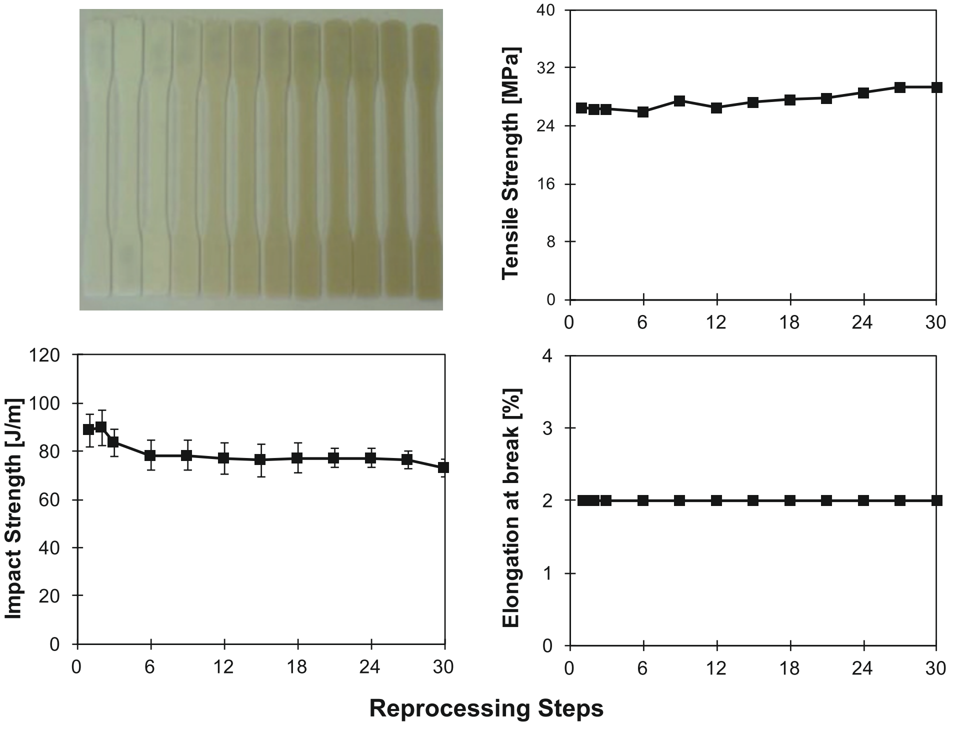

Figure 3.6 Discoloration and mechanical properties of high-impact polystyrene (HIPS) as a function of the number of reprocessing steps (injection molding) [35]

Instead of chain scission, degradation can lead to uncontrolled cross-linking of polymer chains for some polymers. This can be observed in the data of LDPE obtained over 100 extrusion cycles (Figure 3.7). Here, the complex viscosity of LDPE *(left)* increased with the increasing number of extrusion cycles. The cross-linking in LDPE chains occurs due to the formation and reaction of carbon radicals. The same trend was observed in the decreasing MFI values *(right)*. It is important to note that the reprocessing of LDPE is only significantly affected after the 40th extrusion cycle. Using a refreshing rate of less than 10 % of virgin material results in a fraction of < 1 % of 40 times processed material according to Equation (3.1) and thus has no practical relevance in this case. [5]

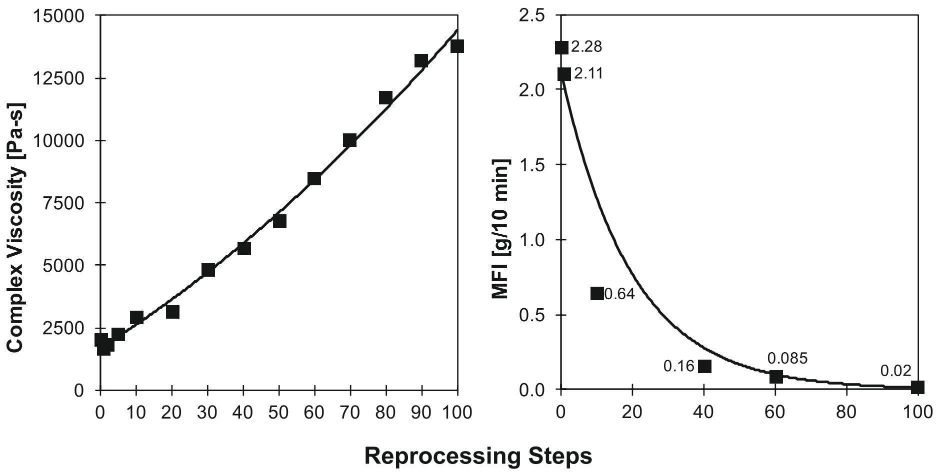

Figure 3.7 Complex viscosity and melt flow index (MFI) of low-density polyethylene (LDPE) during 100 reprocessing steps (extrusion) [5]

In addition to synthetic polymers, more and more biopolymers, which are made from renewable resources, are being recycled. One major market for biopolymers is plastic packaging. Polylactic acid (PLA), which is biodegradable under very specific conditions, is such a polymer. Since the conditions for chemical recycling can only be achieved in specific recycling facilities, the mechanical recycling of PLA is of interest as well. Figure 3.8 shows that multiple injection molding cycles cause degradation, which can be seen in the significant change in MFI. However, the impact strength of PLA remained unchanged even after six cycles, which indicates good recyclability in regards to the service-life properties of the plastic.

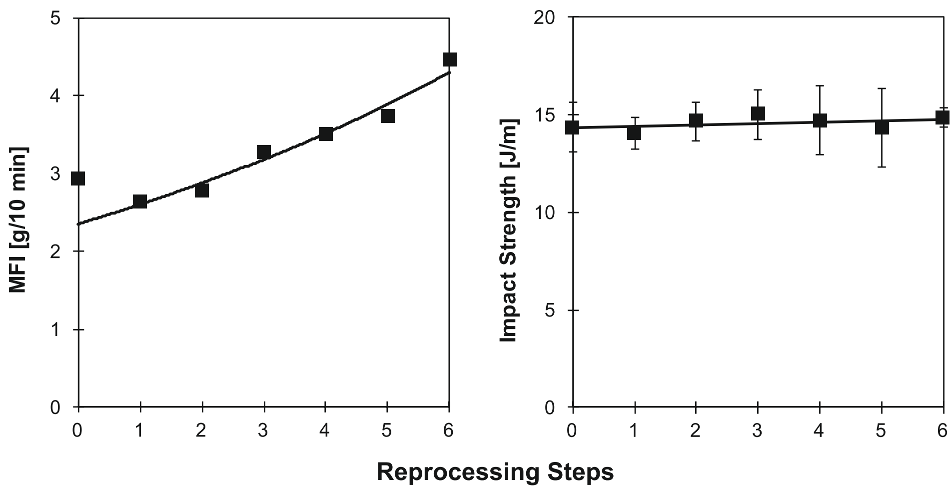

Figure 3.8 Melt flow index (MFI) and impact strength of polylactic acid (PLA) as a function of the number of reprocessing steps (injection molding) [37]

Polycarbonate (PC) is another material with a high potential for recycling. It is identified as plastic number 7 and mostly found in electronic waste. Recycling of PC is important to prevent the leaching of bisphenol A in PC into landfills. Figure 3.9 illustrates the effect of repeated injection molding cycles on the mechanical properties of PC. Tensile strength and modulus remain unchanged after five cycles. In contrast, the elongation at break and the toughness decrease with the increasing number of reprocessing cycles. The toughness of PC shows an approximately 42 % reduction from the virgin resin to the final reprocessing steps, whereas the elongation at break shows a 37 % reduction. [38]

Again, comparing the property changes after multiple processing steps of 100 % of the material (Figure 3.9) with the change in refreshed material, reveals almost unchanged behavior during refreshing. Figure 3.10 shows the same mechanical properties, but for different mixing ratios of virgin and recycled PC. It can be seen that the material follows the linear trend depending on the mixing ratio, similar to the observations with PET.

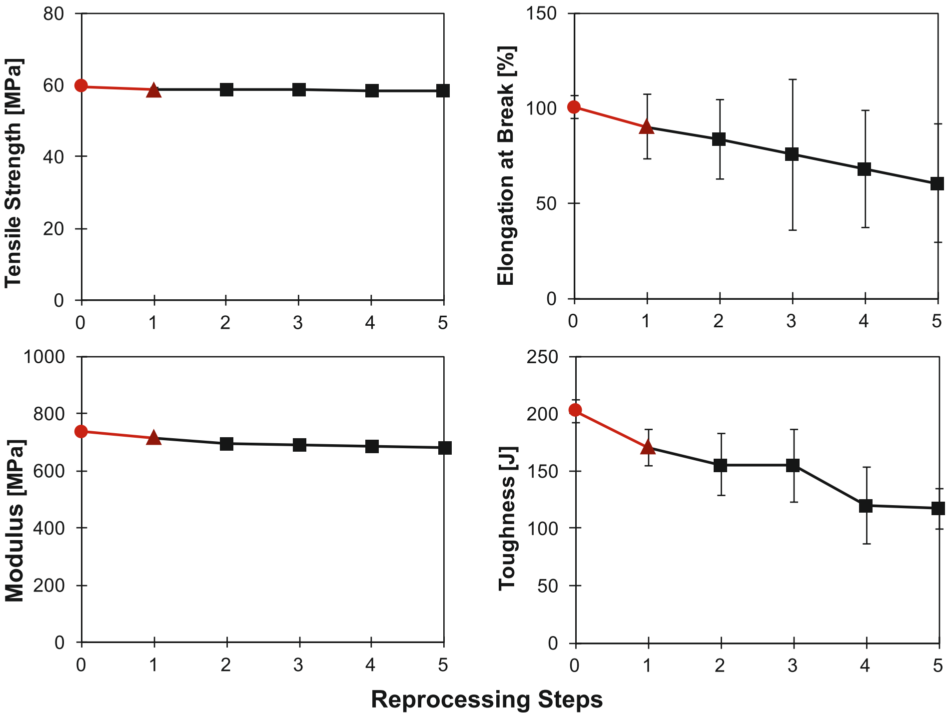

Figure 3.9 Mechanical properties of polycarbonate (PC) as a function of the number of reprocessing steps (injection molding) [38]

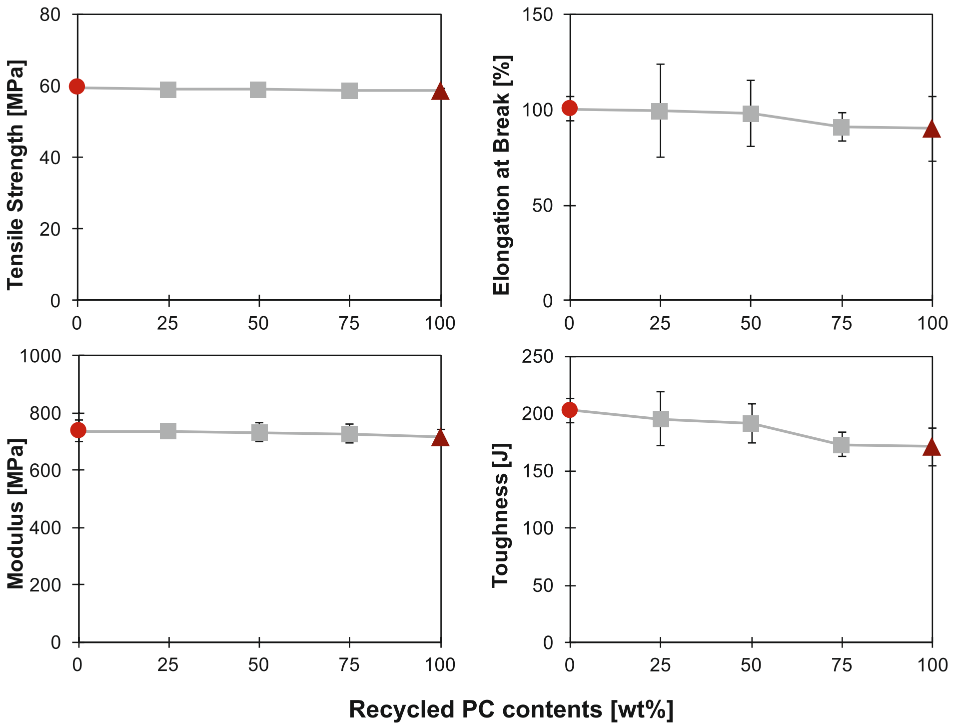

Figure 3.10 Mechanical properties of virgin polycarbonate (PC)/recycled PC blends as a function of the percentage of recycled PC, in the first reprocessing step [38]

For most technical products, the plastics are reinforced with fillers such as fiberglass (GF). One common polymer material is polyamide 66 (PA66). In these materials the fiber length distribution was found to control the performance as will be explained with the example of recycled fiberglass/PA66 composite. The recycling of manufacturing scrap leads to the deterioration in the mechanical properties due to the fiber shortening during compounding and the first injection molding cycle, as presented in Figure 3.11. Although the change in properties is significant, it can be seen that refreshing of recycled material with virgin fiberglass/PA66 has a significant impact on the change in properties. Figure 3.12 shows that the degradation of properties can be minimized with the addition of virgin material. [39, 40]

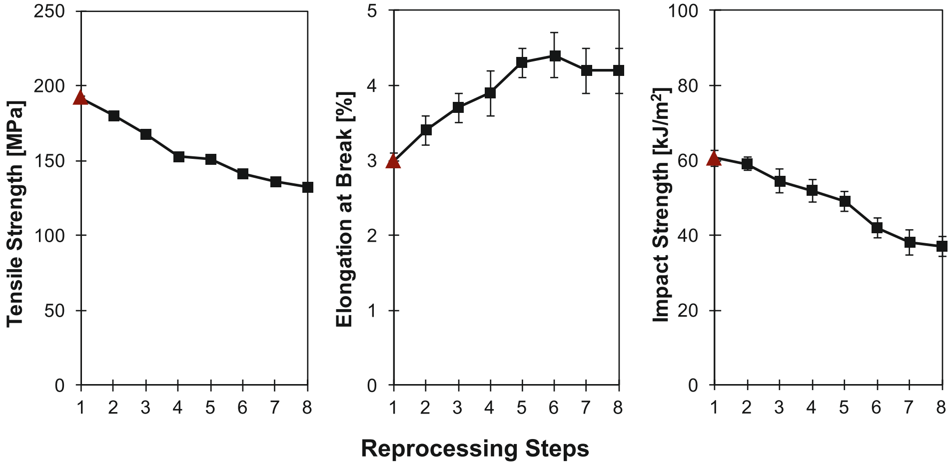

Figure 3.11 Mechanical properties of recycled fiberglass/PA66 composite as a function of the number of reprocessing steps (injection molding) [39, 40]

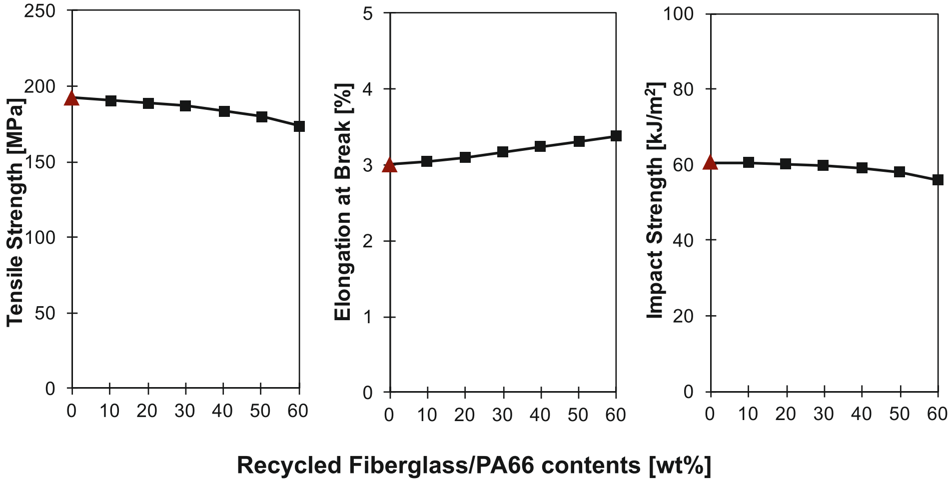

Figure 3.12 Mechanical properties of fiberglass/PA6 composite as a function of the percentage of recycled composite, in the first reprocessing step [39, 40]

3.5 Contaminants

Plastics are hard to clean due to the penetration of contaminants into the polymer matrix. Composites and mixed plastic waste are especially difficult to separate into the different plastic types, which all require different reprocessing techniques and settings. [23]

There are a number of contaminants that can significantly obstruct the recycling process and result in severe deterioration of performance of recycled material. During the extrusion process in which the recycled material is subjected to high temperatures and mechanical stresses, the presence of contaminants may lead to hydrolytic and thermal degradation and subsequent decreases in both the molecular weight and viscosity of the plastic.

In the case of the PET recycling process, the common contaminants are acids and acid-producing compounds, for example, which arise when PET and PVC are mixed. Hydrochloric acid produced from PVC acts as catalyst for chain-cleavage reactions. Likewise, elevated water content can lead to chain cleavage through hydrolysis. Most water contamination comes from the washing process and can be removed by proper drying. Dyes and coloring agents are another source of contamination, leading to undesirable, mostly brownish color in the recycled plastic. Finally, contaminants, such as acetaldehyde (a natural degradation product of PET) and other contaminants arising from misuse of PET by consumers (such as for storage of fuel, pesticides, and other dangerous materials) are potential health hazards in recycled PET products. [23]

3.6 Conclusion: Technical Feasibility of Plastics Recycling

In summary, the recyclability of plastic waste depends on the origin of the waste as well as the sensitivity of the polymer(s) to degradation. In most cases, preconsumer waste (manufacturing scrap) can be reprocessed with little deterioration of properties. The property changes can even be minimized or extended by refreshing the regrind waste with virgin plastic. Although the processing properties such as viscosity are affected, the changes in service-life properties such as mechanical performance are often negligible. In industrial production, the regrind proportion can be as high as 30 %.

The recycling rate of postconsumer waste, however, is low. This is due to technical limitations such as the limited availability of clean and unmixed postconsumer

plastic waste. This rate can only be increased when the recycling process becomes an integral part of the product design process and both the manufacturer and consumer take an active part in the improvement of that process.

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4 Economic Analysis of Plastic Waste Handling

The first step to improve plastic waste handling is analyzing the procedures involved from an economic point of view. In order to do so, we will first review the *fundamentals of economic efficiency*. Afterwards, using these principles, we will analyze the economic efficiency of landfilling, incineration with energy recovery, and recycling, and then compare them.

4.1 Fundamentals of Economic Analysis

4.1.1 Economic Efficiency Calculation

In theory and practice, a variety of techniques to evaluate and compare economic efficiency exist. They are derived from classic capital budgeting, which considers the advantage of an investment with known acquisition costs and was designed for helping select the best long-term investments for financing. [1, 2]

Nowadays, capital budgeting also includes the valuation of companies and processes, via the so-called *economic efficiency calculation*. Its purpose is to measure the profitability of a company or process in order to derive an asking price for that company or process. It also enables the comparison of the efficiency of different processes with each other. [1] Therefore, the economic efficiency calculation can be used to compare landfilling, incineration with energy recovery, and recycling from an economic point of view.

In economic theory and entrepreneurial practice, there are two main approaches to making this calculation:

- *Static methods* determine the economic efficiency under constant framework conditions and explicitly consider only one time period, which is assumed to be representative for all such time periods. A typical time period under review is a year. The data for this time period is obtained by considering the whole planning

period (in general the expected lifetime of an investment) and finally deriving the average cost and profit data for the time period under review. [1, 3]

- *Dynamic methods* also analyze the influence of the time of investment on the economic efficiency. By discounting payments and earnings using identical benchmarks via compound interest calculations, the impact of both the amount and the time of the investment on the profitability are considered. These methods are in general closer to reality, which is a clear advantage over static methods. If, for example, an investment in a new machine needs to be analyzed, dynamic methods enable one to include factors such as learning effects and decreasing manufacturing costs, which have a big impact on the economic efficiency. [1, 4, 5, 6]

The problems of dynamic methods are the data collection and the uncertainty of future payments, earnings, and market behavior (e. g., inflation), which can lead to inaccuracies in the results. For this reason, static methods are still more frequently used. In practice, static and dynamic methods are often used in combination, since companies do not want to rely on only one of these methods alone. [1]

In the following, static methods will be used to analyze economic efficiencies of plastic waste handling.

4.1.2 Static Economic Efficiency Calculation

As mentioned in Section 4.1.1, static economic evaluations consider only one average period (e. g., a year), which is assumed to be representative for the lifetime of the process. These methods focus on a pure financial measure of the profitability, which can be thought of in two ways:

- *Absolute profitability:* Investing in and/or running a business or process is economically better than not running it.
- *Relative profitability*: Investing in and/or running business A or process A is economically better than investing in and/or running business B or process B.

Static methods assume constant payments and earnings and do not take into account the changing value of cash over time. In theory, there are four methods to statically analyze the economic efficiency. These methods are built on each other, but differ in regard to their target measures. [1, 3, 7]

4.1.3 Profit Comparison Method

The *profit comparison method (PCM)* used in this chapter computes the profit of plastic waste handling processes by subtracting the total costs of these processes from the total revenues. The two types of profitability considered are:

- *Absolute profitability:* the profit of a waste handling procedure
- *Relative profitability:* the profit of a particular waste handling procedure as compared to the profit of another waste handling procedure

The costs included in the calculation are: [3, 5]

- *Initial investment cost*
- *Capital cost*: depreciation and interest
- *Fixed costs*: lease rental charges and/or land costs, fixed salaries, and setup costs
- *Variable costs*: costs of material and tools; direct labor costs; energy, electricity, and water costs; maintenance costs; and taxes

For plastic waste handling, where the revenue comes from depends on the procedure: waste-to-energy (WTE) plants derive revenue from selling electricity produced, and recycling plants from selling the recycled pellets or plastic products.

After summing up all costs and revenues for each plastic waste handling procedure, the average cash flows for one representative time period or unit need to be determined to estimate the profit of each procedure. Here the absolute and relative profitability will be determined for handling of **1 ton (t) of plastic waste**. [3]

4.2 Economic Analysis of Landfilling

As described in Section 1.2.1 landfills are required to comply with federal regulations, which include among other things location restrictions, design specifications, operating standards, and closure requirements. These regulations have a great influence on the cost to build, operate, and finally close landfills. [8, 9]

Besides regulatory issues, *landfill costs* are site specific; thus, they vary based on factors such as terrain, soil type, climate, site restrictions, and amount of waste disposed. For economic analyses, the costs of landfills are mainly grouped into four categories: [9, 10, 11, 12, 13]

- Construction costs
- Operations costs
- Closure costs
- Postclosure and maintenance costs

To analyze the profit of landfilling, a large landfill with a footprint of 365.76 m × 365.76 m (1,200 ft × 1,200 ft, approximately 33 acres) will be analyzed. As already mentioned in Chapter 2.2.1, the trend in the United States is towards large landfills. The average landfill has a yearly disposal of 70,000 t (for a total of 134.40 Mt per year on 1,908 landfills). The landfill considered here has a yearly disposal of 200,000 t, or 500 to 600 t daily.

Although most of the literature values were based on the U.S. customary or imperial system (feet [ft], acres), the Appendix (Chapter 8) includes calculations both for the imperial and metric system. Table 4.1 summarizes important assumptions that are required for the economic analysis. [11, 12, 13]

Table 4.1 Assumptions for Economic Analysis of Landfill

Lifetime [years]	11	
Postclosure care period [years]	30	
Final surface grades [acres] | [hectares (ha)]	34.00	13.76
Bottom of landfill [acres] | [hectares (ha)]	33.50	13.56
Disposal capacity constructed acre [yd^3/acre] | [m^2/m^3]	60,000	19.39
Total capacity [yd^3] | [m^3]	4,000,000	3,058,104
In-place density of waste [t/yd^3] | [t/m^3]	0.55	0.72
Weight capacity per acre [t/acre] | [t/m^2]	33,000	49.42
Waste per day [t]	500 – 600	
Waste per year [t]	200,000	
Total weight capacity [t]	2,227,500	
Total overall weight of landfill (11 years) [t]	2,200,000	

To calculate the profit of landfilling, the costs must be considered first. Therefore, the total overall costs of the 13.35 ha (33 acres) landfill will be summarized and finally divided by total weight of municipal solid waste (MSW) disposed over the landfill's lifetime (2,200,000 t).

The first cost category is *construction*, which is divided into that for the support facility and that for the liner construction. Based on the 365.76 m × 365.76 m (1,200 ft × 1,200 ft) footprint, the landfill's access road has a length of approximately 381.00 m (1,250 ft), in total 1,524.00 m (5,000 ft). Including possible setbacks for the landfill from the property line required by the state regulatory agency and additional area required for other facilities, the security fence has a length of 1,828.82 m (6,000 ft). The costs per foot or per meter of road and fence are given in the Appendix in Table 8.1 (imperial) and Table 8.2 (metric), respectively. The space and costs for support buildings, including office buildings, maintenance buildings, shacks, and tool sheds, are found in Table 8.1 (imperial) and Table 8.2 (metric). In addition, every landfill plant needs one modular truck scale and an associated computer system. [13]

The bottom of the landfill with an area of 13.56 ha (33.5 acres) needs a liner and leachate system. After performing a site survey, the bottom area first needs to be cleared and grubbed. Once completed, liner construction grades and elevations are established by excavation. It is assumed that the landfill has a minimal structural fill berm constructed along the landfill's perimeter to provide anchoring for the

liner elements and structural toe stability for the final waste slope. After establishing the base grades, the landfill's liner and leachate management system, including clay liner, geomembrane, geocomposite, and granulator soil, is constructed. Besides these physical acts of construction and installation, management and quality oversight are required, typically done by independent third-party consultants. The detailed statement of costs is also found in Table 8.1 (imperial) and Table 8.2 (metric).

On average, the overall *construction costs* for the completed landfill total **$21,582,950**, as seen in Table 4.2. [11, 13]

Table 4.2 Construction Costs of Landfill

	Minimum	Maximum	Average
Support facility construction [$]	1,175,300	1,790,600	1,482,950
Liner construction [$]	11,256,000	28,944,000	20,100,000
Total construction costs [$]	**12,431,300**	**30,734,600**	**21,582,950**

Operating costs include staffing, utilities, equipment operations, leachate disposal and treatment, scale operations, paperwork, record keeping, billing, engineering staffing, environmental monitoring, and daily cover applications. Assuming waste processing of 200,000 t per year, which is equivalent to waste receipt of 500 to 600 t per day, this landfill would at minimum require a front-end loader for onsite hauling of bulk material and small construction tasks (e.g., CAT 950H), a bulldozer equipped with a trash rack to spread dirt and waste (e.g., CAT D7), and a steel-wheeled compactor to compact the waste and achieve maximum possible in-place density (e.g., CAT 826G). Additional equipment such as water spray trucks (for holding dust down), a scraper, a backhoe, several pickup trucks, and a road grader would also be needed. [14, 15, 16]

The salaries of all employees are based on average U.S. values. Summarizing all operations costs, the yearly operations costs amount to **$1,567,198**, or **$17,239,178** after 11 years, as presented in Table 4.3. Detailed operations cost calculations are shown in Table 8.3 in the Appendix. [11, 13, 17, 18, 19, 20, 21]

Table 4.3 Operations Costs of Landfill

Operations [$]	1,357,198
Leachate collection and treatment [$]	30,000
Environmental sampling and monitoring [$]	60,000
Engineering services [$]	120,000
Total operations costs per year [$]	**1,567,198**
Total operations costs of landfill (11 years) [$]	**17,239,178**

After use for disposing of waste for 11 years, the landfill must be closed. Due to sloping, the final surface grades needing capping and covering are approximately 13.76 ha (34 acres). The closure process starts with surveying the surface to receive a final cap and cover. Once this step is done, construction of the final cap and cover begin, which includes a geomembrane cap and vegetative soil, seed, mulch, and fertilizer. To prevent air and soil pollution, run-off and gas control systems are installed. Besides these physical acts of construction and installation, management and quality oversight are required. A detailed cost breakdown is shown in Table 8.4 (imperial) and Table 8.5 (metric) in the Appendix. Summarizing the mentioned categories, *closure costs* of the considered landfill range from **$7,718,000** to **$11,084,000**, with an average total cost of **$9,401,000**. [11, 12]

Once a landfill is closed, RCRA prescribes the care for and maintenance of landfills for a minimum of 30 years. *Postclosure and maintenance costs* are mainly divided into site security maintenance, landfill cover, and mechanical systems maintenance, monitoring wells and gas probes, and environmental monitoring. For 1 year, these costs range between $72,182 and $100,232 for the complete landfill, which is shown in Table 8.7 (imperial) and Table 8.8 (metric) in the Appendix. Over 30 years, the complete postclosure and maintenance costs add up to **$2,586,210**.

To finally calculate the cost per ton of plastic waste, the total costs of all categories are summed up and divided by the total waste disposed of in the landfill (2,200,000 t).

Table 4.4 Total Costs of Landfill

Category	Minimum	Maximum	Average
Construction costs [$]	12,431,300	30,734,600	21,582,950
Operations costs [$]	17,239,178	17,239,178	17,239,178
Closure costs [$]	7,718,000	11,084,000	9,401,000
Postclosure/maintenance costs [$]	2,165,460	3,006,960	2,586,210
Total costs [$]	**39,553,938**	**62,064,738**	**50,809,338**
Total costs per ton [$/t]	**17.98**	**28.21**	**23.10**

As shown in Table 4.5, the total average cost of landfilling 1 t of plastic waste is **$23.10**.

The revenue from landfilling 1 t of plastic waste is **$0.00**. Nevertheless it is possible for landfill owners to receive revenue by selling carbon credits, selling electricity generated from landfill gas (LFG) to the local power grid, or selling LFG to a direct end user or pipeline. However, the revenue received represents a negligible percentage of the operating costs of a landfill and is therefore set to $0.00. [9, 22]

Applying the profit comparison method, the last step is to calculate the overall profit of landfilling 1 t of plastic waste.

Table 4.5 Total Profit per Ton of Plastic Waste for Landfill

	Minimum	Maximum	Average
Revenues per ton [$/t]	0.00		
Costs per ton [$/t]	17.98	28.21	23.10
Profit per ton [$/t]	**−17.98**	**−28.21**	**−23.10**

Subtracting the cost per ton from the revenue per ton, the average profit of landfilling plastic waste is **−$23.10 per ton**. This means landfilling is not absolutely profitable (profit < $0.00).

The figure of −$23.10 per ton is the costs for a big landfill. The bigger the landfill, the smaller the relative costs. If the average waste per day were for example only 450 t, but the landfill is constructed for 550 t per day, the yearly waste would be around 165,000 t and after 11 years only 1,815,000 t. The landfill would have to be closed due to national regulations; the total costs would be the same and the costs per ton would be on average **$28.00**.

Another big cost factor that is not included in the calculations is the costs for cleaning up landfills in cases of accidents. Since most of the landfills are not cleaned up afterwards due to high costs, the experiences with these costs are comparably low. But some examples can be found and allow us to estimate this cost. In 2008, a dike failed at the Tennessee Valley Authority's Kingston Fossil Plant. A total of 5.4 million yd^3 of coal ash cascaded into the Emory and Clinch Rivers and smothered about 300 acres of land. Up until 2015, about **$1.2 billion** were spent to clean up the area, and more will probably follow. This is about 19 times more than the maximum costs for the landfill we are considering here. [23]

In the future, these costs for landfilling will probably increase substantially. Since land is becoming a more and more scarce resource, the costs for land and construction are likely to rise. This trend can be seen in the tipping fee, also called the gate fee, of landfills in the United States. Between 1985 and 2010, this fee increased from **$8.22** to **$43.99** per ton of waste. This price should approximately represent the costs of landfilling (including an overhead and a profit margin). The increase was likely caused by states implementing RCRA Subtitle D regulations or their state's equivalent. The costs caused by accidents or cleaning also increase this fee. The amount of the tipping fee further shows that the calculated costs for a large landfill are relatively low and that the average costs of landfilling in the United States are probably higher than **$23.10 per ton**. But since the focus now and in the future in the United States is on large landfills, the analysis in this book is also focused on large landfills. [13, 22, 24, 25]

4.3 Economic Analysis of Incineration with Energy Recovery (Waste-to-Energy Facilities)

As already mentioned in Section 1.2.2, the most widespread type of waste-to-energy plants in the United States are mass-burn facilities (64 out of 84), and therefore we use an example of one for this profitability analysis. A plant diagram of a typical mass-burn facility is shown in Figure 1.3. [26]

The profit analysis of mass-burn facilities is mainly split into three categories: [27]

- Investment costs
- Operating and maintenance costs
- Revenues from sale of heat and electricity generated

The actual profit for a waste incineration plant depends on a wide range of factors, especially the capacity of the plant and the type of energy production. The facility considered here is a cogeneration facility and produces both heat and electricity. Since new WTE facilities have an expected lifetime of 35 years, this period was assumed for the facility under consideration here as well. As in the landfill analysis, the complete profit of plastic combustion over the facility's lifetime is summed up and divided by the total plastic waste burned (3,500,000 t). The important general assumptions of this analysis are shown in Table 4.6, and in more detail in Table 8.8 in the Appendix. [28, 29]

Table 4.6 Assumptions for Economic Analysis of Waste-to-Energy (Mass-Burn) Plant

Lifetime [years]	35
Yearly waste capacity [t]	100,000
Total waste capacity (35 years) [t]	3,500,000
Steam generator efficiency [%]	80
Percentage of plastic in MSW [%]	12.8
Dollar–Euro exchange rate [$/€]	1.2125
Purchasing power parity (PPP) conversion factor of Croatia	0.6

Data for *investment costs* was taken from a waste-to-energy plant in Croatia, since this was the only comprehensible data available. To realistically transfer this data to the U.S. market, it first needed to be converted from dollars to Euros at an average for the last 17 years of **$1.2125** per Euro. [30]

Furthermore, the prices were adjusted using the *purchasing power parity (PPP)* conversion factor, which represents the number of units of a country's currency required to buy the same amount of goods and services in that country as a U.S.

dollar would buy in the United States. The PPP conversion factor of Croatia was consistently 0.6 over the last 15 years and therefore is used for these calculations. [31]

Investment costs vary substantially with respect to several factors, including the design of the WTE plant, its capacity, and the local infrastructure. Construction of a road, a weighing area, and waste reception storage is necessary. The combustion chamber-steam generator system includes a system for feeding waste into the combustion chamber, an air supply for the combustion chamber, a combustion chamber, ash removal and storage, flue gas channels, and a steam generator with steam output. The water and steam system consists of a water treatment facility, an air-cooled condenser, and a condensation turbine. Flue gas cleaning, which represents an important part of the overall waste combustion process, is ensured by a flue gas cleaning system involving a semi-dry treatment, a bag filter, and a selective noncatalytic reduction (SNCR) system. Additional initial costs are design, construction, electromechanical installations, and other smaller costs. Summarizing all these costs, the total investment for the WTE plant amounts to **$113,781,924**, as shown in Table 4.7 and in more detail in Table 8.9 in the Appendix. [29]

Table 4.7 Investment Costs of Waste-to-Energy Plant

Infrastructure and waste storage [$]	9,296,569
Combustion system and steam generator [$]	39,409,370
Water and steam system [$]	16,167,946
Design [$]	4,041,986
Construction [$]	14,146,953
Electromechanical installations [$]	10,104,966
Other investment costs [$]	12,125,960
Flue gas cleaning system [$]	8,488,172
Total investment costs [$]	**113,781,924**

Operating and maintenance costs are analyzed annually and divided into personal salaries, operation and maintenance costs as well as heat and electricity costs. The plant runs three shifts daily. Per shift, 15 workers, 5 environmental engineers, 3 maintenance engineers, and 1 facility manager are required. Salaries used for the calculations are average U.S. salaries. The annual salaries of all personnel amount to $3,507,126. Maintenance costs of the combustion system are proportional to the waste flow and estimated at 3% of total investment costs. Additional annual machine and emission costs are process water, natural gas, bottom ash disposal, and bag filter residues costs. Total annual machine and emission costs are $10,190,980. Assuming electricity consumption of 0.1 MW/t_{waste} with a price of $0.0996 per kWh and a heat consumption of 0.05 MW/t_{waste} with a price of $0.0048 per kWh, the annual heat and electricity costs are $111,600. Operating

and maintenance costs add up to $ 13,809,706 per year and $ 483,339,715 after 35 years, as presented in Table 4.8. A more detailed calculation is provided in Table 8.10 in the Appendix. [21, 29, 32, 33, 34, 35]

Table 4.8 Operating and Maintenance Costs of Waste-to-Energy Plant

Personnel salaries per year [$]	3,507,126
Machine and emission costs per year [$]	10,190,980
Heat and electricity costs per year [$]	111,600
Yearly operating and maintenance costs [$]	**13,809,706**
Overall operating and maintenance costs [$]	**483,339,715**

The revenues from plastic combustion come from selling the electricity and heat produced by these plants. These revenues depend on the average lower heating factor of burned material. Compared to general MSW, the average lower heating value of plastics is high. Based on the composition of plastics in the MSW stream (Table 2.1), the lower heating value of plastics in waste is **36.14 MJ/kg** (detailed calculations are found in Table 8.11 in the Appendix). The general MSW has an average lower heating value of only **15.05 MJ/kg** (detailed calculations are found in Table 8.12 in the Appendix). All values and assumptions necessary for the revenue calculations are presented in Table 4.9. [36, 37]

Table 4.9 Assumptions for Revenue Calculations from Sale of Energy Generated in Waste-to-Energy Plant

Percentage heat of produced energy [%]	75
Percentage electricity of produced energy [%]	25
Energy per cubic meter in gas [kWh/m^3]	12.5
Average lower heating value MSW [MJ/kg]	15.05
Average lower heating value plastic [MJ/kg]	36.14
Costs/Revenue per kWh electricity [$/kWh]	0.0996
Cost/Revenue per cubic ft gas [$/ft^3]	0.0035
Cost/Revenue per cubic meter gas [$/m^3]	0.1236

Assuming a percentage of plastics in MSW of 12.8 %, 12,800 t of plastics waste (out of 100,000 t) are incinerated annually. Theoretically, the energy produced through plastics combustion is therefore 462,650,880 MJ per year, 75 % of which produces heat and 25 % of which produces electricity. Assuming a steam generator efficiency of 80 %, the electricity produced yearly amounts to 25,702,827 kWh, and the heat produced yearly to 77,108,480 kWh. [38]

The average price of electricity for customers in the United States in January 2016 was $ 0.0996 per kWh. If WTE plants produce 25,702,827 kWh/year, annual re-

venues from selling electricity generated by plastics combustion are $2,560,001. Supposing an energy content of 12.5 kWh per cubic meter gas, the generated heat would produce 6,168,678 m^3 of gas per year. With an average gas price of $0.1236 per m^3, annual revenues of selling gas produced by plastics combustion are $762,458.13. [35]

Summing up the revenues of the sale of both the electricity and heat and multiplying it by the plant lifetime of 35 years, total overall revenues of incinerating plastics add up to **$116,286,088**, as shown in Table 4.10.

Table 4.10 Total Revenue from Sale of Energy Generated in Waste-to-Energy Plant

Yearly revenue for electricity [$]	2,560,001
Yearly revenue for heat [$]	762,458
Yearly revenue of plastic waste combustion [$]	**3,322,458**
Total revenue of plastic waste combustion [$]	**116,286,088**

Finally, to calculate the profit from combustion of 1 t of plastic waste, the costs need to be subtracted from the revenues. Therefore, the investment, operations, and maintenance costs are added and divided by total waste burned over the plant's lifetime (3,500,000 t). Then the total revenues of plastic waste combustion are divided by the total amount of plastic burned over 35 years (448.000 t). These calculations result in costs of $170.61 and revenues of $259.97 per ton of plastic waste, which leads to a profit of **$88.96** per ton of plastic waste burned, as shown in Table 4.11.

Table 4.11 Profit per Ton from Combustion of Plastic Waste

Revenues per ton of plastic waste burned [$/t]	259.57
Costs per ton of plastic waste burned [$/t]	170.61
Profit per ton of plastic waste burned [$/t]	**88.96**

The profit of **$88.96** per ton of plastic waste burned is an absolute profit (profit > $0.00). As already mentioned, this value can only be reached theoretically. The calculation assumed that no plastic waste was recycled or treated any other way. Furthermore, in a real scenario, plastic waste would not be combusted separately from other waste. But due to its high average lower heating value, plastic waste combustion results in high energy production and is absolutely profitable.

To review and check the WTE-plant analysis, the profit of combustion of 1 t of MSW was calculated and compared to the average tipping fee of combustion of 1 t of waste in the United States. The costs of burning 1 t of MSW are equivalent to the costs of incinerating 1 t of plastic waste ($170.61). To determine revenues of MSW combustion, an average lower heating value of 15.05 MJ/kg was calculated (see

Table 8.12 in the Appendix). This resulted in a yearly revenue (from heat and gas) of $ 10,808,957, or **$ 378,313,500** after 35 years. Dividing the total revenues by the total incinerated MSW over the plant's lifetime, the revenue from combustion of 1 ton of MSW is $ 108.09.

Subtracting costs from revenues, the total profit of MSW combustion is − $ 62.52 per ton of MSW.

Table 4.12 Profit per Ton from Combustion of Municipal Solid Waste (MSW)

Revenues per ton of MSW [$/t]	108.09
Costs per ton of MSW [$/t]	170.61
Profit per ton of MSW [$/t]	**− 62.52**

The average tipping fee for combustion of 1 t of MSW in the United States is **$ 64.96 per ton** (Table 8.13) and represents approximately the costs of waste combustion. This fee only differs by **$ 2.44** (3.75 %) from the calculated value and therefore indicates reasonable assumptions and calculations of the previous WTE plant analysis. [39, 40, 41]

A factor not being included in the profit analysis is the case of rebuilding a plant: a new plant could be built on the site of the existing WTE plant, which reduces the capital cost for land in the new facility to zero. This is a big economical advantage, especially compared to landfill plants, the land from which cannot be used again after closure for a long postclosure period. [42]

4.4 Economic Analysis of Plastics Recycling

The third plastic handling method is *recycling*. Figure 4.1 shows the plastics recycling process beginning and ending with the consumer.

After plastic is thrown away and collected within the single recycling stream, material recovery facilities (MRF) sort the material into the seven plastic recycling groups shown in Table 3.1. [43]

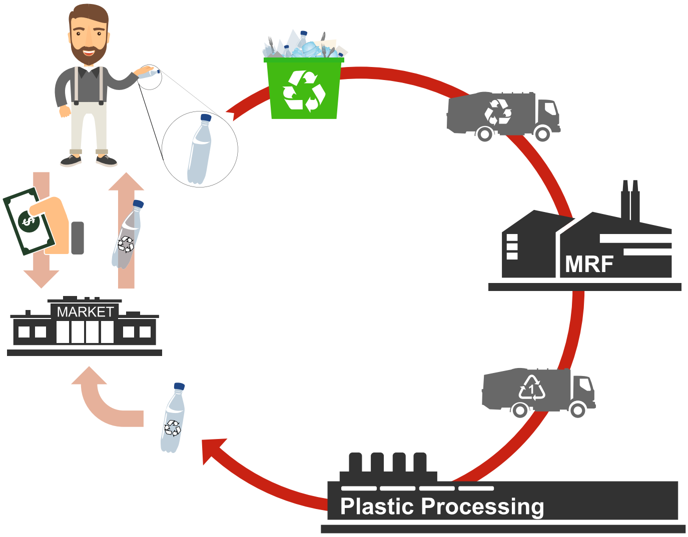

Figure 4.1 Overview of the plastics recycling process

The higher the resin number, the harder the recycling of that plastic. In the MRF, plastics are sorted into three groups: first, number 2 plastic (HDPE) is sorted out manually and next, number 1 plastic (polyethylene terephthalate [PET]) is optically separated from numbers 3 to 7 plastics with an automated IR detector. Due to its good recycling properties, number 1 plastic is the most valuable and at present the only plastic in the United States that is recycled, reprocessed, and resold as pure material in significant quantities. Consequently, the economic analysis of the plastic recycling process in this book will be based on PET recycling.

There are three steps to the economic analysis of the profitability of PET recycling that will be analyzed in the following:

- The cost of material recovery in the MRF (Section 4.4.1)
- The cost of plastic reprocessing (Section 4.4.2)
- The revenue derived from selling recycled PET (Section 4.4.3)

4.4.1 Materials Recovery Facility Costs

Plastic waste is collected by dump trucks together with all the other recyclable materials such as metal, paper, and glass waste and brought to a *materials recovery facility (MRF)*. A MRF is a processing facility where waste is sorted and prepared for additional processing. Configurations of the MRF processing line vary depending upon how waste is collected and received at MRFs. The four different ways of collecting waste are source-separated, dual-stream, single-stream, and mixed-waste

collection. Due to advances in automated processing equipment, less upfront separation is required, and so many source-separated MRFs gave way to dual-stream MRFs, which in turn are being replaced by single-stream MRFs in some locations. For this reason, a semi-automated MRF for single-stream recycling is considered for the analysis of plastics recycling in this book. A flowchart of the process is shown in Figure 4.2. The solid lines represent the flow of PET. [44]

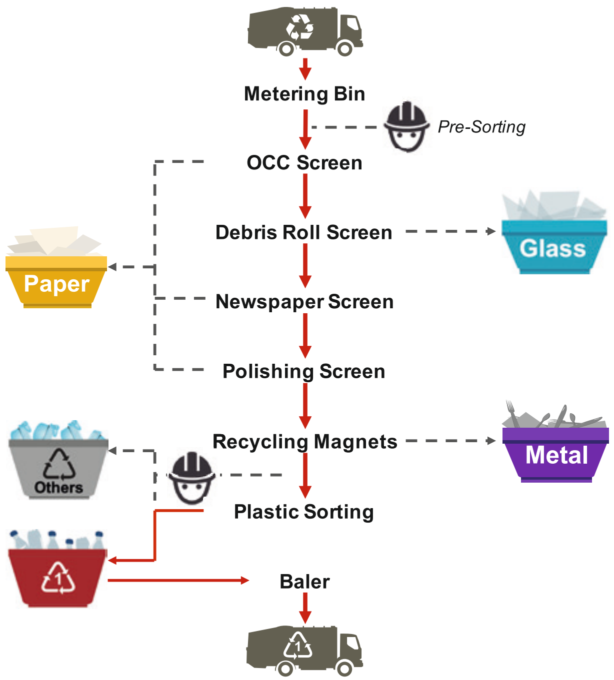

Figure 4.2 Schematic of materials recovery facility (MRF). OCC screen, old corrugated cardboard screen.

As trucks arrive at the MRF, they unload recyclable waste onto the tipping floor, where the material is stored until processing. Usually, the tipping floor is sized to hold at least two days of incoming waste to allow a buffer against unscheduled equipment downtime and to provide sufficient material for the MRF to operate during an extra shift. The dumped waste is grabbed by a loader to fill a *metering bin*; this serves to produce a constant flow. This constant feed rate prevents surges, allows for more efficient manual sorting in the presort area, and maximizes the efficiency of automated equipment encountered later in the processing line. During the manual presorting, large contaminants, bulky recyclables, and items that could damage downstream sorting equipment or pose a threat to personnel are removed. [44, 45]

As material leaves the presort station, it is transferred to the next machine, the so-called *old corrugated cardboard (OCC) screen*. It is composed of several rotating star-shaped disks, which separate the OCC from all the other materials by using size and dimension. All non-OCC materials fall through the disks onto the next screen. Below the OCC screen is a *debris roll screen*, which acts as a glass breaker. It breaks glass into quarter-sized pieces, which then fall through the debris roll screen and go into the glass trailer for transportation to a glass recycler.

After OCC and glass are removed, residual waste is routed to a *newspaper screen*, which uses the same concept as the OCC screen. The difference between these screens is the distance between the disks. Disks of the newspaper screen are closer together, so that the newspaper material stays on the disks and the smaller materials fall through. The *polishing screen* has even closer disks, which separate remaining paper waste from other materials. [44, 45]

OCC, newspapers, and other paper materials are finally routed to a paper platform, where the paper waste is checked manually and contaminants, which "acted" like paper when passing through the three paper screens, are removed from the paper waste before paper is sent out to a paper recycler. [44, 45]

A second system, called an *eddy current separator*, induces an electrical current in conducting metals such as aluminum. This in turn induces a magnetic field in these materials, repelling the aluminum and thus removing it from the waste stream. [44, 45]

The only materials remaining in the system are numbers 1 to 7 plastics (Table 3.1). In a first step, number 2 plastics (HDPE) are taken out manually (see Section 2.3.1 Manual Sorting). Afterwards, the residual plastics are sorted by an *optical sorter* (see Section 2.3.2.3 Near Infrared Sorting). This machine shoots a ray of light into the plastic and analyzes how the light reflects back to determine if the item is a number 1 (PET) or numbers 3 to 7 plastics. The optical system shoots a controlled blast of air on the item, which directs it to either the number 1 or the numbers 3 to 7 plastic storage area. Nonplastic materials do not receive any air shot and fall down to the residue conveyor, ending in the trash. [44, 45]

Sorted PET is then interim stored in a separate material bunker until the loose material is compacted by a *baler* into a large, bricklike bale to prepare the material for shipping to a plastic processing company. [44, 45]

The costs of the MRF process are split into two categories, investments and operating costs. As in the landfill and WTE facility analysis, all costs over the plant's lifetime are summarized first and afterwards converted to a cost per 1 t of plastic waste processed. The assumptions for the economic analysis are presented in Table 4.13 and in greater detail in Table 8.14 and Table 8.15 in the Appendix. [46, 47]

Table 4.13 Assumptions for Economic Analysis of Materials Recovery Facility

Lifetime [years]	10
Yearly working hours [h]	4,160
Waste handled per hour [t]	30
Yearly waste handling [t]	120,000
Total waste handling (10 years) [t]	1,200,000
Residues rate [%]	2
Correctness of manual sorting [%]	91

Since the factory runs 52 weeks per year, 5 days per week in 2 shifts with an effective working time of 8 hours each shift, the yearly working hours add up to 4,160 hours. Since 30 tons are handled per hour (restricted by the capacity of the metering bin), around 120,000 tons of waste is handled per year, resulting in a total waste handling of 1,200,000 tons of waste after 10 years. [47]

Investment costs for the MRF are divided into buildings and site, machine, and equipment costs. For an 80,000 ft^2 large area, initial costs for the land and site work are $ 1,395,000, and buildings costs for the scale house and MRF building are $ 9,200,000. Construction, planning, and surveying costs amount to $ 3,500,000, so the total investment costs for the buildings and site add up to $ 14,095,000. The investment costs of all machines for the MRF (Figure 4.2) amount to $ 2,163,000. Additional equipment are conveyors, rolling stock (e.g., front-end loaders and forklifts), and collection cars, the costs of which add up to $ 1,400,000. Summing up the investment costs from these three categories, the total investment costs of a MRF are **$ 17,658,000**, as shown in Table 4.14 and in more detail in Table 8.16 in the Appendix. [46, 47, 48]

Table 4.14 Total Investment Costs of Materials Recovery Facility

Building and site investment costs [$]	14,095,000
Machine investments costs [$]	2,163,000
Additional equipment investment costs [$]	1,400,000
Total investment costs [$]	**17,658,000**

Operating and maintenance costs of the MRF are divided into seven different categories. The yearly operating and maintenance costs are $ 8,254,465, so overall operating and maintenance costs of $ 82,544,659 after 10 years, as shown in Table 4.15 and in more detail in Table 8.17 in the Appendix.

Table 4.15 Total Operating and Maintenance (O&M) Costs of Materials Recovery Facility

Personnel salaries per year [$]	2,552,000
Facility costs per year [$]	343,000
Machine O&M costs per year [$]	128,565
Conveyor O&M costs per year [$]	12,320
Rolling stock O&M costs per year [$]	701,780
Residues costs [$]	96,000
Transportation and collection costs [$]	4,420,800
Yearly O&M costs [$]	**8,254,465**
Overall O&M costs (10 years) [$]	**82,544,659**

The largest group of personnel is the sorters for presorting, manual HDPE sorting, and quality control. A detailed breakdown of personnel is provided in Table 8.17 in the Appendix. The yearly salaries amount to $ 2,552,000. The salaries used for the calculation are average yearly U. S. salaries. [18, 19, 20, 21, 48]

Facility costs include consumables, insurance, administration, and baling wire and amount yearly to $ 343,000. Operating and maintenance costs of machines as well as conveyors involve yearly maintenance and electricity consumption ($ 0.0966 per kWh) and add up to yearly $ 140,885. The rolling stock has a high consumption of diesel, so the yearly costs are $ 701,780. Assuming that 2 % of the waste is residues and that all residues are landfilled, yearly costs for residues are $ 96,000. The largest part of operating and maintenance costs is generated by transportation and collection: assuming transportation and collection costs of $ 36.84 per ton, yearly costs for 120,000 t are $ 4,420,800.

Summarizing the investment costs and overall operating and maintenance costs, the total MRF costs are **$ 100,202,659**, or **$ 83.50** per ton of plastics waste (Table 4.16).

Table 4.16 Total Costs of Materials Recovery Facility

Investments costs [$]	17,658,000
Operating and maintenance costs [$]	82,544,659
Total costs (10 years –1,200,000 t) [$]	**100,202,659**
Costs per ton of plastic waste [$/t]	**83.50**

4.4.2 Plastic Reprocessing Costs

After PET is baled in the MRF, the bales are transported to a *plastic reprocessing facility*, where they are further treated, as schematically presented in Figure 4.3.

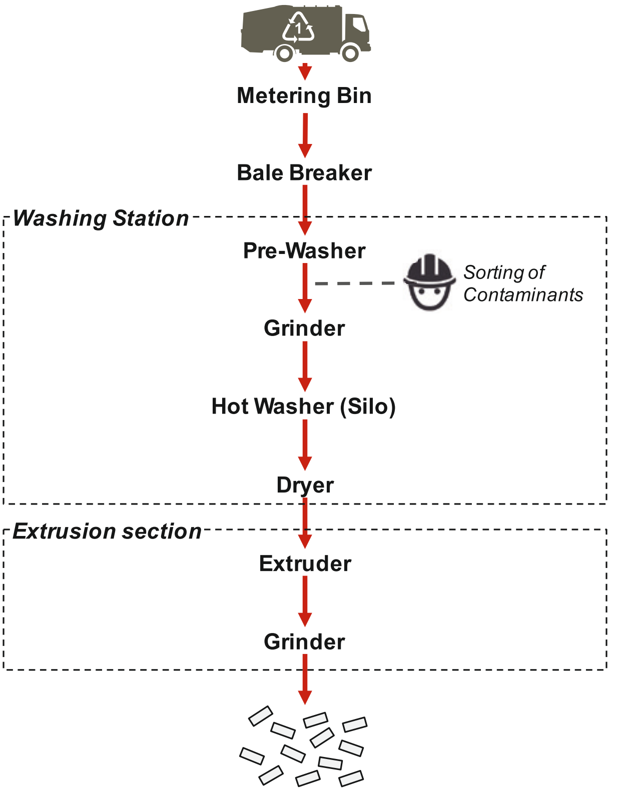

Figure 4.3 Schematic of Plastic Reprocessing Facility

From the tipping floor, PET bales are grabbed by a loader and laid into a metering bin, which constantly meters the plastic waste into a bale breaker. The bale breaker dismembers the PET bales into individual free flowing items (e.g., food containers and bottles). [49, 50]

The individual items are conveyed to a washing station. After a short prewashing to remove labels and dirt from the outside of the items and a manual hand sorting of contaminants, PET items are ground into flakes by a wet granulator. These ground flakes are transported to a silo for hot washing, which removes the last dirt and glue. In a final step at the washing station, these clean flakes are dried. [49, 50]

The dry flakes are metered to an extrusion section, which melts, vacuum degasses, and finally grinds the clean washed flakes to produce food-grade natural PET pellets. These are stored in big sacks and are ready to be used to make new products. [49, 50]

As for the MRF process, costs of the PET process are split into two categories, investments and operating costs, summarized over the factory's lifetime and then divided by the tons processed over the factory's lifetime to yield the cost per ton of

plastic waste. The assumptions for the economic analysis are presented in Table 4.17 as well as Table 8.18 in the Appendix.

Table 4.17 Assumptions for Economic Analysis of Plastic Reprocessing Facility

Lifetime [years]	10
Yearly working hours [h]	6,240
Yearly PET capacity [t]	15,000
Total waste capacity (10 years) [t]	150,000
Separation efficiency [%]	91
Dollar to British Pound conversion rate [$/£]	1.46

Investment costs include building and site, machine, and additional equipment costs. Since the source of some of the investment costs were the United Kingdom, a dollar to pound conversion rate of 1.46 $/£ (as of April 26, 2016) was used for the calculations. Including costs for design and project management, civil engineering, land, and site work, the building and site investments added up to $4,140,000. The metering bin, bale breaker, washing station, and PET extrusion section costs were $25,852,220. These costs included conveyors and installation costs. For auxiliary equipment, further costs of $150,000 were incurred. Summed up, the investment costs for the PET reprocessing plant were **$30,142,220**, as shown in Table 4.18 (and in more detail in Table 8.19 in the Appendix). [47, 49, 51]

Table 4.18 Total Investment Costs of Plastic Reprocessing Facility

Building and site investment costs [$]	4,140,000
Machine investment costs [$]	25,852,220
Additional equipment investment costs [$]	150,000
Total investment costs [$]	**30,142,220**

Operating and maintenance costs include personnel salaries, maintenance, machine operating, and rolling stock operating costs. Assuming the factory runs 52 weeks per year, 5 days per week in 3 shifts with an effective working time of 8 hours each shift, the yearly working hours are 6,240 hours and result in personnel salaries of $2,193,290 per year, which are mainly for sorters. Maintenance costs of the machines are assumed as 5% of the investment costs and therefore amount to $1,292,611. Operating costs are caused by energy and water consumption especially for washing and extruding, which consume a high amount of energy, and lead to operating costs of $1,022,773 per year. Costs for diesel for the rolling stock are $87,097 per year. These four categories result in total operating and maintenance costs of **$4,595,772** per year, so **$45,957,723** after 10 years, as presented in Table 4.19. Detailed calculations of operating and maintenance costs are provided in Table 8.20 in the Appendix. [19, 20, 21, 47, 49]

Table 4.19 Total Operating and Maintenance Costs of Plastic Reprocessing Facility

Personnel salaries per year [$]	2,193,290
Maintenance costs per year [$]	1,292,611
Machine operating costs per year [$]	1,022,773
Rolling stock operating costs per year [$]	87,097
Yearly O&M costs [$]	**4,595,772**
Overall O&M costs (10 years) [$]	**45,957,723**

Summarizing investment and overall operating and maintenance expenses, processing 150,000 tons of PET in 10 years cost **$76,099,943**, or **$507.33** per ton of PET, as it is presented in Table 4.20. Since only 14.39 % of plastic waste is PET (Table 2.1), the costs of plastic processing of 1 t of plastic waste are **$73.01**.

Table 4.20 Total Costs of Plastic Reprocessing Facility

Investments costs [$]	30,142,220
Operating and maintenance costs [$]	45,957,723
Total costs (10 years; 150,000 t) [$]	**76,099,943**
Costs per ton of PET [$/t]	**507.33**
Costs per ton of plastic waste (14.39 % PET) [$/t]	**73.01**

4.4.3 Revenues from Selling Recycled Plastic

The revenues from the PET recycling process come from selling the PET pellets produced to companies that produce new PET products for different applications, such as carbonated drink bottles (blow molding), food containers (thermoforming), or fibers (spinning).

In April 2016, the market price of 1 kg of PET pellets in the United States was between $ 1.17 and $ 1.34, so on average $ 1.26. [52]

Calculating the revenues of plastic recycling, it needs to be remarked that only 14.39 % of the plastic waste is PET (Table 2.1), so only this 14.39 % of 1 t of plastics waste is recycled in a best-case scenario, which means 143.9 kg out of 1 t. Furthermore, the efficiencies of both optical sorting during material recovery (89.18 %) and manual sorting during PET processing need to be considered. [47, 49, 53]

With an average price of $ 1.26/kg for recycled PET, revenues from recycling 1 t of plastic waste are $ 146.75, as shown in Table 4.21.

Table 4.21 Revenues from Recycling per Ton of PET Plastic Waste

Amount of PET in 1 t of plastic waste [kg]	143.90
Separation efficiency of plastic recycling [%]	89.18
Separation efficiency of PET processing [%]	91.00
Price of recycled PET [$ /kg]	1.26
Total revenues per ton of plastic waste [$]	**146.75**

As also shown in Table 2.1, small amounts of the other plastics are recycled. Currently, these other plastics produce close to no revenue due to a lack of reprocessing procedures for them in the United States. They are normally landfilled and so their revenues are not considered in this analysis. [53]

4.4.4 Profitability

Finally, to calculate the profitability, the total costs per ton of waste need to be subtracted from its revenues.

The costs of both MRF and PET processing add up to $ 156.51 per ton of plastic waste, and the revenues of recycling 1 t of plastic waste are $ 146.75. Thus, the absolute profit from recycling 1 t of plastic waste is **−$ 9.76** (see Table 4.22).

Table 4.22 Profit from Recycling per Ton of PET Plastic Waste

Revenues per ton of plastic waste [$ /t]	146.75
Total costs per ton of plastic waste [$ /t]	156.51
Profit per ton of PET plastic waste [$ /t]	**−9.76**

Since the profit is negative, recycling of plastic waste is not absolutely profitable. For this to have an absolute profit, the break-even price of recycled PET would need to be **$1.34**/kg instead of $ 1.26/kg.

This profitability depends significantly on the consumers. If plastic waste is not disposed of in the recycling trash can, plastic waste will not end up in the MRF, and so it will not be reprocessed at all. In this analysis, it was assumed that all waste was disposed of properly.

4.4.5 Oil Price as a Factor in Profitability of Plastics Recycling

Oil is the most important raw material for plastics. As already mentioned, 1 kg of plastic requires about 2 kg of crude oil (including processing and raw materials for plastics). For this reason, the oil price has a great influence on the plastic price and

the profitability of the whole plastic recycling process. The lower the oil price, the lower the price of the recycled plastic, the less profitable the recycling process becomes. Furthermore, a lower oil price reduces the costs of producing new, or virgin, plastic material, which is another challenge for plastics recycling.

In 2015 and 2016, low global oil prices significantly reduced the profitability of plastics recycling in the United States. In Newark, for example, the value for 1 bale of recycled plastics decreased from $ 230 to $ 112. One of the consequences was that Infinitus Energy, which had just opened a $ 35 million recycling center in Montgomery, Alabama, in 2014, shut that facility down in October 2014 since it was incurring losses only. [54]

Figure 4.4 shows the changing price of 1 t of regrind PET compared to 1 barrel (158.9873 L) of oil. Since the original prices of the plastics were in Euros, the rate of 1 Dollar per Euro was taken from X-Rates. For a better comparison of different years, prices were inflation-adjusted based on the prices of October 2008 (both PET and oil). [55, 56, 57, 58]

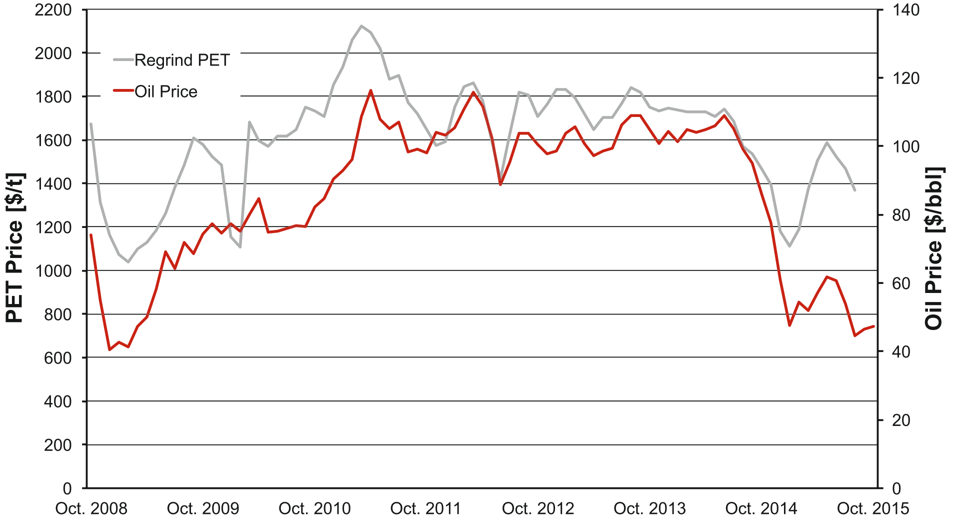

Figure 4.4 Oil (1 barrel (bbl) = 158.9873 L) and PET(1 t regrind) prices between October 2008 and October 2015 (inflation-adjusted)

Figure 4.4 demonstrates that the PET price is following the oil price changes, since the peaks of the regrind PET price graph line are lagging behind the peaks of the oil barrel price graph line by approximately 1 month. This can especially be observed in November 2009, October 2010, November 2014, and August 2015.

To analyze price correlations between PET and oil, a helpful tool is the calculation of the *Pearson product-moment correlation coefficient* $r_{x,y}$, which is a measure of de-

gree of linear dependence between two variables. The calculation for $r_{x,y}$ is given in Equation (4.1).

$$r_{x,y} = \frac{\operatorname{cov}(x,y)}{\sigma_x \sigma_y} = \frac{\sum_{k=1}^{n}(x_k - \overline{x})(y_k - \overline{y})}{\sqrt{\left(\sum_{k=1}^{n}(x_k - \overline{x})^2\right)\left(\sum_{k=1}^{n}(y_k - \overline{y})^2\right)}} \quad (4.1)$$

The correlation coefficient ranges from $r_{x,y} \in [-1,1]$. A correlation coefficient $r_{x,y}$ of 1 implies a perfect relationship between x and y (a positive correlation). A value of −1 implies a perfect opposing relationship between the x and y (a negative correlation). A value of 0 implies no correlation between the variables. [59] The correlation between the two prices is shown graphically in Figure 4.5.

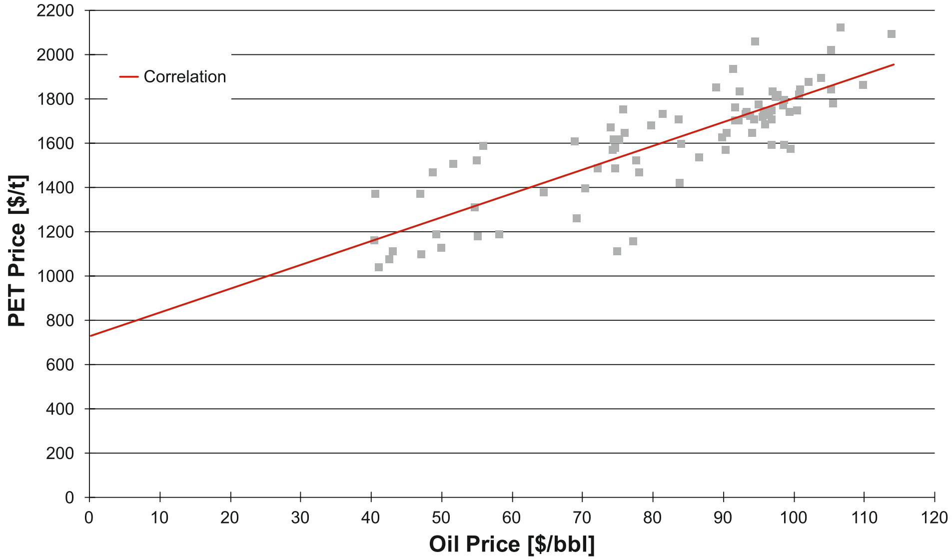

Figure 4.5 Correlation between PET price (per ton) and oil price (per barrel). bbl, barrel (158.9873 L)

For inflation-adjusted prices, the correlation coefficient is 0.84. This value reflects the results shown in Figure 4.4 and Figure 4.5: prices of PET and oil have a positive but not perfectly linear correlation.

Based on the correlation curve and knowing that the break-even price of recycled PET is $ 1.34 per kilogram, or $ 1,340.00 per ton, the required oil price for profitability is about $ 59.00 per barrel, as presented in Figure 4.6. In April 2016, the oil price was around $ 45 per barrel, which is too low to make plastic recycling profitable.

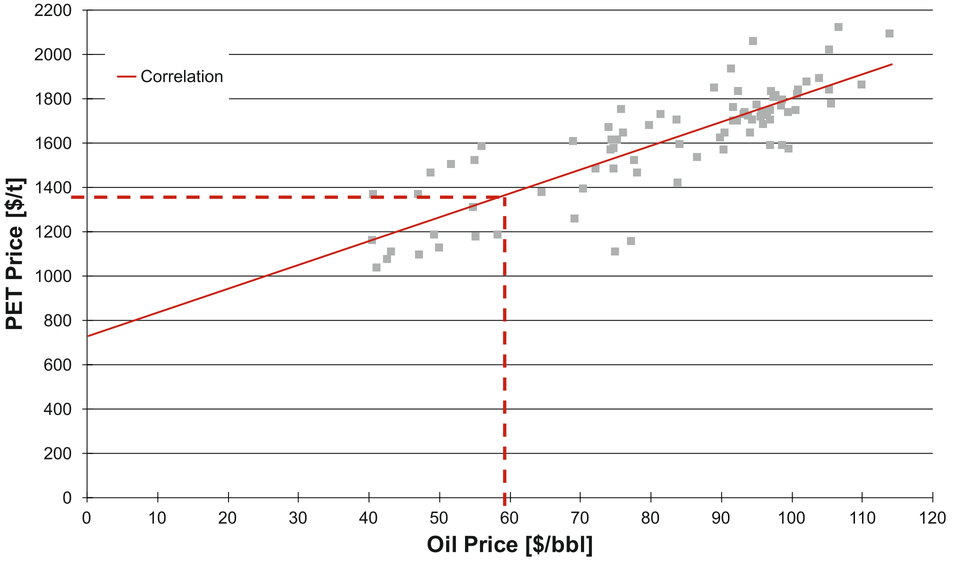

Figure 4.6 Required oil price per barrel for break-even recycled PET price per ton

4.5 Conclusion: Economical Feasibility of Plastics Recycling

In the economic analysis presented using the static profit comparison method, the profit of handling plastic waste was analyzed for three different procedures. The profits of the three waste handling procedures for 1 t of waste are summarized in Figure 4.7. These numbers presume an ideal handling of plastic waste, which means all waste is disposed of properly, so that the plastic waste composition conforms with the plastic waste composition found in the MSW in 2013 (Table 2.1).

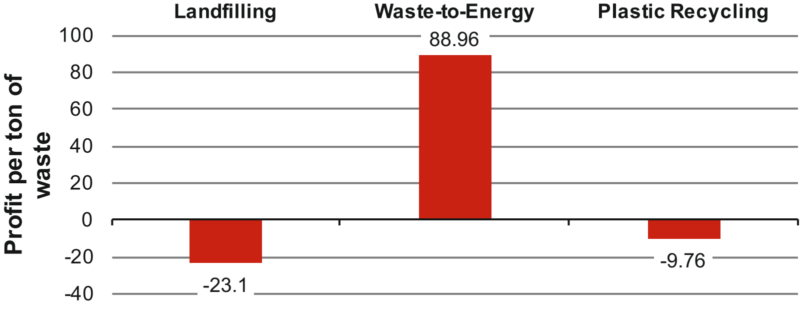

Figure 4.7 Profitability of recycling 1 t of plastic for three different waste handling procedures

Incineration with energy recovery (waste-to-energy) is the only handling method with absolute profitability (profit > $ 0.00) and therefore relative profitable as well. However, this is only valid in the case of incineration of plastics only and no other materials, which is really a theoretical assumption.

As already mentioned during this analysis, the numbers depend significantly on the size and yearly capacity of the facilities. The bigger the facility, the lower the costs and the higher the profit.

In the future, costs for landfilling will probably increase due to a lack of land available, so its profitability will further decrease.

The profitability of plastic recycling depends on two factors, which cannot be influenced by the factory: (1) the oil price and (2) the plastic recycling ratio of consumers, which depends on whether consumers recycle their waste properly, so that all waste plastic gets to the recovery factories to be recycled.

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5 Environmental Analysis of Plastic Waste Handling

Chapter 4 showed that incineration with energy recovery is economically the best method of plastic waste handling. However, to improve waste handling and address the challenges resulting from the continuous increase of plastic waste mentioned in Chapter 2, plastic waste handling methods have to be analyzed from an *environmental point of view* as well. For present and especially future society, environmental aspects have a much higher priority than economic ones: at least 8 million tons of plastics are leaked into the ocean each year, which is equivalent to dumping the contents of one garbage truck into the ocean every minute. If the plastic waste handling does not change, the leakage is expected to increase to two trucks per minute by 2030 and even four per minute by 2050. There is only one planet and this planet needs to be protected. An environmentally sensitive handling of plastic waste is critical to the protection of the environment. [1]

As already mentioned in Section 1.2, recycling is the preferred method of waste handling by the Environmental Protection Agency (EPA), but only 9.2 % of the total plastic waste is recycled (Table 2.1). Chapter 5 will explain why from an environmental point of view, compared with landfilling and incineration, recycling is the most favorable option.

5.1 Environmental Analysis of Landfilling

The percentage of plastic waste in landfills is increasing compared to its percentage in the total MSW because of the low percentage of plastic waste recycled, only 9.2 %, and incinerated, only 9.9 %, both of which are lower than the percentages of total MSW recycled and incinerated (recycling: 34.2 %; WTE: 12.9 %). Because of its current treatment, plastics make up 17.6 % of the total waste in landfills, which is significantly more than the 12.8 % it makes up of total MSW. Only food scraps account for a larger percentage of waste in landfills (21.1 %). Waste disposal of plastic in landfills has several negative effects on the environment. [2]

First of all, disposing of plastic waste in landfills is equivalent to the loss of scarce resources. As already mentioned in Chapter 2, producing 1 kg of plastic requires 2 kg of crude oil, which is lost in cases where plastics are disposed of in landfills and not recycled. Furthermore, landfills occupy land, which is becoming a more and more scarce resource as well. The 1,908 landfills in the United States covered an area of around 120,000 ha in 2013. Knowing that plastics make up 17.6 % of the total waste in landfills means they occupy around 21,120 ha. According to a study by Yale University, the available space for landfills that meet the RCRA D regulations will only last for another 70 years, even if parts of these areas can be reused in some cases. Bearing in mind that plastic waste is increasing continuously and over 80 % of it is placed in landfills, this scarcity of land is becoming a big ecological challenge for plastic waste handling. [3, 4, 5, 6, 7]

As a result of disposing of plastic in landfills, the occupied soil and its groundwater is polluted by *leachate*. Leachate describes liquid, whose primary source is precipitation, that passes through the landfilled waste and collects and dissolves chemicals from the refuse as it percolates. Even if the activity of landfills in general is limited to 30 years and RCRA D regulates the aftercare of landfills, leachates cannot be completely prevented and make a revival of the land nearly impossible. [8, 9, 10]

Another way plastics in landfills are polluting the environment is via greenhouse gas (GHG) production. Since plastics normally do not contain biodegradable carbon, they do not generate methane gas (CH_4) and are not considered as storing any carbon when landfilled. The only emissions associated with landfilling plastics are from transportation to the landfill and moving waste into the landfill. But the relatively new, so-called “environmentally friendly” plastic bags, being biodegradable and taking about 3 years to break down into practically nothing, produce greenhouse gases. After being placed in a landfill, the organic plastic bags are initially decomposed by aerobic bacteria and afterwards broken down through fermentation into gases and short-chain organic compounds. These compounds form substrates for the growth of methanogen bacteria, which convert the fermentation products into biogas consisting of approximately 50 % biogenic carbon dioxide (CO_2) and 50 % CH_4 (methane).

At present, the amount of GHGs produced by these biodegradable plastics is low, especially compared to incineration (see Section 5.2). However, if the production of biodegradable plastics increases and its waste is disposed of in landfills, the GHG production will become a bigger issue of landfilling. [2, 11, 12]

The biggest environmental pollution caused by landfilling plastics is marine pollution. Through mismanagement in landfills, the United States releases between about 0.04 and 0.11 Mt of plastic waste into the ocean every year, and this is rising. *Microplastics* are especially a huge risk. Due to ultraviolet (UV) radiation, plastics in landfills start degrading and disintegrate into their different chemical com-

ponents and additives. Both the big and small pieces of plastic pose a risk for marine animals or birds. Often they cannot distinguish between plastics and food and eat the plastic waste, which afterward stays in their bodies and causes intestinal obstructions. [13, 14]

5.2 Environmental Analysis of Incineration with Energy Recovery (Waste-to-Energy Facilities)

As has been pointed out already, the percentage of plastic waste being incinerated with energy recovery is 9.9 % and is lower than the percentage of MSW that is being incinerated (12.9 %).

As already described in Sections 1.2.2 and 4.3, WTE facilities burn waste, including plastic waste, to produce electricity. This incineration leads to an ecologically valuable reduction of plastic waste: the remaining, nonhazardous combustion ash amounts to about 25 % of the weight of the unprocessed waste input and about 10 % of its volume. This reduction of weight and especially volume is highly important for the environment, considering that land is a scarce resource (Section 5.1). Including landscaping and auxiliary buildings, a WTE plant, which lasts over 30 years, processes 1 Mt of waste each year on less than 10 ha of land. In total, this would be 30 Mt of waste on 10 ha of land per plant. Landfilling the same amount, 30 Mt of waste, would require 300 ha of land. Furthermore, a new plant could be built on the site of the existing WTE plant. Landfill sites cannot be used for anything else again and new green fields must be converted to landfills. [15, 16, 17, 18, 19]

WTE facilities can also help to reduce fossil fuel use and foreign oil dependence. Operating continuously (24 hours a day, 7 days a week), they provide baseload electricity to communities. One ton of MSW has the chemical content of 0.4 t of oil: 1 t of nonrecycled plastic has the chemical content of 1.4 t of oil. [18, 20]

But combustion also induces negative ecological impacts. First of all, burning plastic means burning of valuable, scarce resources. As already mentioned in Chapter 2, to produce 1 kg of plastic requires 2 kg of oil. Even if the burned oil produced energy, it would be much more sustainable to use this scarce resource in a different way. The ash from burning plastic waste, although its weight and volume are lower than the untreated MSW, ends up in landfills and therefore requires land. Most states have strict regulations to ensure that ash does not exhibit any toxicity characteristics, but the influence of plastic ash on the environment has not been completely understood yet. [15, 20]

Another controversial subject of waste-to-energy plants, more than any other plastic handling method, is noise. Trucks bringing solid waste to the facility, plant operations, and fans are sources of noise pollution. [21]

The biggest issue of burning plastic is the generation of pollutants, especially CO_2. Since plastic is created from a fossil fuel, its combustion is considered an anthropogenic source of carbon emissions. An EPA study revealed that incinerators are the dirtiest electricity production option, releasing more greenhouse gases than coal-fired power stations per unit of energy generated.

Table 5.1 shows the *net emission factor* for combustion of 1 t of high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyethylene terephthalate (PET) in metric tons of a carbon dioxide equivalent ($MtCO_2E$)[1] calculated using the EPA's *Waste Reduction Model (WARM)*. This factor includes the emissions associated with transporting (903 km per shipment) the plastic waste to WTE facilities and emission savings associated with the avoided emissions of burning conventional fossil fuels for utilities. It shows that the production of greenhouse gases through waste combustion is much higher than the emission savings. [11, 22]

Table 5.1 Net Emissions Factor Due to Combustion for Various Plastics

Material	Transportation to Combustion [$MtCO_2E/t$]	CO_2 from Combustion [$MtCO_2E/t$]	Utility Emissions Avoided [$MtCO_2E/t$]	Net Emissions Factor [$MtCO_2E/t$]
HDPE	0.033	3.075	−1.664	1.444
LDPE	0.033	3.075	−1.664	1.444
PET	0.033	2.249	−0.871	1.411

CO_2, dioxins, and particles contribute to negative effects for the environment, such as climate change, smog, and acidification, and for the human body, such as asthma, lung damage, cardiac problems, and nervous system damage. [15, 23]

■ 5.3 Environmental Analysis of Recycling

The recycling rate of plastic materials in 2013 was 9.2 %, much lower than the recycling rate of the general MSW (34.2 %). Despite this low rate, plastic recycling has a big positive ecological impact: it provides opportunities to reduce quantities of waste requiring disposal, oil usage, and carbon dioxide emissions. [16, 24]

[1] $MtCO_2E$ (metric tons of carbon dioxide equivalent): This describes how much global warming a given type and amount of greenhouse gas causes using the equivalent of CO_2 as a reference.

Recycling of plastics means waste reduction. In 2013, the total plastic waste produced was 35.5 million tons. Even at the relatively low recycling rate of 9.2 %, it means 3.27 million tons were neither landfilled nor burned, thus not polluting the environment. [16, 25]

Furthermore, plastic recycling is equivalent to the reuse of scarce resources, especially oil. Nowadays, plastics are almost completely derived from petrochemicals, which are produced from fossil oil and gas. Since manufacturing of plastics also requires energy, a similar additional quantity of fossil fuels is used for their production. Reprocessing plastics is consequently the same as reuse of this important resource. [24]

The key benefit of recycling plastic is *the reduction of required plastics production:* less production means less energy use, which simultaneously leads to the reduction of CO_2 and greenhouse gas emissions. Considering the difference between the energy use for producing virgin PET and HDPE and for reprocessing these products at the end of their life, recycling only these two plastics in the United States could save enough energy each year to power 750,000 homes. [26]

Table 5.2 Net Emissions Factor Due to Combustion and Energy Savings for Recycled versus Virgin Plastics

		HDPE	LDPE	PET
Virgin input [$MtCO_2E/t$]	Process energy	1.560	1.905	1.796
	Transportation energy	0.036	0.036	0.036
	Process non-energy	0.172	0.172	0.100
Recycled input [$MtCO_2E/t$]	Process energy	0.118	0.118	0.118
	Transportation energy	0.045	0.045	0.045
	Process non-energy	–	–	–
Savings by recycling [$MtCO_2E/t$]	Process energy	− 1.442	− 1.787	− 1.678
	Transportation energy	0.009	0.009	0.009
	Process non-energy	− 0.172	− 0.172	− 0.100
	Total savings	**− 1.605**	**− 1.950**	**− 1.769**

Table 5.2 shows the difference between emissions from manufacturing 100 % virgin material and 100 % recycled material, calculated using the WARM method, which breaks down the emission into

- Process energy emissions
- Transportation emissions
- Process non-energy emissions

It can be seen that manufacturing of recycled HPDE, LDPE, and PET significantly reduces GHG emissions compared to producing the same amount of virgin material. Among these plastics, LDPE recycling shows the largest GHG emission savings. [11, 26]

Reduction of waste, energy use, and GHG emissions are several positive effects of recycling plastics on the environment. These positive ecological impacts are reflected in the EPA's waste management hierarchy, which superordinates recycling to incineration and landfilling of plastics waste. [16, 25]

5.4 Conclusion: Environmental Necessity of Plastics Recycling

Considering all waste handling options from an ecological point of view, it has been established that recycling clearly is the best way to handle plastic waste. Besides the reduction of waste, it leads to energy savings and decreased GHG emissions.

Recycling is not only a waste management strategy; it further implements the concept of industrial ecology, that there is no waste but only new products. [27]

On this account, the recycling process needs to be improved so that it is both ecologically and economically desirable. Therefore, Chapter 6 will consider two different ways of economically improving the plastics recycling process and making it even more indispensable from an ecological perspective.

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6 Optimization of Plastics Recycling

Chapter 5 concluded that recycling is the best option for handling plastic waste from an environmental point of view and can significantly contribute to minimizing air, soil, and marine pollution.

But, as presented in Chapters 2, 3, and 4, there are two central issues with recycling: on the one hand, only 9 % of plastic waste in the United States is recycled at the moment due to technical limitations (see Chapter 3) and, on the other hand, recycling is currently unprofitable from an economic point of view due to low oil prices (see Chapter 4). Recycling and selling 1 t of recycled plastic results in a loss of around $ 10.

To improve both the profitability and the recycling rate, two process optimization possibilities are presented in this chapter.

6.1 Optimization I: Reduction of Sorting Processes

The first process optimization proposed is reducing the number of sorting processes. Therefore, the so-called *dual-stream recycling* would need to be implemented. Dual-stream recycling means that the plastic waste is directly separated by consumers in their households, which is similar to systems established in Europe (see Section 7.1). Consequently, the sorting process in the materials recovery facility (MRF) is not required anymore. The optimized process is shown in Figure 6.1. [1]

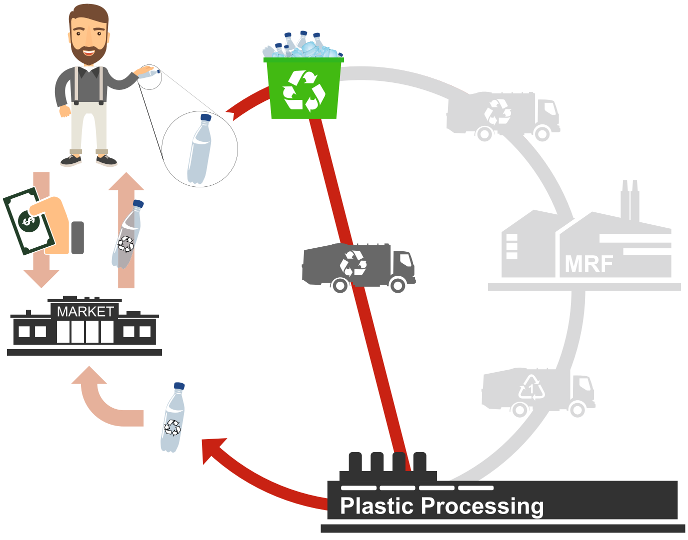

Figure 6.1 Optimization I: Dual-stream recycling. MRF, materials recovery facility.

To calculate the profitability of the optimized process, the original profitability calculation of the plastic recycling process is used as a basis. The costs of polyethylene terephthalate (PET) processing as well as the revenues realized by selling recycled PET remain unchanged. Processing 1 t of plastic waste costs **$73.01** and the revenues for sale of 1 t of recycled plastic are **$146.75**. But to handle the plastic in the same facility, some additional machines and processes need to be installed. Analyzing the additional costs, such as investment and operating and maintenance costs, is done in two steps. The assumptions for this optimization are shown in Table 6.1 and in more detail in Table 8.21 in the Appendix.

Table 6.1 Optimization I: Assumptions

Lifetime [years]	10
Yearly working hours [h]	6,240
Yearly plastic waste handling [t]	100,000
Total plastic waste capacity (10 years) [t]	1,000,000
Yearly PET capacity [t]	15,000
Total PET waste capacity (10 years) [t]	150,000
Separation efficiency [%]	91

Additional investment costs are split up into building and site, machine, and equipment costs. To handle plastic waste in only one facility, additional land, site work, and buildings, as well as a scale house are required. These building and site costs amount to $1,775,000. Furthermore, three new machines need to be installed: a

metering bin, an optical PET sorting machine, and a baler. The investment costs of all machines add up to $925,000. For additional conveyors, rolling stock, and waste collection cars, total costs are $1,250,000. As presented in Table 6.2, total additional investment costs are **$3,950,000** (see also Table 8.22 in the Appendix). [2, 3, 4]

Table 6.2 Optimization I: Additional Investment Costs

Additional building and site investment costs [$]	1,775,000
Additional machine investment costs [$]	925,000
Additional equipment investment costs [$]	1,250,000
Total additional investment costs [$]	**3,950,000**

Additional operating and maintenance costs are salaries of the additional personnel, operating and maintenance costs of the machines and the rolling stock, and especially transportation and collection costs. Yearly operating and maintenance costs are **$5,549,307**, so overall **$55,493,073**, as presented in Table 6.3 and in more detail in Table 8.23 in the Appendix. [3, 5, 6, 7, 8]

Table 6.3 Optimization I: Additional Operating and Maintenance (O&M) Costs

Personnel salaries per year [$]	963,000
Facility costs per year [$]	250,000
Machine O&M costs per year [$]	66,656
Rolling stock O&M costs per year [$]	585,650
Transportation and collection costs [$]	3,684,000
Yearly O&M costs [$]	**5,549,307**
Overall O&M costs (10 years) [$]	**55,493,073**

Summarizing both additional investment and operating and maintenance costs, total additional costs are **$59,443,073**. Since 100,000 t of plastic waste must be handled per year in this new facility area (to gain 15,000 t of PET waste, around 100,000 t of plastic waste has to be sorted), the additional costs of 1 t of plastic waste are **$59.44**.

Knowing that the revenues of recycling 1 t of plastic waste are **$146.75** and the costs for further processing the plastic waste are **$73.01**, the profitability of this optimization is calculated in Table 6.4.

Table 6.4 Total Profit per Ton of Plastics Recycled

Revenues per ton of plastics recycled [$/t]	146.75
Sorting [$]	59.44
PET processing [$]	73.01
Profit per ton of plastics recycled [$/t]	**14.30**

Table 6.4 shows that the profit of this optimization would be **$14.30** per ton of plastic waste recycled, so this process optimization has absolute profitability. Compared to the current plastic recycling procedure, the profit of the optimization is **$24.06** higher.

But this optimization has two risks, which cannot be included in the calculations. First, this optimized process depends even more on the disposal behavior of consumers than the current recycling process already does. If consumers not only have to distinguish between recyclables and non-recyclables but also between plastics, paper, glass, and metals, the risk of not properly disposing of plastic waste increases.

Second, the optimization has hidden costs for the transportation and collection of waste. The analysis only considered the recycling of plastic waste. In daily life, paper, glass, and metals should be recycled as well. If all of these materials were collected individually, transportation and collection costs would increase immensely.

6.2 Optimization II: Upcycling of Plastic Waste by Blending

The second optimization possibility considered in this book includes the *extension of the analyzed PET reprocessing* to recycling polypropylene (PP) and low-density polyethylene (LDPE) by blending them into a compound. The process is presented in Figure 6.2.

Due to its desirable physical properties such as high tensile strength, high stiffness, and high chemical resistance, PP has been widely used as a packaging material. However, it shows poor impact strength at low temperatures and is susceptible to environmental *stress cracking*. LDPE is mostly used for bags and packaging films. Owing to its low mechanical properties but ease of processing, it is recycled and used for garbage bags. Therefore, blends of LDPE and PP have become a subject of great economic interest to improve the processing and mechanical properties of PP. [9]

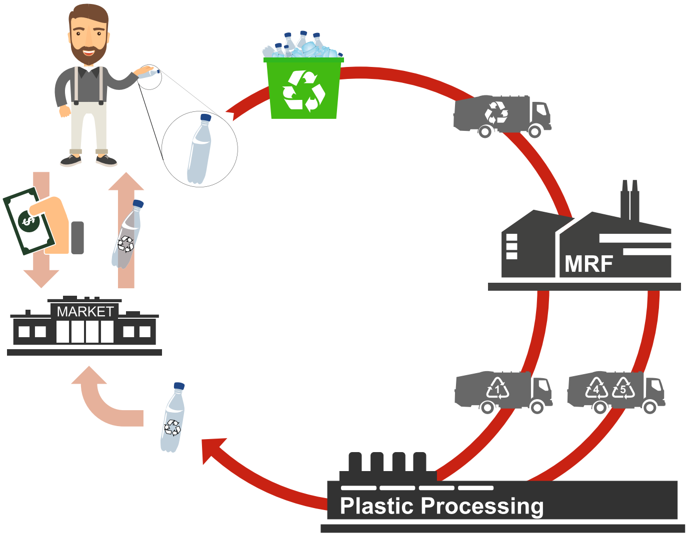

Figure 6.2 Optimization II: Extension of the process by blending recycled polypropylene (PP) and low-density polyethylene (LDPE). MRF, materials recovery facility.

Combinations of LDPE and PP are frequently found in polymer waste streams. But since their densities are very similar (PP: 946 kg/m^3, LDPE: 940 kg/m^3), they cannot be easily separated from each other by conventional sorting methods. Another motivation for blending recycled PP-LDPE is the high impact it has as shown in Table 2.1. PP and LDPE accounted for almost 50 % of the total plastic waste in 2013. Not recycling these two plastics means wastage of important resources. However, it needs to be determined if blending recycled PP and LDPE would be economically profitable and as a result would optimize the plastic recycling process. [10, 11, 12]

Material tests showed that recycled PP and LDPE blends have material properties similar to virgin PP–LDPE blends. The effects of processing on the properties of recycled PP, recycled LDPE, and their blends were investigated using *melt flow index (MFI) measurements* (see Section 3.4 Plastic Degradation Mechanisms). These MFI measurements showed an increase with increasing amounts of rLDPE in blends, thus a decrease of the viscosity with increasing amounts of rLDPE, which is due mainly to the higher degradation of rLDPE, as shown in Figure 6.3.

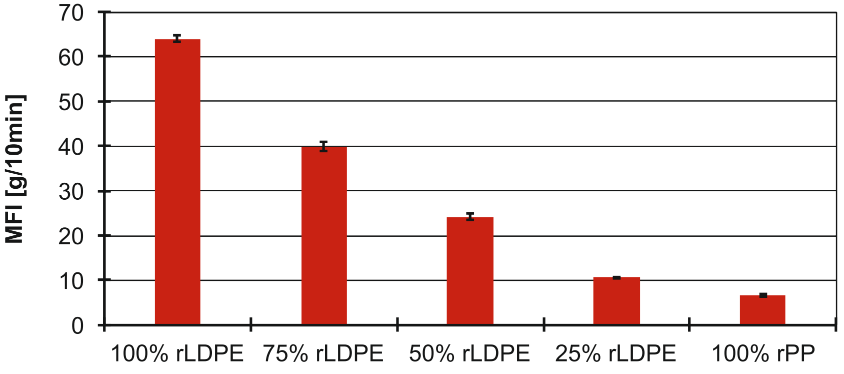

Figure 6.3 Melt flow index (melt) of recycled low-density polyethylene (rLDPE), recycled polypropylene (rPET), and their blends

These results also correspond to the mechanical tests. The higher the amount of rLDPE, the higher the maximum tensile strain but the lower the maximum tensile stress (Figure 6.4).

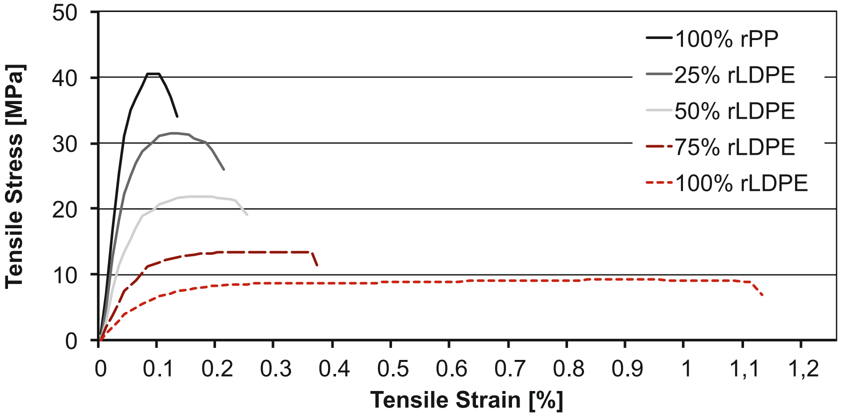

Figure 6.4 Tensile stress and tensile strain of recycled low-density polyethylene (rLDPE), recycled polypropylene (rPP), and their blends

Accordingly, blending recycled PP and LDPE can improve material properties to some extent. To calculate the profitability of optimization II, additional costs are calculated first. Afterwards, the revenues from selling rLDPE-rPP blends are calculated. From these, the profit of the optimization can be computed.

6.2.1 Additional Costs of LDPE–PP Recycling

To calculate the costs of optimization II, the plastic recycling process in Section 4.4 serves as a basis. The important assumptions are presented in Table 4.13, Table 4.17, and Table 6.5.

Table 6.5 Optimization II: Assumptions

Lifetime [years]	10
Percentage of PET in plastic waste [%]	14.39
Percentage of LDPE–PP in plastic waste [%]	45.70
Average price of recycled PET pellets [$/kg]	1.26
Average price of recycled LDPE–PP pellets [$/kg]	0.68
Total waste capacity (10 years) [t]	150,000
Separation efficiency [%]	91

First, the MRF process is extended by machines that are required to sort LDPE and PP. Since their densities are nearly the same and the optical sorter uses material densities to distinguish between different plastics, only one new sorter is required. Total investment as well as operating and maintenance costs are **$1,165,734**, or **$0.97** per t of plastic, as shown in Table 6.6 and in more detail in Table 8.24 in the Appendix. [2]

Table 6.6 Optimization II: Additional Costs of Low-Density Polyethylene and Polypropylene (LDPE–PP) Blending for Materials Recovery Facility (MRF)

Additional investment costs [$]	900,000
Additional O&M costs [$]	265,734
Overall additional MRF costs [$]	**1,165,734**
Additional MRF costs per ton [$/t]	**0.97**

Second, the plastic waste process needs to be adapted. Since plastics are sorted in the MRF first and transported separately to the plastic processing factory, PET and LDPE–PP are processed independently from each other. That means that a second metering bin, bale breaker, and washing station are required, as well as an LDPE–PP extruder. The yearly capacity for LDPE–PP is the same as for PET. Thus, investment costs for the metering bin, bale breaker, and washing station are the same as for PET. The LDPE–PP extruder is a bit cheaper than the PET extruder. Total machine investment costs of plastic processing are $24,069,560 (conveyers and installation included). In addition, facility space and rolling stock need to be expanded. These investments result in total costs of **$26,069,560** (Table 6.7 and Table 8.25 in the Appendix). [2, 13]

Table 6.7 Optimization II: Additional Investment Costs for Plastic Processing

Building and site investment costs [$]	1,950,000
Machine investments costs [$]	24,069,560
Additional equipment investment costs [$]	50,000
Total investment costs [$]	**26,069,560**

Since LDPE–PP requires an individual process, operation and maintenance costs are also similar to PET processing. All materials are processed in the same facility, therefore no additional plant manager, marketing manager and maintenance engineer is required. Another big difference between PET and LDPE–PP processing is electricity consumption of the extrusion process: LDPE–PP has a lower melting temperature than PET and consequently a lower electricity consumption. Yearly operation and maintenance costs of LDPE–PP processing are **$ 3,738,649**, thus **$ 37,386,493** after 10 years (Table 6.8 and Table 8.26 in the Appendix). [2, 13]

Table 6.8 Optimization II: Additional Operating and Maintenance (O&M) Costs of Plastic Processing

Personnel salaries per year [$]	1,500,000
Machine maintenance costs per year [$]	1,203,478
Machine operating costs per year [$]	948,073
Rolling stock operating costs per year [$]	87,097
Yearly additional O&M costs [$]	**3,738,649**
Overall additional O&M costs (10 years) [$]	**37,386,493**

Summarizing all additional investment and operating and maintenance costs over the factory's lifetime, total additional costs of the optimization process are $ 63,456,053, or $ 423.04 per t of LDPE–PP waste. Assuming a combined LDPE–PP content of 45.70 % in the plastic waste (Table 2.1), additional processing costs per 1 t of LDPE–PP plastic are $ 193.33 (Table 6.9).

Table 6.9 Optimization II: Additional Costs per Ton for Plastic Processing

Investments costs [$]	26,069,560
Operating and maintenance costs [$]	37,386,493
Total costs (10 years – 150,000 t) [$]	**63,456,053**
Costs per ton of LDPE–PP [$/t]	**423.04**
Costs per ton of plastic waste (45.70 %) [$/t]	**193.33**

6.2.2 Additional Revenues of LDPE–PP Recycling

To calculate the revenues of the LDPE–PP recycling process, the main task is to determine the selling price of rLDPE–rPP blends.

The results of the material analysis agreed with the behavior of virgin material: a higher amount of PP in blends leads to increased stiffness and strength of the material, which are desirable physical properties for packaging material. However, a greater portion of LDPE in the blends increased the maximum strain of material. Depending on the choice of application for the material, the ability of the material to elongate can also be an important criterion.

This shows that the value of a product is regulated by its demand. Determining an explicit selling price based on material properties is, also due to a lack of experience in this area, relatively arbitrary.

Since the ratio between LPDE (22.94 % of plastic waste) and PP (22.76 % of plastic waste) in the plastic waste is nearly identical, a ratio of 50 % LDPE and 50 % PP in the blend is assumed. For this reason, the price of recycled LDPE–PP pellets used for the following calculations is $ 0.68 per kg, which is the mean value of rLDPE ($ 0.46 per kg) and rPP ($ 0.90 per kg) for April 2016. [14]

Calculating the revenues of plastic recycling, it needs to be remarked again that only 457 kg of 1 t of plastic waste is LDPE–PP (Table 2.1). The efficiencies of both the optical sorting at the MRF and the manual sorting during LDPE–PP processing need to be included as well. With an average price of $ 0.68 per kg, additional revenues through optimization II are **$ 245.71** (Table 6.10).

Table 6.10 Optimization II: Additional Revenues

Amount of LDPE-PP in plastic waste [kg]	457.00
Separation efficiency of MRF process [%]	86.45
Separation efficiency of PET processing [%]	91.00
Price of recycled LDPE–PP [$/kg]	0.68
Total revenues from recycling LDPE–PP [$]	**245.71**

6.2.3 Total Profit of Optimization II

Totaling revenues and costs from both the PET process (Chapter 4.4) and optimization II and subtracting the costs from the revenues, the profit from recycling 1 t of plastic waste is **$ 41.65** (Table 6.11).

Table 6.11 Optimization II: Total Profit per Ton of Plastics Recycled

Revenues per ton of plastics [$/t]	392.46
Costs per ton of plastics [$/t]	350.81
Profit per ton of plastics recycled [$/t]	**41.65**

With optimization II, the profit would increase by **$ 51.41** per ton and make plastic recycling absolutely profitable. The implementation of a LDPE–PP process is relatively expensive, but since the additional costs of the MRF are very low, the profit increases significantly.

But as already mentioned earlier in this book, this is an ideal case with the prerequisite that all plastic is sorted and disposed of properly by consumers. Furthermore, the selling price of the rLDPE–rPP is of great importance for the revenue of the optimization process, and thus the profitability of the whole plastics recycling process. Figure 6.5 shows this dependence.

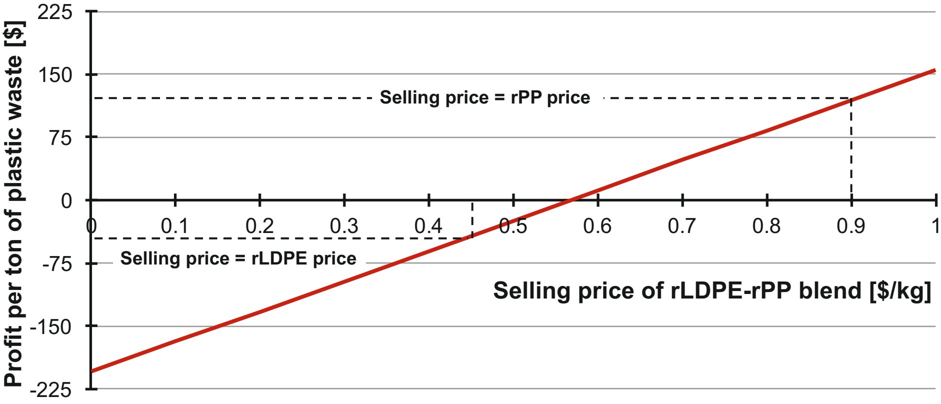

Figure 6.5 Profitability of recycling 1 t of plastic waste as a function of the selling price of the recycled low-density polyethylene–polypropylene (rLDPE–rPP) blends

If the blend were sold for the price of rLDPE, plastic recycling would have a profit of around −$ 60 per ton of plastic waste. If the blend were sold for the price of rPP, the recycling process would have a profit of around $ 120 per ton of plastic waste and be absolutely profitable.

Furthermore, as analyzed in Section 4.4.5, the price of oil is an important factor for optimization II as well. The dependence of rLDPE and rPP prices on the price of oil are the same as for rPET. Assuming the oil prices of April 2016, optimization II turns plastic recycling into a profitable process.

6.3 Optimization III: Increasing the Recycling Rate

As presented in Section 6.2, upcycling[1] of plastic waste by blending several polymers improves the recycling process from both an economic and ecological point of view. In an optimal scenario, the recycling rate of plastic waste in the United States could be increased by 45.7 % based on the numbers of 2013 (see Table 2.1).

However, the problem of this upcycling scenario is that the blended plastics become number 7 plastics (mixed plastic) and are therefore difficult to recycle a second or even a third time. Even if blending can improve the material properties, it is still desirable from an ecological perspective to recycle all plastics separately. Thus, multiple reprocessing cycles could be executed.

As mentioned in Section 6.2, separating PP (density: 946 kg/m^3) and LDPE (density: 940 kg/m^3) is nearly impossible by conventional and economically efficient sorting methods. However, based on the necessity of recycling discussed in Chapter 5, research regarding the separation of each plastic type has intensified. One organization in the United States trying to increase the recycling rate of plastics is the *Closed Loop Fund (CLF)*. It is a social impact fund that invested $ 100 million to increase the recycling of products and packaging. It is their aim by 2025 to proof replicable recycling processes that will help unlock additional investments in recycling. [15, 16]

One of their approaches is the improvement of recycling of numbers 3 to 7 plastics. Even in major markets, no viable options for recycling these plastics exist. As a result, much of this material is being landfilled. Therefore, CLF partnered with QRS Recycling and Canusa Hershman Recycling to create a state-of-the-art plastic recovery factory in Maryland with a capacity to handle more than 50,000 t/year. This $ 15 million project was supported by a $ 2 million investment from CLF and $ 13 million from other private sources. [16] In QRS Recycling's Maryland facility, mixed numbers 3 to 7 plastics in bales from single-stream MRFs are transformed into a high-quality, postconsumer PP and PE flake that can be used by various plastics manufacturers. [16] One of the most significant challenges of this business model besides the sorting process is contamination. Bales of mixed plastics (numbers 3 to 7) often contain a high level of contamination. Certain materials out of these residues can have a costly impact on the process. [16]

Furthermore, the profitability of the business model is still unclear. Recycled LDPE and PP could probably be sold for $ 0.45 per kg (LDPE) and $ 0.90 per kg (PP), but the processing costs are difficult to calculate. In addition, for some feedstocks

[1] Upcycling is the process of transforming waste materials into new materials or products of better quality or for better environmental value.

(mainly numbers 3 and 6 plastics), there is not yet any market and so value for the recycled plastics yet. Thus, these plastics would probably be landfilled, which creates negative impacts both environmentally and ecologically. [16]

However, an increasing recycling rate of plastics has to be the aim of the plastics industry. The environmental value is the highest of all optimization scenarios, mainly because plastics can be recycled several times. And even if the process might not be profitable yet, the economic potential is high.

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7 Plastic Waste of the World: Increasing Potential of Recycling

In addition to the detailed analysis of the plastics recycling market and its potential future, this book provides an outlook on waste handling and recycling in the global market. In order to understand the global effects of waste generation in general and plastics in particular, differentiating between countries by income is more useful than by geographic region. The following data was collected in the 2012 report on global solid waste management by the World Bank. [1] The numbers are only estimates because the data from some countries was missing, was from different years, and was based on slightly different assessment methodologies. Figure 7.1 shows the dependence of waste generation on income level. Low-income countries produce the least and high-income countries the most solid waste per capita. The wide ranges, such as from 0.7 to 14 kg/capita/day for high-income-level countries, result from disparities within the income-level groups. The waste generated is projected to grow in all geographic areas and income levels due to the increase in population and urbanization. However, the higher the income level of a country, the lower is its projected growth rate of waste generation.

Waste collection is instrumental to access the resources buried inside the waste. However, collection rates vary between 41 % in low-income countries and 98 % in high-income countries, mainly due to the associated cost of collection. In low-income countries, collection services account for 80 to 90 % of the municipal solid waste (MSW) budget. In high-income countries, they can be as low as 10 % of the MSW budget. Consumers can be required to separate their waste at the source, such as into different bins, or the unsegregated waste can be separated in sorting facilities. Developing countries use mainly single-stream systems where recyclables are collected by waste pickers during the collection process, starting prior to collection and ending at the disposal sites. In high-income countries, single-stream or multiple-stream systems, such as a combination of curbside pickup and community bins, are used, where collection is frequent and sorting facilities are highly mechanized and efficient. The total amount of recyclables and their quality depend on the degree of separation.

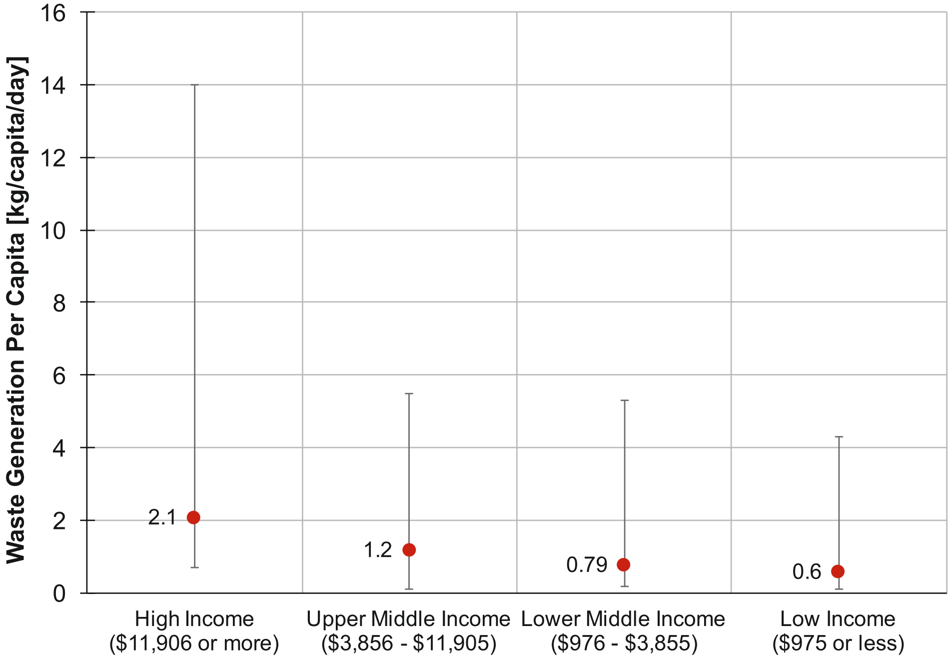

Figure 7.1 Current waste generation per capita by income level (showing the upper and lower limits and the median [dot] waste generation) [1]

The *waste composition* is important to estimate the potential of recycling valuable resources and of energy recovery. Waste composition influences the frequency of collection and disposal and is impacted by factors such as economic development, climate, energy sources, and cultural norms.

As shown in Figure 7.2, the organic fraction tends to be highest in low-income countries and lowest in high-income countries. With progressing urbanization and increase in wealth of a population, more inorganic materials (plastics, paper, and aluminum) are consumed. It is important to note that the total amount of organic waste per capita is on average still 1.5 times higher in high-income countries than in low-income countries. The same is true for all other fractions; for example, the total amount of plastic waste and paper waste is 4.9 times and 22 times higher, respectively. Geography and climate influence the waste composition. It determines the use of building materials (e.g., wood, brick, or steel), horticultural waste, and ash content. The last is related to the predominant energy source as well. Regions where energy for cooking, heating, and lighting is generated by coal and wood fires have a much higher ash content. See, for example, Figure 7.11, which shows the breakdown of waste in China for 2000, where the ash content is included in "Other".

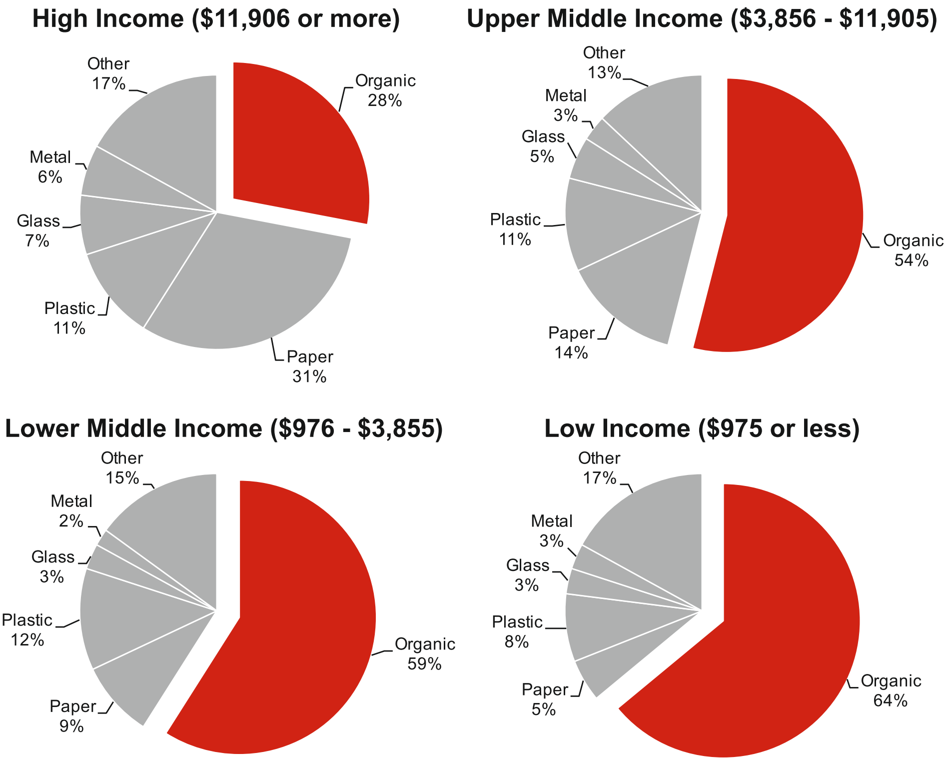

Figure 7.2 Global waste composition by income level. Organic: food scraps, yard waste, wood, and process residues; paper: paper scraps, cardboard, newspaper, magazines, bags, boxes, and wrapping paper; plastic: bottles, packaging, containers, bags, lids, and cups; glass: bottles, broken glassware, light bulbs, and colored glass; metal: cans, foils, tins, nonhazardous aerosol cans, appliances (white goods), railings, and bicycles; other: textiles, leather, rubber, multi-laminates, e-waste, appliances, ash, and other inert material. [1]

The waste disposal data has the highest uncertainty because most countries do not record this kind of data. MSW management practices include (a) landfilling, (b) waste-to-energy (WTE), (c) composting, (d) recycling or recovery from waste, and (e) open burning. In general, most low- and middle-income countries dispose of their MSW in open dumps. Disposal in several of the upper middle-income countries can be classified as controlled dumping, because their landfills are poorly operated. In high-income countries, landfilling and WTE are the most common methods of MSW disposal. Dumping of waste can lead to environmental burdens such as (a) contamination of groundwater and surface water by leachate, (b) soil contamination through contact with waste or leachate, (c) air pollution from uncontrolled and unfiltered burning of waste, (d) spreading of disease, (e) odor in landfills, and (f) uncontrolled release of methane by anaerobic decomposition of waste. [2]

Greenhouse gases from MSW are becoming a major concern. Postconsumer waste is estimated to contribute almost 5 % (1,460 $MtCO_2E$) of the total global GHG emis-

sions. More detailed numbers by country and composition can be found in [1] and [2].

The amount of waste, its composition, and, in particular, the amount of plastic waste vary in the different countries and regions of the world. In the remainder of this chapter, plastics recycling in China, as the largest plastics material and product manufacturer, and in Europe, as the second largest in plastics production, will be taken as examples for more detailed analyses of plastics recycling. [3] Figure 7.3 shows that the global plastics market has increased from 245 Mt in 2008 to 269 Mt in 2015 and that the greatest growth can be seen in China.

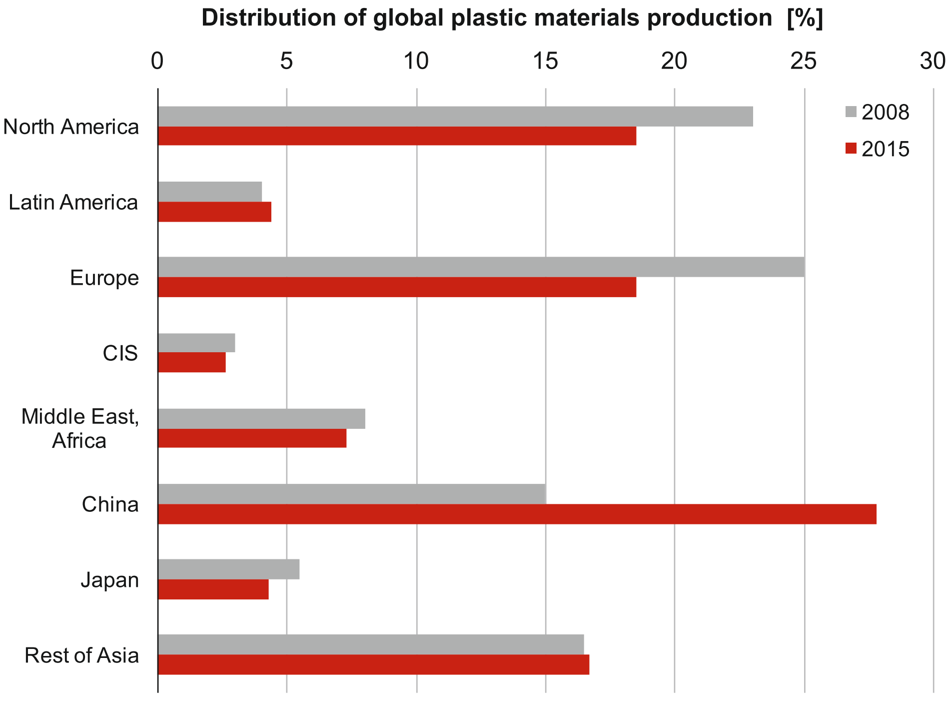

Figure 7.3 Distribution of global plastic materials production in 2008 (total: 245 Mt) and in 2015 (total: 269 Mt). [3] CIS: Commonwealth of Independent States (former Soviet Union).

7.1 Plastic Waste Handling in Europe

Europe has a very strong plastics industry, which has remained relatively consistent over the last decade. Similar to the United States, four sectors—packaging, building and construction, automotive, and electrical equipment—represent about 75 % of the demand for plastics; see Figure 7.4.

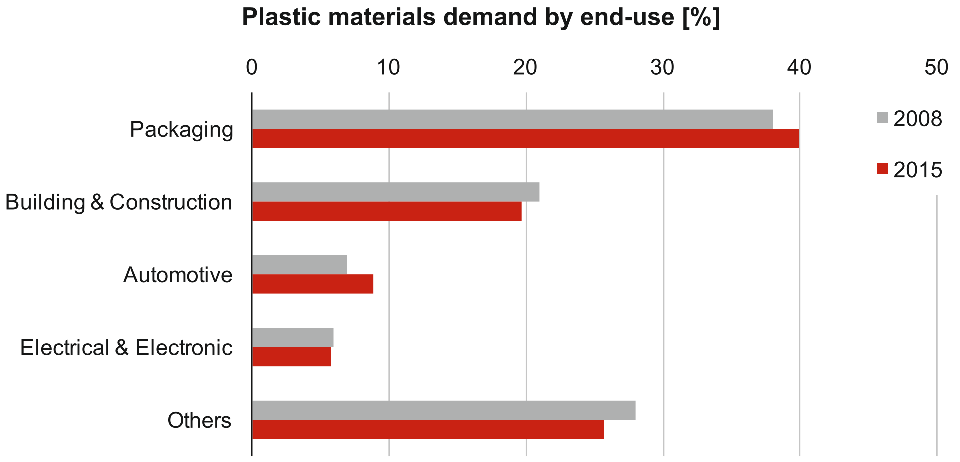

Figure 7.4 Europe's plastic materials demand by end use in 2008 (EU-27, Norway, and Switzerland) of 48.4 Mt and in 2015 (EU-28, Norway, and Switzerland) of 49 Mt. Others: consumer and household goods, furniture, agriculture, medical devices, etc. [3]

Analyzing the demand for specific types of plastic, Figure 7.5 shows similar numbers as the United States. PP and PE account for almost half of the demand in comparison to all other plastics. The shares have remained almost unchanged over the last decade.

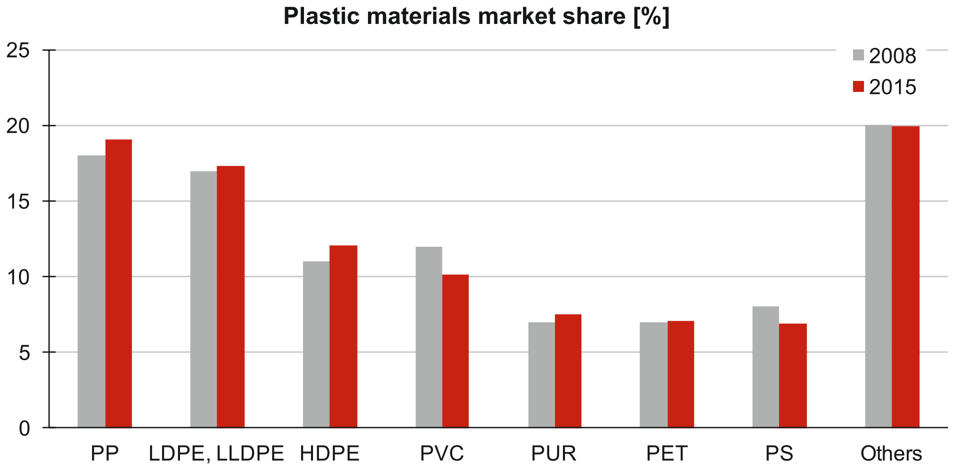

Figure 7.5 Europe's plastic materials market share in 2008 (EU-27, Norway, and Switzerland) and in 2015 (EU-28, Norway, and Switzerland) including thermoplastics, polyurethanes, and other plastics (thermosets, adhesives, coatings, and sealants) without fibers. Others: ABS, PBT, PC, PMMA, and PTFE. [3]

Comparing the data presented for Europe's plastic materials demand (Figure 7.4) with its generation of postconsumer waste (Figure 7.6), a difference due to the short service life of plastic packaging is observed. Although the numbers are different, the same effect was observed in the United States (Section 3.2.2.1) In contrast to the United States, much of the packaging is collected from the commercial and industrial sector. From MSW, mainly PET and HDPE bottles are recovered because the contaminations (colorants and food residue) make it difficult to recycle other packaging materials.

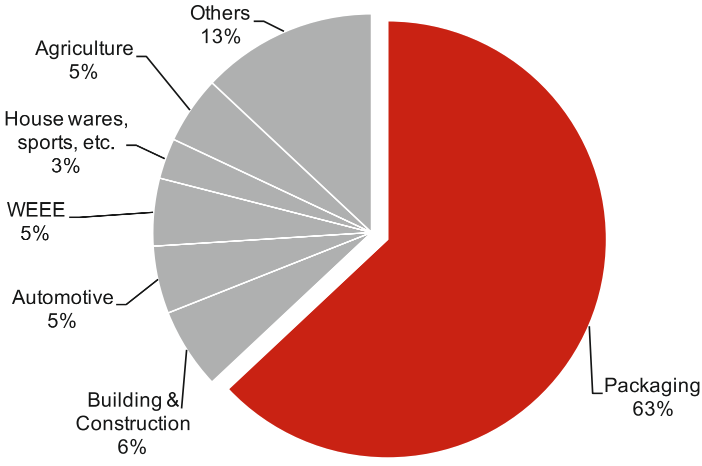

Figure 7.6 Percentages of postconsumer plastic waste in Europe (EU-27, Norway, and Switzerland) by application in 2008 [4]

In contrast, plastics used in construction have a much longer service life, between 30 to 40 years. This explains the discrepancy between the demand for plastic in this sector (21 %) and the relatively low contribution (6 %) to plastic waste. Exact numbers for 2002 for Western Europe show that 7.3 Mt of plastic was consumed in this sector, but only 1 Mt of plastic waste was generated (about 14 % of consumption).

Analysis of the demand for specific types of plastic in Europe (Figure 7.5) shows that PP and PE account for almost half of the demand in comparison to all other plastic materials. The shares have remained almost unchanged over the last decade.

In Europe, only three of the common waste management treatments are used: disposal in landfills, WTE, and recycling. Because of the landfill ban in Switzerland, Austria, Netherlands, Germany, Sweden, Luxembourg, Denmark, Belgium, and Norway, which started as early as 1996, landfilling has constantly declined and energy recovery and recycling have increased (Figure 7.7). In 2014, out of the

25.8 Mt of postconsumer waste collected, 39.5 % and 29.7 % was recovered through energy recovery processes and recycling, respectively. Only 10.2 Mt, or 30.8 %, ended up in landfills. All countries with a landfill ban have landfilled less than 5 % of postconsumer waste. In 2016, two more countries, Poland and Estonia, agreed to the voluntary landfill ban. [3]

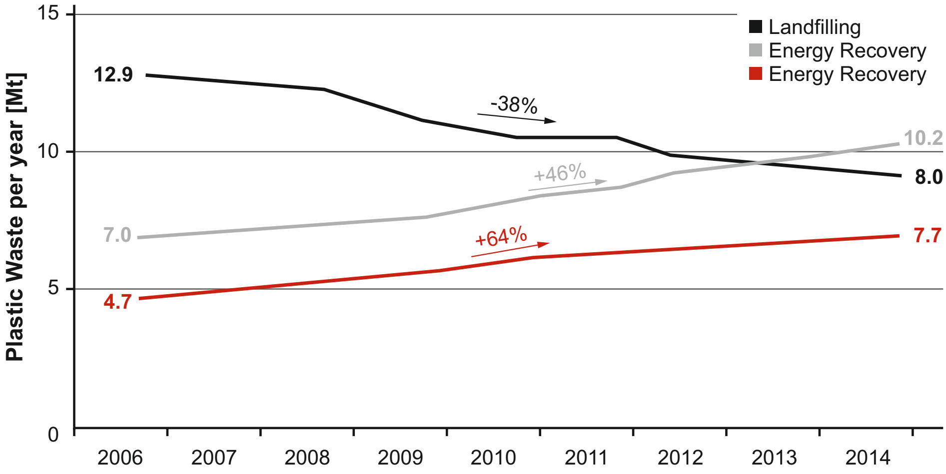

Figure 7.7 Plastic waste treatment in Europe (EU-28, Norway, and Switzerland) from 2006 to 2014 [3]

Since plastic packaging is the most significant waste stream, we will take a closer look at its treatment. In Europe in 2008, 41.8 % of the packaging waste was landfilled and 58.2 % was recovered. Out of the recovered fraction, energy conversion accounted for 29.2 %, while mechanical recycling and feedstock recycling amounted to 28.5 % and 0.5 %, respectively.

Denmark has the highest rate of recovery at 98 %, although this is mainly due to its high rate of incineration (76 %). As the biggest contributor to plastic packaging waste generation, Germany also has a high rate of recovery at 95 %, and mechanically recycles the greatest amount of plastic packaging waste in Europe (1 Mt). Germany is also one of only two countries that chemically recycles plastic packaging waste (0.054 Mt in Germany and 0.0005 Mt in Poland). A compilation of the waste treatments within the different sectors can be seen in Figure 7.8.

It should be noted that some of the recovered plastic waste from Europe is sold to China and Hong Kong (88 % of exported European Union [EU] waste, or 1.85 Mt, in 2006). Only about 1 Mt of plastic waste is imported to Europe from various non-EU countries (2004). Inter-European trade in recovered plastic waste exists as well.

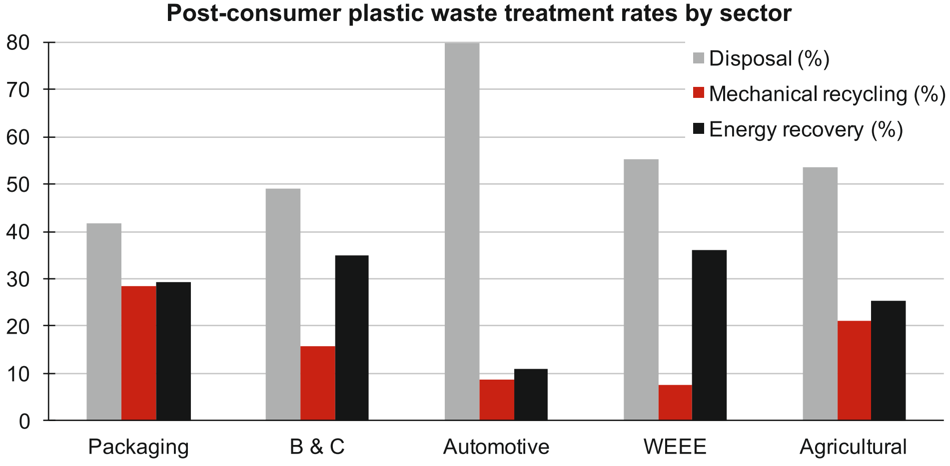

Figure 7.8 Europe's postconsumer plastic waste treatment rates by sector in 2008; feedstock recycling accounted for 0.5 % of both packaging and automotive plastic waste [4] B & C, building and construction; WEEE, waste electrical and electronics equipment.

The recycling system in Germany will be used as a European example to highlight some differences with the U.S. system. The dual system, chosen as Optimization Scenario I (see Section 6.1), organizes household packaging waste collection (via a yellow bin or yellow bag that is left curbside) and ensures presorting by the consumer and professional recycling of packaging in appropriate facilities. The disposal services (collection, sorting, and recycling of packaging) are financed via participation payments of packaging manufacturers and are executed by commissioned disposal companies. Participation is mandatory and allows the manufacturers to label their products with the *green dot ("Grüner Punkt")*. Since manufacturers are required to pay for their packaging products by weight, material consumption has decreased since the system was introduced due to use of thinner glass, paper, plastic bottles, and films. This further reduces the amount of waste that needs recycling.

For both glass and plastic bottles a *deposit and return system* exists. The deposit is paid by the consumer upon purchase of a product. It ranges from €0.15 for refillable bottles to €0.25 for disposable bottles. The empty bottle can be returned to stations similar to vending machines that automatically scan and accept or reject the bottle and reimburse the deposit for all refillable bottles. Due to their light weight and the reduction of use of virgin plastics, the refillable PET bottles are slightly more ecologically friendly than refillable glass bottles and significantly more so than disposable bottles.

This deposit, or payment, system is also used for plastic bags. Whereas in countries like the United States the consumer is generally incentivized for not using a plastic bag in the grocery store, in Germany the consumer has to pay for the bag.

The price ranges from a few cents to €1 in most stores. While this payment system has been common in grocery stores for years, it was just recently (April 2016) expanded to all stores, including retailers. Although it is still voluntary, most stores are participating and charge €0.05 to €0.20 per plastic bag. Most paper bags continue to be free of charge.

All these improvements are possible due to mechanized collection, efficient recycling, waste treatment facilities, and continued education of the consumer over the last three decades. Last but not least, the economic strength of Germany and other European countries enables the investment in such projects and initiatives.

7.2 Plastic Waste Handling in China

As a consequence of China's fast economic growth, in 2013 the country bypassed all other countries and regions and became the world's largest producer of plastic products. Its domestic consumption of plastics has skyrocketed as well. [5]

China is also the main market for postconsumer plastic waste. The demand for postconsumer plastic waste is spread across seven main sectors of the economy, with the top three, packaging, construction, and appliances, accounting for almost 80% of the total demand, as shown in Figure 7.9. However, there are different estimates of the balance of end uses of these materials. For example, the proportion of postconsumer plastic waste used in textiles could be significantly higher than that shown in the graph and packaging accordingly lower. [6]

The packaging sector accounts for over 40% of the demand for postconsumer plastic waste in China, mainly for use in the production of bottles and bags. Polyethylene (PE) is typically used to make bottles for shampoo, detergent, and industrial oil. Recycled PET is almost exclusively used in fiber applications, but its use in packaging is now growing as well. Polypropylene (PP) is used to make cement and fertilizer bags. [6]

Construction has been a fast-growing sector in China, accounting for about 20% of the demand, mostly to make pipes and boards. The main postconsumer plastic waste used is recycled polyvinyl chloride (PVC), but small amounts of PE and PP are also used. Extruded polystyrene (XPS) board is used as insulating material for walls and roofs. Waterproof film to protect construction sites from the weather is made from recycled PE. There are some newer applications, such as wood-plastic composites in which postconsumer plastic waste (again recycled PE and recycled PP) are compounded with wood fibers. [6]

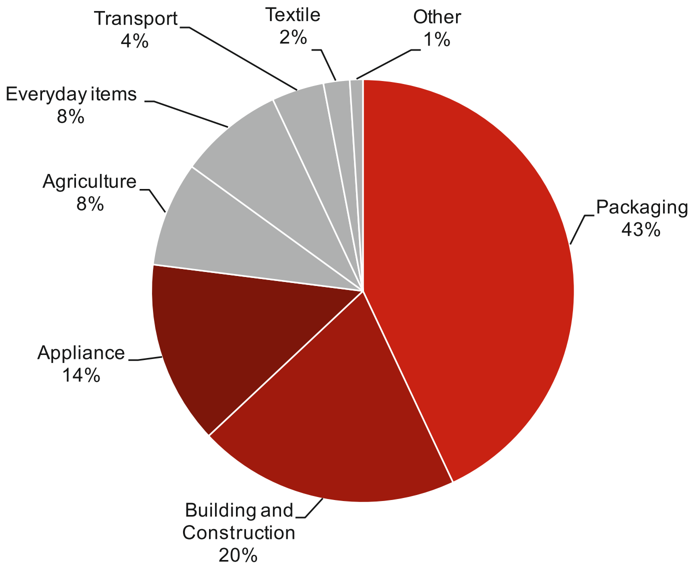

Figure 7.9 Postconsumer plastic waste demand by sector in China in 2011. Courtesy of CBI (China) Co., Ltd., Shanghai, China. [6]

Figure 7.10 shows the composition of the plastic waste China imported from the United States in 2011; the category "Others", which accounts for 60 % of the plastic waste imported, includes recycled PET, recycled PP, etc.

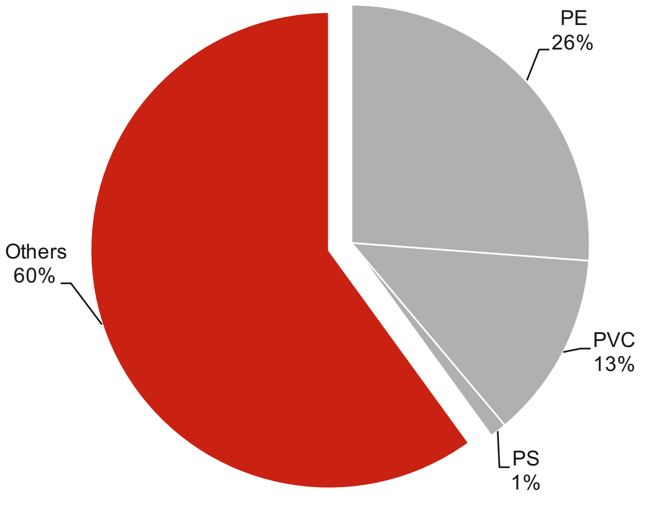

Figure 7.10 The composition of U.S. exports of plastic waste to China including Hong Kong and the South Asian Region in 2011 [7]

The announcement of Operation Green Fence in February 2013 aimed to reduce the amount of poor quality postconsumer plastic waste imported to China. The focus was on lower contamination and an increasing proportion of single (or sorted) polymers. Therefore, the amount of plastic imported by China has stagnated. More recent numbers show that this trend is continuing. For example, China imported 2 Mt of postconsumer plastic waste (from all countries) during the period from January to April 2016, which is down 11 % compared to the same period in 2015. [8, 9, 10]

With more plastic waste now remaining in the United States, American recycling firms are losing money processing the materials that they would normally send overseas. This means much more plastic waste is ending up in landfills until the recycling infrastructure is updated. [5]

The domestic sourcing of postconsumer waste in China is more difficult. As explained earlier, the MSW composition is strongly influenced by the energy source. Figure 7.11 shows the difference in the percentages of plastic waste in MSW based on whether coal or gas is used for heating. In 2000 about 2 Mt and 13 Mt of plastic was present in postconsumer waste from coal-heated and gas-heated households in China, respectively. [11]

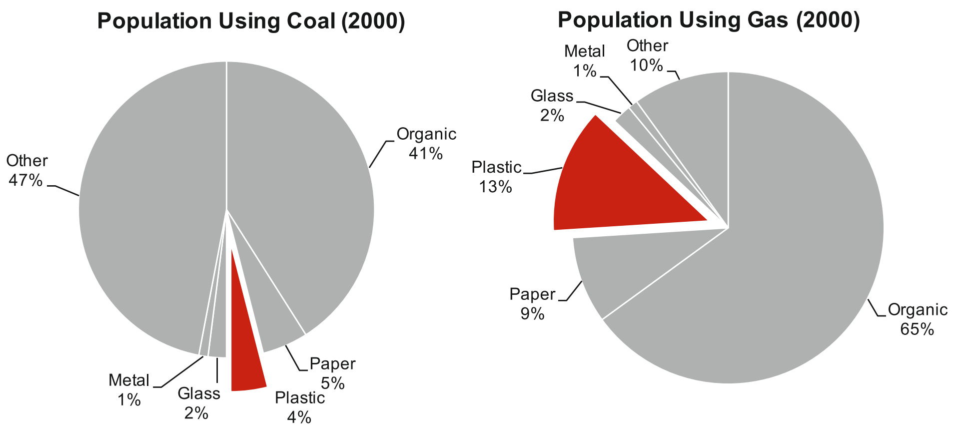

Figure 7.11 Municipal waste composition in China in 2000 [7]

As shown in Figure 7.12, the amount of domestically available postconsumer plastic waste was still smaller than the plastic waste fraction in MSW, because the collection is inefficient. However, the amount of domestically available postconsumer plastic waste is steadily growing to meet the demand of the growing industry.

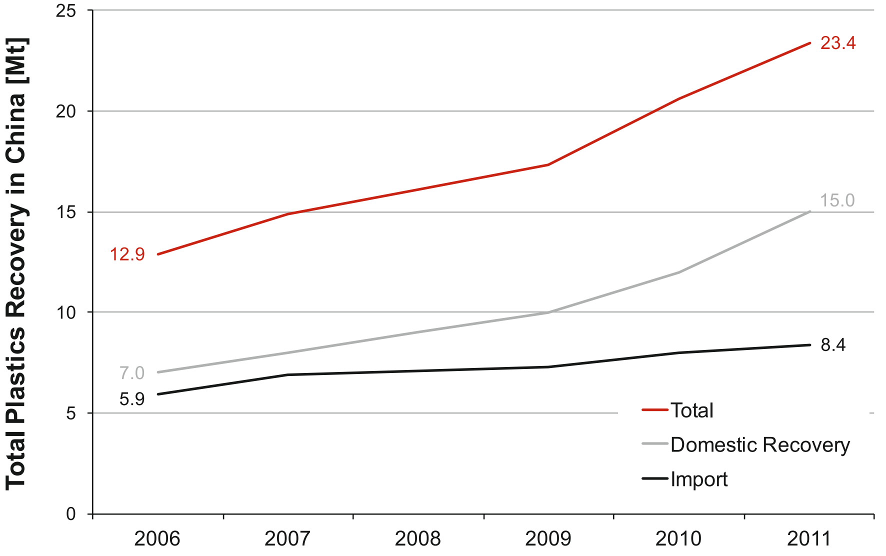

Figure 7.12 Total postconsumer plastic waste recovery in China from 2006 to 2011 [7]

The predicted MSW composition of 2030 is shown in Figure 7.13. This will result in 68 Mt of plastic waste per year in China, which is over 4.5 times higher than in 2000. With the increasing efficiency of the collection process, this has huge potential for providing the needs of China for plastic waste domestically. However, if the collection process is not improved, this will not be possible and there will be catastrophic environmental consequences.

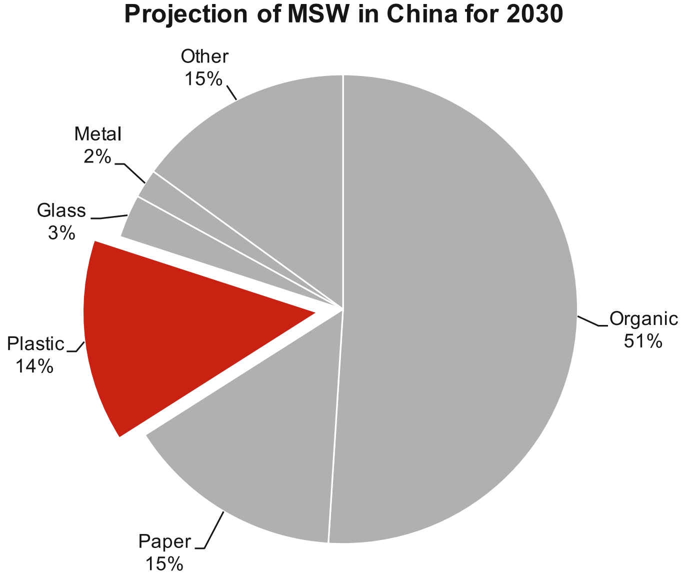

Figure 7.13 The estimated municipal solid waste (MSW) composition in China in 2030 [11]

Today the recycled plastics market is still dominated by thousands of small manufacturers and reprocessors using low-tech equipment and without any antipollution practices in place. They are often family run, operate without any environmental protection controls, and produce low-quality recycled products.

Starting with the recycling collection, Chinese cities have thousands of individual bottle collectors. These are people who offer small amounts of money to households for their recyclable products. They sell them to "recycling stores", who in turn sell them to the reprocessing companies. The quality of the recycling collection materials is not uniform. As a result, the reprocessors can only produce low-quality products at high quantities, such as plastic bags, disposable dishware, and stationery items. Some of these cheap products are shipped back to Europe and North America. However, the majority are consumed in China. [8]

Due to the huge gap between the low-quality domestic sources and higher-quality imported postconsumer plastic waste sources, most of China's recyclers do not consider sourcing plastic waste domestically. Regardless of the source, they tend to add considerably higher amounts of additives, such as cheap fluorine surfactants, during reprocessing thus making future recycling difficult. Furthermore, wastewater from these processes is discharged untreated and residues are disposed of by uncontrolled burning. [6, 9, 12]

Thus, China is also leading the world in terms of plastic waste. China is responsible for an estimated 28 % of the plastic debris in our waterways. With another 300 million urban residents expected by 2025 and growing rates of consumption, the prediction of 68 Mt of plastic waste for China will likely become a reality. Therefore, proper waste management would have a huge impact. [5, 13]

More recently, there has been great interest in waste incineration, because burning waste will address landfill space limitation issues and the energy from incineration will generate revenue for the communities. However, the unsorted Chinese urban waste stream with high proportions of damp organic material reduces the efficiency of incineration, as was explained in detail in the economic analysis in Section 4.3. Much more fuel is required to burn damp waste, increasing the costs and decreasing or even nullifying the profits from energy generation. Another problem is the poor regulation of waste incinerators in China. The resulting toxic air pollution is an environmental and public health issue in the region. Another alternative mentioned earlier is using anaerobic bacteria to decompose organic waste and even to capture the methane as a fuel source, which has recently sparked some interest. [8, 14, 15]

7.3 Plastic Waste in the Future

Due to the global growth of plastic materials in many industry sectors, the generation of plastic waste has increased. From 1950 to 2012, the growth of the industry was 8.7 % on average per year, which equals a total increase from 1.7 Mt in 1950 to the 322 Mt in 2015. [3, 16] In parallel, the percentage of plastic waste in MSW grew as well, which demonstrates the rising significance of plastics in our daily life. Today, an average person living in Western Europe or North America consumes 100 kg of plastic each year, mostly in the form of packaging. Asia uses just 20 kg per person, but this number is predicted to grow rapidly as economies in the region expand. [19] Our standard of living directly correlates to the amount of plastic in our MSW. Waste generation rates tend to be much higher in urban centers. Today, more than 50 % of the world's population lives in cities, and the rate of urbanization is increasing quickly. By 2050, as many people will live in cities as the population of the whole world in 2000. This will add challenges to waste disposal. [1, 16]

As shown in Chapter 4, recovering plastic from the waste stream for recycling or for incineration with energy recovery has the potential to minimize these problems. As of today, only about 10 % and 30 % of the plastic in MSW is recycled in the United States and Europe, respectively. In addition, much of the recovered plastic is exported to countries with lower environmental regulations, which was noted for the example of China. Furthermore, WTE facilities require air emissions controls and produce hazardous ash. [16]

Chapter 5 explains why recycling is the necessary method of handling our plastic waste, even if the process is currently not profitable. However, the two optimization scenarios in Chapter 6 showed that plastic recycling has the potential to be profitable if the process is changed or extended. In the future, this potential will increase, both for the United States and worldwide!

Based on the growth predictions, citizens and corporations will likely need to assume more responsibility for waste generation and disposal, specifically, in terms of product design and waste separation. Also likely to emerge will be a greater emphasis on "urban mining". [1]

Figure 7.14 shows an even broader view of the economic potential of plastics recycling, identified by Project MainStream, a multi-industry, global initiative launched in 2014 by the World Economic Forum and the Ellen MacArthur Foundation, with McKinsey & Company as knowledge partner. Currently, only 5 % of the material value of plastic packaging is captured worldwide after one use, corresponding to $ 4 billion to $ 6 billion per year. The actual value yield of recycling is only 36 %. By blending plastics, such as LDPE and PP during recycling, and thereby improving the properties of the recycled material, this yield can be increased significantly.

Furthermore, the current worldwide plastic recycling rate is only 14 %. Levers for an enhanced recycling rate are secondary markets, a global plastic protocol, technological innovations, and enabling policies. By increasing both the value yield and the recycling rate, the captured material value could be between $ 80 billion and $ 120 billion per year. [16]

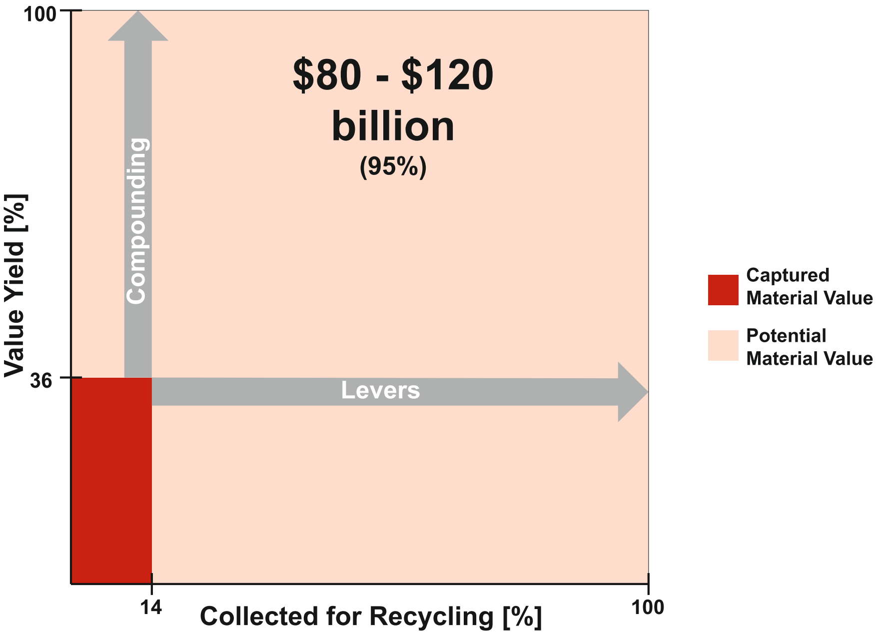

Figure 7.14 Economic potential of recycling plastic waste [16]

This potential analysis reflects the results of Chapter 6 of this book: recycling is not only the best waste handling method for our environment, but also its economic potential value is high. It is the duty of our society to exploit the maximum potential of the plastic recycling process.

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8 Appendix

This chapter shows the detailed numbers and calculations of the economic analysis in Chapter 4 and the optimization scenarios in Chapter 6.

Since these calculations are based and depend on several assumptions (e.g., efficiencies, size of factories, waste capacity, exchange rate, salaries), the tables enable the analysis of different scenarios for landfilling, incineration with energy recovery, and recycling of plastic waste.

> Yet more detailed spreadsheets used in these analyses can be downloaded from http://files.hanser.de/fachbuch/9781569906767_Spreadsheets.zip. These can be adapted to allow you to obtain results for your own ideas and scenarios.

8.1 Economic Analysis of Landfilling

Table 8.1 Economic Analysis of Landfill: Construction Costs (imperial)

Buildings	Area [sq ft]	Costs [$/sq ft] Min.	Max.	Average	Total Costs [$] Min.	Max.	Average
Maintenance buildings	10,000	50.00	70.00	60.00	500,000.00	700,000.00	600,000.00
Office buildings	3,000	60.00	100.00	80.00	180,000.00	300,000.00	240,000.00
Shacks and tool sheds	1,000	10.00	20.00	15.00	10,000.00	20,000.00	15,000.00
IT	**Pieces**	**Costs per unit [$/piece] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Associated computer systems	1	50,000.00	75,000.00	62,500.00	50,000.00	75,000.00	62,500.00
Modular truck scales	1	50,000.00	75,000.00	62,500.00	50,000.00	75,000.00	62,500.00
Roads	**Area [sq ft]**	**Costs [$/sq ft] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Perimeter access roads (gravel)	120,000	1.00	2.00	1.50	120,000.00	240,000.00	180,000.00
Perimeter access roads (asphalt)	0	6.00	9.00	7.50	0.00	0.00	0.00
Security Barrier	**Length [ft]**	**Costs [$/ft] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Fence	6,000	10.00	20.00	15.00	60,000.00	120,000.00	90,000.00
Gates	5	1,000.00	2,000.00	1,500.00	5,000.00	10,000.00	7,500.00
Signages (200 ft intervals)	30 pc.	10.00	20.00	15.00	300.00	600.00	450.00
Washing	**Pieces**	**Costs per unit [$/piece] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Wheel washing facilities	1	200,000.00	250,000.00	225,000.00	200,000.00	250,000.00	225,000.00
Liner Construction	**Area [acre]**	**Costs [$/acre] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Clear and grub	33.50	1,000.00	3,000.00	2,000.00	33,500.00	100,500.00	67,000.00
Site survey	33.50	5,000.00	8,000.00	6,500.00	167,500.00	268,000.00	217,750.00
Excavation	33.50	100,000.00	330,000.00	215,000.00	3,350,000.00	11,055,000.00	7,202,500.00
Perimeter berm	33.50	10,000.00	16,000.00	13,000.00	335,000.00	536,000.00	435,500.00
Clay liner	33.50	32,000.00	162,000.00	97,000.00	1,072,000.00	5,427,000.00	3,249,500.00
Geomembrane	33.50	24,000.00	35,000.00	29,500.00	804,000.00	1,172,500.00	988,250.00
Geocomposite	33.50	33,000.00	44,000.00	38,500.00	1,105,500.00	1,474,000.00	1,289,750.00
Granular soil	33.50	48,000.00	64,000.00	56,000.00	1,608,000.00	2,144,000.00	1,876,000.00
Leachate system	33.50	8,000.00	102,000.00	55,000.00	268,000.00	3,417,000.00	1,842,500.00
QA/QC	33.50	75,000.00	100,000.00	87,500.00	2,512,500.00	3,350,000.00	2,931,250.00
Total Costs					**12,431,300.00**	**30,734,600.00**	**21,582,950.00**

Table 8.2 Economic Analysis of Landfill: Construction Costs (metric)

Buildings	Area [sq m]	Costs [$/sq m] Min.	Max.	Average	Total Costs [$] Min.	Max.	Average
Maintenance buildings	929	538.18	753.46	645.82	500,000.00	700,000.00	600,000.00
Office buildings	279	645.82	1,076.36	861.09	180,000.00	300,000.00	240,000.00
Shacks and tool sheds	93	107.64	215.27	161.45	10,000.00	20,000.00	15,000.00
IT	**Pieces**	**Costs per unit [$/piece] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Associated computer systems	1	50,000.00	75,000.00	62,500.00	50,000.00	75,000.00	62,500.00
Modular truck scales	1	50,000.00	75,000.00	62,500.00	50,000.00	75,000.00	62,500.00
Roads	**Area [sq m]**	**Costs [$/sq m] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Perimeter access roads (gravel)	11,149	10.76	21.53	16.15	120,000.00	240,000.00	180,000.00
Perimeter access roads (asphalt)	0	64.58	96.87	80.73	0.00	0.00	0.00
Security Barrier	**Length [m]**	**Costs [$/m] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Fence	1,829	32.81	65.62	49.21	60,000.00	120,000.00	90,000.00
Gates	2	3,280.80	6,561.60	4,921.20	5,000.00	10,000.00	7,500.00
Signages (200 ft intervals)	30 pc.	10.00	20.00	15.00	300.00	600.00	450.00
Washing	**Pieces**	**Costs per unit [$/piece] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Wheel washing facilities	1	200,000.00	250,000.00	225,000.00	200,000.00	250,000.00	225,000.00
Liner Construction	**Area [sq m]**	**Costs [$/sq m] Min.**	**Max.**	**Average**	**Total Costs [$] Min.**	**Max.**	**Average**
Clear and grub	13.56	2,471.05	7,413.16	4,942.11	33,500.00	100,500.00	67,000.00
Site survey	13.56	12,355.27	19,768.43	16,061.85	167,500.00	268,000.00	217,750.00
Excavation	13.56	247,105.41	815,447.84	531,276.63	3,350,000.00	11,055,000.00	7,202,500.00
Perimeter berm	13.56	24,710.54	39,536.87	32,123.70	335,000.00	536,000.00	435,500.00
Clay liner	13.56	79,073.73	400,310.76	239,692.25	1,072,000.00	5,427,000.00	3,249,500.00
Geomembrane	13.56	59,305.30	86,486.89	72,896.10	804,000.00	1,172,500.00	988,250.00
Geocomposite	13.56	81,544.78	108,726.38	95,135.58	1,105,500.00	1,474,000.00	1,289,750.00
Granular soil	13.56	118,610.60	158,147.46	138,379.03	1,608,000.00	2,144,000.00	1,876,000.00
Leachate system	13.56	19,768.43	252,047.52	135,907.97	268,000.00	3,417,000.00	1,842,500.00
QA/QC	13.56	185,329.06	247,105.41	216,217.23	2,512,500.00	3,350,000.00	2,931,250.00
Total Costs					**12,431,300.00**	**30,734,600.00**	**21,582,950.00**

Table 8.3 Economic Analysis of Landfill: Operations Costs

Personnel	Units	Unit Costs [$/unit]	Total Costs [$]
Facility Manager	2	89,033.00	178,066.00
Equipment Operators	4	59,455.00	237,820.00
Scale House Attendant	2	37,428.00	74,856.00
General Laborers	4	29,539.00	118,156.00
Equipment Operating Costs	**Usage [h]**	**Cost per Hour [$/h]**	**Total Costs [$]**
Bulldozer	3,180	55.00	174,900.00
Compactor	3,180	50.00	159,000.00
Front-End-Loader	3,180	50.00	159,000.00
Grader	3,180	30.00	95,400.00
Site Repairs and Maintenance	**Units**	**Unit Costs [$/unit]**	**Total Costs [$]**
Perimeter access roads (gravel)	1	160,000.00	160,000.00
Leachate Collection and Treatment	**Gallons**	**Costs per Gallon [$/gallon]**	**Total Costs [$]**
Leachate Collection and Treatment Costs	1,500,000.00	0.02	30,000.00
Others	**Units**	**Unit Costs [$/unit]**	**Total Costs [$]**
Environmental Sampling and Monitoring	1	60,000.00	60,000.00
Engineering Services (Consulting, in-house staff)	1	120,000.00	120,000.00
Operation costs per year [$]			**1,567,198.00**
Total operation costs (11 years) [$]			**17,239,178.00**

Table 8.4 Economic Analysis of Landfill: Closure Costs (imperial)

Task	Area [acre]	Costs [$/acre]			Total Costs [$]		
		Min.	Max.	Average	Min.	Max.	Average
Final grade survey	34.00	3,000.00	6,000.00	4,500.00	102,000.00	204,000.00	153,000.00
Gas management layer	34.00	24,000.00	32,000.00	28,000.00	816,000.00	1,088,000.00	952,000.00
Compacted clay cap	34.00	26,000.00	51,000.00	38,500.00	884,000.00	1,734,000.00	1,309,000.00
Geomembrane cap	34.00	18,000.00	23,000.00	20,500.00	612,000.00	782,000.00	697,000.00
Geocomposite	34.00	33,000.00	44,000.00	38,500.00	1,122,000.00	1,496,000.00	1,309,000.00
Cover and vegetative soil	34.00	13,000.00	26,000.00	19,500.00	442,000.00	884,000.00	663,000.00
Seed, mulch, fertilize	34.00	1,000.00	2,000.00	1,500.00	34,000.00	68,000.00	51,000.00
Gas management system	34.00	29,000.00	35,000.00	32,000.00	986,000.00	1,190,000.00	1,088,000.00
Run-off control system	34.00	5,000.00	7,000.00	6,000.00	170,000.00	238,000.00	204,000.00
QA/QC	34.00	75,000.00	100,000.00	87,500.00	2,550,000.00	3,400,000.00	2,975,000.00
Total		**227,000.00**	**326,000.00**	**276,500.00**	**7,718,000.00**	**11,084,000.00**	**9,401,000.00**

Table 8.5 Economic Analysis of Landfill: Closure Costs (metric)

Task	Area [sq m]	Costs [$/sq m]			Total Costs [$]		
		Min.	Max.	Average	Min.	Max.	Average
Final grade survey	13.76	7,413.16	14,826.32	11,119.74	102,000.00	204,000.00	153,000.00
Gas management layer	13.76	59,305.30	79,073.73	69,189.51	816,000.00	1,088,000.00	952,000.00
Compacted clay cap	13.76	64,247.41	126,023.76	95,135.58	884,000.00	1,734,000.00	1,309,000.00
Geomembrane cap	13.76	44,478.97	56,834.24	50,656.61	612,000.00	782,000.00	697,000.00
Geocomposite	13.76	81,544.78	108,726.38	95,135.58	1,122,000.00	1,496,000.00	1,309,000.00
Cover and vegetative soil	13.76	32,123.70	64,247.41	48,185.55	442,000.00	884,000.00	663,000.00
Seed, mulch, fertilize	13.76	2,471.05	4,942.11	3,706.58	34,000.00	68,000.00	51,000.00
Gas management system	13.76	71,660.57	86,486.89	79,073.73	986,000.00	1,190,000.00	1,088,000.00
Run-off control system	13.76	12,355.27	17,297.38	14,826.32	170,000.00	238,000.00	204,000.00
QA/QC	13.76	185,329.06	247,105.41	216,217.23	2,550,000.00	3,400,000.00	2,975,000.00
Total		**560,929.27**	**805,563.63**	**683,246.45**	**7,718,000.00**	**11,084,000.00**	**9,401,000.00**

Table 8.6 Economic Analysis of Landfill: Postclosure and Maintenance Costs (imperial)

Task	Area [acre]	Costs [$/acre] per Year			Total Costs [$] per Year		
		Min.	Max.	Average	Min.	Max.	Average
Security and fencing repair	34.00	3.00	6.00	4.50	102.00	204.00	153.00
Cap and cover maintenance	34.00	300.00	567.00	433.50	10,200.00	19,278.00	14,739.00
Leachate machinery maintenance	34.00	900.00	1,200.00	1,050.00	30,600.00	40,800.00	35,700.00
Landfill gas machinery maintenance	34.00	450.00	570.00	510.00	15,300.00	19,380.00	17,340.00
Wells/Probes	34.00	20.00	30.00	25.00	680.00	1,020.00	850.00
Environmental monitoring	34.00	450.00	575.00	512.50	15,300.00	19,550.00	17,425.00
Total (per year)		2,123.00	2,948.00	2,535.50	72,182.00	100,232.00	86,207.00
Total (30 years)		**63,690.00**	**88,440.00**	**76,065.00**	**2,165,460.00**	**3,006,960.00**	**2,586,210.00**

Table 8.7 Economic Analysis of Landfill: Postclosure and Maintenance Costs (metric)

Task	Area [sq m]	Costs [$/sq m] per Year			Total Costs [$] per Year		
		Min.	Max.	Average	Min.	Max.	Average
Final grade survey	13.76	7.41	14.83	11.12	102.00	204.00	153.00
Gas management layer	13.76	741.32	1,401.09	1,071.20	10,200.00	19,278.00	14,739.00
Compacted clay cap	13.76	2,223.95	2,965.26	2,594.61	30,600.00	40,800.00	35,700.00
Geomembrane cap	13.76	1,111.97	1,408.50	1,260.24	15,300.00	19,380.00	17,340.00
Geocomposite	13.76	49.42	74.13	61.78	680.00	1,020.00	850.00
Cover and vegetative soil	13.76	1,111.97	1,420.86	1,266.42	15,300.00	19,550.00	17,425.00
Total (per year)		5,246.05	7,284.67	6,265.36	72,182.00	100,232.00	86,207.00
Total (30 years)		**157,381.43**	**218,540.02**	**187,960.73**	**2,165,460.00**	**3,006,960.00**	**2,586,210.00**

8.2 Economic Analysis of WTE

Table 8.8 Economic Analysis of Waste-to-Energy Plant: Assumptions

General	
Price level ratio of purchasing power parity conversion factor (Croatia)	0.6
Lifetime [years]	35
Yearly waste capacity [t]	100,000
Total waste capacity (35 years) [t]	3,500,000
Steam generator efficiency [%]	80
Percentage of plastic in MSW [%]	12.8
Percentage heat of produced energy [%]	75
Percentage electricity of produced energy [%]	25
Energy per cubic meter in gas [kWh]	12.5
Average lower heating value MSW [MJ/kg]	15.05
Average lower heating value plastic [MJ/kg]	36.14
Costs/Revenue per kWh electricity [$/kWh]	0.0996
Cost/Revenue per cubic ft gas [$/cubic ft]	0.0035
Cost/Revenue per cubic meter gas [$/cubic meter]	0.1236

Table 8.9 Economic Analysis of Waste-to-Energy Plant: Investment Costs

Type of Costs	Costs Croatia [€]	PP conversion factor	Euro-Dollar-Rate	Costs USA [$]
Infrastructure and waste storage	4,600,000.00	0.60	1.21	9,296,569.33
Combustion system and steam generator	19,500,000.00			39,409,370.00
Water and steam system	8,000,000.00			16,167,946.67
Design	2,000,000.00			4,041,986.67
Construction	7,000,000.00			14,146,953.33
Electro-mechanical installations	5,000,000.00			10,104,966.67
Semi-dry-treatment	1,200,000.00			2,425,192.00
Bag filter	2,200,000.00			4,446,185.33
Selective non-catalytic reduction (SNCR) system	800,000.00			1,616,794.67
Other investment costs	6,000,000.00			12,125,960.00
Total	**4,200,000.00**			**113,781,924.67**

Table 8.10 Yearly Operating and Maintenance Costs [$]

Personal Salaries	Number p. shift	Cost p. person p. year [$]	Shifts per day	Total Costs [$]
Worker	15	29,539.00	3	1,329,255.00
Environmental Engineer	5	88,513.00	3	1,327,695.00
Maintenance Engineer	3	62,715.00	3	564,435.00
Manager (Energy Engineering)	1	95,247.00	3	285,741.00
Machine and Emission Costs	**Costs Croatia [€]**	**PP conversion factor**	**Euro-Dollar-Rate**	**Costs USA [$]**
System maintenance (3% of invest.)	1,689,000.00	0.60	1.21	3,413,457.74
Process water	12,000.00			24,251.92
Natural gas	85,000.00			171,784.43
Reagent for SNCR	80,000.00			161,679.47
Reagent for semi-dry treatment	70,000.00			141,469.53
Bottom ash-disposal	1,380,000.00			2,788,970.80
Flying ash from steam generator	138,000.00			278,897.08
Bag filter residues	1,575,000.00			3,183,064.50
Emission fees	13,560.00			27,404.67
Type of cost	**Consumption per ton of waste [MWh/t]**	**Consumption per year [MWh]**	**Costs per MWh [$/MWh]**	**Total Costs [$]**
Electricity	0.10	10,000.00	99.60	99,600.00
Heat	0.05	5,000.00	9.89	2,472.03
Yearly operating and maintenance costs [$]				**102,072.03**
Overall operating and maintenance costs (35 yrs) [$]				**102,072.03**

Table 8.11 Economic Analysis of Waste-to-Energy Plant: Average Lower Heating Value (LHV) of Plastic

Type of plastic	LHV [MJ/kg]	% in Waste [%]	Total [MJ/kg]
PET	23.2	14.39	3.34
HDPE	44.6	17.16	7.65
PP	42.7	22.76	9.72
LDPE	42.2	22.94	9.68
PVT	19.2	6.98	1.34
PS	42.0	2.77	1.16
Others	25.0	13.00	3.25
Total [MJ/kg]			**36.14**

Table 8.12 Economic Analysis of Waste-to-Energy Plant: Average Lower Heating Value (LHV) of Municipal Solid Waste

Type of waste	LHV [MJ/kg]	% in Waste [%]	Total [MJ/kg]
Paper	19.12	27.00	5.16
Glass	0.00	4.54	0.00
Metals	0.00	9.07	0.00
Plastics	36.14	12.80	4.63
Rubber and Leather	31.28	3.04	0.95
Textiles	16.05	5.95	0.95
Wood	11.63	6.21	0.72
Food	6.05	13.84	0.84
Yard Trimmings	6.98	13.48	0.94
Other	21.05	4.07	0.86
Total [MJ/kg]			**15.05**

Table 8.13 Economic Analysis of Waste-to-Energy (WTE) Plant: Tipping Fee

State	Number of WTE plants	Average WTE Tip Fee [$/t]	Total
Alabama	1	25.00	25.00
Connecticut	7	64.00	448.00
Florida	12	52.92	635.04
Iowa	1	64.00	64.00
Massachusetts	7	69.00	483.00
Minnesota	9	55.00	495.00
New Hampshire	2	69.00	138.00
New Jersey	5	85.00	425.00
New York	10	72.34	723.40
Washington	3	98.00	294.00
Wisconsin	2	51.00	102.00
Total	59		3,832.44
Overall Average Tipping Fee			**64.96**

8.3 Economic Analysis of Recycling

Table 8.14 Economic Analysis of Plastics Recycling: Overall Assumptions

Percentage of PET in plastic waste [%]	14.39
Average price of recycled PET flakes [$/lb]	0.57
Price of recycled PET pellets [$/kg]	1.26
Electricity price [$/kWh]	0.0996
Diesel price [$/gallon]	2.198
Diesel price [$/l]	0.5807
Water price [$/gallon]	0.015
Water price [$/l]	0.0040

Table 8.15 Economic Analysis of Plastics Recycling: Materials Recovery Facility (MRF) Assumptions

Lifetime [years]	10
Processing building size (sq. ft)	80,000
Waste handled per hour [t]	30
Yearly waste handling [t]	120,000
Total waste handling (10 years) [t]	1,200,000
Residues rate [%]	2
Correctness of manual plastic sorting [%]	91
Shifts per day	2.0
Hours per shift [h]	8.5
Breaktime per shift [h]	0.5
Effective working time [h]	8.0
Work days per week [days]	5.0
Weeks per year [weeks]	52.0
Yearly working hours [h]	4,160.0

Table 8.16 Economic Analysis of Plastics Recycling: Materials Recovery Facility (MRF) Investment Costs

Building and Site	**Initial Investment**
Land [$]	675,000.00
Site work [$]	720,000.00
Scale house [$]	600,000.00
MRF building [$]	8,600,000.00
Construction, planning & surveying [$]	3,500,000.00
Machines	**Initial Investment**
Metering bin [$]	150,000.00
OCC screen [$]	175,000.00
Debris roll screen [$]	220,000.00
Newspaper screen [$]	400,000.00
Polishing screen [$]	280,000.00
Recycling magnets [$]	35,000.00
Eddy current separator [$]	128,000.00
Optical plastic sorting machine [$]	225,000.00
Baler [$]	550,000.00
Additional Equipment	**Initial Investment**
Conveyor [$]	50,000.00
Rolling stock (e.g. front-end loader) [$]	350,000.00
Collection cars [$]	1,000,000.00
Total Investment Costs [$]	**17,658,000.00**

Table 8.17 Economic Analysis of Plastics Recycling: Material Recovery Facility (MRF) Operating and Maintenance Costs

Personnel Salaries per Year	**Number p. Shift**	**Cost p. Person p. Year [$]**	**Shifts per Day**		**Total Costs per Year [$]**
Plant Manager	1	89,000.00	2		178,000.00
Operations foreman	2	55,000.00			220,000.00
Sorters	25	30,000.00			1,500,000.00
Scale house attendant	2	37,500.00			150,000.00
Equipment operators	4	35,000.00			280,000.00
Spotters on tip floor	2	31,000.00			124,000.00
Marketing manager	2	50,000.00	1		100,000.00
Facility Costs					**Costs per Year [$]**
Consumables/Services					28,000.00
Baling Wire					250,000.00
Insurance					45,000.00
Administration					20,000.00
Machines - Operating Costs	**Efficiency [%]**	**Electricity Consumption [kW]**	**Running Hours per Year [h]**	**Electricity Costs per kWh [$/kWh]**	**Yearly Electricity Costs[$]**
Metering bin	100.00	15.00	4160	0.0996	6,215.04
OCC screen	70.00	8.50			3,521.86
Debris roll screen	97.00	30.00			12,430.08
Newspaper screen	85.00	5.50			2,278.85
Polishing screen	91.00	10.00			4,143.36
Recycling magnets	98.00	4.00			1,657.34
Eddy current separator	97.00	9.00			3,729.02
Optical PET sorting machine	98.00	13.00			5,386.37
Baler	100.00	63.00			26,103.17
Machines - Maintenance Costs					**Maintenance Costs per Year [$]**
Metering bin					100.00
OCC screen					10,000.00
Debris roll screen					10,000.00
Newspaper screen					13,000.00
Polishing screen					10,000.00
Recycling magnets					5,000.00
Eddy current separator					5,000.00
Optical PET sorting machine					5,000.00
Baler					5,000.00
Conveyor - Operating Costs	**Efficiency [%]**	**Electricity Consumption [kW/h]**	**Running Hours per Year [h]**	**Electricity Costs per kWh [$/kWh]**	**Yearly Electricity Costs[$]**
Conveyor	100.00	5.60	4,160	0.0996	2320.28
Conveyor - Maintenance Costs					**Maintenance Cost per Year [$]**
Conveyor					10,000.00
Rolling Stock - Operating Costs	**Efficiency [%]**	**Diesel Consumption [L/t]**	**Waste per Year [t]**	**Diesel Price [$/L]**	**Yearly Diesel Costs [$]**
Rolling stock	100.00	10.00	120,000	0.5807	696,780.53
Rolling Stock - Maintenance Costs					**Maintenance Cost per Year [$]**
Rolling stock					5,000.00
Residues Costs	**Percentage of residues [%]**	**Residues per Year [t]**	**Tipping Fee per Ton [$]**		**Total Costs per Year [$]**
Residues costs per year	2	2,400	40		96,000.00
Transportation and Collection Costs	**Tons Collected per Year**		**Transportation Costs per Ton [$/t]**		**Transportation Costs per Year [$]**
Transportation and collection per year	120,000		36.84		4,420,800.00
Yearly operating and maintenance costs [$]					8,254,465.90
Overall operating and maintenance costs (10 yrs) [$]					82,544,659.03

Table 8.18 Economic Analysis of Plastics Recycling: Plastic Recycling Facility (PRF) Assumptions

Lifetime [years]	10
Processing Building Size (sq. ft)	70,000
Yearly PET capacity [t]	15,000
Total waste capacity (10 years) [t]	150,000
Separation efficiency [%]	91
Dollar - Pound rate [$/£]	1.46
Shifts per day	3.0
Hours per shift [h]	8.5
Breaktime per shift [h]	0.5
Effective working time [h]	8.0
Work days per week [days]	5.0
Weeks per year [weeks]	52.0
Yearly working hours [h]	6,240.0

Table 8.19 Economic Analysis of Plastics Recycling: Plastic Recycling Facility (PRF) Investment Costs

Building and Site	**Initial Investment [£]**	**Dollar - Pound Rate [$/£]**	**Initial Investment**
Design and project management	800,000.00	1.46	1,168,000.00
Civil engineering	1,200,000.00		1,752,000.00
Land [$]			590,000.00
Site work [$]			630,000.00
Machines	**Initial Investment [£]**	**Dollar - Pound Rate [$/£]**	**Initial Investment [$]**
Bale breaker	5,620,000.00	1.46	8,205,200.00
Flake washing plant (includes granulating, drying, washing)	9,444,000.00		13,788,240.00
PET extrusion	2,643,000.00		3,858,780.00
Metering bin			150,000.00
Additional Equipment			**Initial Investment [$]**
Rolling stock (e.g., front-end loader) [$]			150,000.00
Total Investment Costs [$]			**30,142,220.00**

Table 8.20 Economic Analysis of Plastics Recycling: Plastic Recycling Facility (PRF) Operating and Maintenance Costs

Personnel Salaries per Year	**Number p. Shift**	**Cost p. Person p. Year [$]**		**Shifts per Day**		**Total Costs [$]**
Sorting and bale breaking	6	30,000.00		3		540,000.00
Flake washing	2	30,000.00				180,000.00
PET extrusion	2	30,000.00				180,000.00
Waste processing	2	30,000.00				180,000.00
Equipment operators	4	35,000.00				420,000.00
Maintenance staff	2	62,715.00				376,290.00
Plant manager	1	89,000.00				267,000.00
Marketing manager	1	50,000.00		1		50,000.00
Machines - Maintenance Costs	**Investment costs [$]**			**Maintenance [%]**		**Maintenance costs [$]**
Maintenance costs of machines		25,852,220.00		5		1,292,611.00
Machines - Operating Costs	**Electricity Consumption [kWh/t]**	**Electricity Price [$/kWh]**	**Water Consumption [L/t]**	**Water Price [$/l]**	**Tons per Year [t]**	**Total Costs [$]**
Bale breaker	8.00	0.0996	0.00	0.0040	15,000	11,952.00
Flake washing plant	350.00		1.80			523,006.99
PET extrusion	325.00		0.40			485,573.78
Metering bin	1.50		0.00			2,241.00
Rolling Stock - Operating Costs	**Diesel Consumption [L/t]**	**Waste per Year [t]**		**Diesel Price [$/L]**		**Yearly Diesel Costs [$]**
Rolling stock	10.00	15,000		0.5807		87,097.57
Yearly operating and maintenance costs [$]						4,595,772.33
Overall operating and maintenance costs (10 yrs) [$]						**45,957,723.32**

8.4 Optimization I: Reduction of Sorting Processes

Table 8.21 Economic Analysis of Optimization I: Assumptions

Percentage of PET in plastic waste [%]	14.39
Average price of recycled PET flakes [$/lb]	0.57
Price of recycled PET pellets [$/kg]	1.26
Electricity price [$/kWh]	0.0996
Diesel price [$/gallon]	2.198
Diesel price [$/L]	0.5807
Water price [$/gallon]	0.015
Water price [$/L]	0.0040
Lifetime [years]	10
Processing-building size (sq. ft)	80,000
Working hours per year [h]	6,240
Plastic waste handled per year [t]	100,000
Total plastic waste capacity (10 years) [t]	1,000,000
PET handled per year [t]	15,000
Total waste capacity (10 years) [t]	150,000
Separation efficiency [%]	91
Dollar-British Pound exchange rate [$/£]	1.46
Shifts per day	3.0
Hours per shift [h]	8.5
Break time per shift [h]	0.5
Effective working time per shift [h]	8.0
Work days per week [days]	5.0
Weeks per year [weeks]	52.0
Working hours per year [h]	6,240.0

Table 8.22 Economic Analysis of Optimization I: Additional Investment Costs

Additional Building and Site Investment Costs	**Initial Investment [$]**
Additional land [$]	85,000.00
Additional site work [$]	90,000.00
Scale house [$]	600,000.00
Additional building [$]	1,000,000.00
Additional Machine Investment Costs	**Initial Investment [$]**
Metering bin [$]	150,000.00
Optical PET sorting machine [$]	225,000.00
Baler [$]	550,000.00
Additional Equipment Investment Costs	**Initial Investment [$]**
Conveyor [$]	50,000.00
Additional rolling stock [$]	200,000.00
Collection cars [$]	1,000,000.00
Total Additional Investment Costs [$]	**3,950,000.00**

Table 8.23 Economic Analysis of Optimization I: Additional Operating and Maintenance Costs

Personnel Salaries per Year	**Number per Shift**	**Cost per Person per Year [$]**	**Shifts per Day**		**Total Costs [$]**
Sorters	6	30,000.00	3		540,000.00
Scale house attendant	2	37,500.00			225,000.00
Equipment operators	1	35,000.00			105,000.00
Spotters on tip floor	1	31,000.00			93,000.00
Facility Costs per Year					**Costs per Year [$]**
Baling wire					250,000.00
Machines: Operating Costs	**Efficiency [%]**	**Electricity Consumption [kW]**	**Running Hours per Year [h]**	**Electricity Costs per kWh [$/kWh]**	**Electricity Costs per Year[$]**
Metering bin	100.00	15.00	6,240	0.0996	9,322.56
Optical PET sorting machine	98.00	13.00			8,079.55
Baler	100.00	63.00			39,154.75
Machines: Maintenance Costs					**Maintenance Costs per Year [$]**
Metering bin					100.00
Optical PET sorting machine					5,000.00
Baler					5,000.00
Rolling Stock: Operating Costs	**Efficiency [%]**	**Diesel Consumption [L/t]**	**Waste per Year [t]**	**Diesel Price [$/L]**	**Diesel Costs per Year [$]**
Rolling stock	100.00	10.00	100,000	0.5807	580,650.44
Rolling Stock: Maintenance Costs					**Maintenance Costs per Year [$]**
Rolling stock					5,000.00
Transportation and Collection Costs	**Tons per Year [t]**		**Transportation Costs per Ton [$/t]**		**Transportation Costs per Year**
Transportation and collection per year	100,000		36.84		**3,684,000.00**
Yearly operating and maintenance costs [$]					5,549,307.31
Overall operating and maintenance costs (10 years) [$]					**55,493,073.09**

8.5 Optimization II: Upcycling of Plastic Waste by Blending

Table 8.24 Economic Analysis of Optimization II for Materials Recovery Facility (MRF): Additional Costs

Additional Investment Costs					**Initial Investment [$]**
LDPE-PP optical sorter [$]					900,000.00
Additional Operating Costs	**Efficiency [%]**	**Electricity consumption [kW]**	**Running hours per year [h]**	**Electricity costs per kWh [$/kWh]**	**Electricity costs per year [$]**
LDPE-PP optical sorter	95.00	40.00	4160	0.0996	16,573.44
Additional Maintenance Costs					**Maintenance costs per year [$]**
LDPE-PP optical sorter [$]					10,000.00
Overall additional MRF costs [$]					**1,165,734.40**
Additional MRF costs per ton [$/t]					**0.97**

Table 8.25 Economic Analysis of Optimization II for Plastic Recycling Facility (PRF): Additional Investment Costs

Building and Site	Initial Investment [£]	Dollar-British Pound Exchange Rate [$/£]	Initial Investment [$]
Design and project management	500,000.00	1.46	730,000.00
Land [$]	590,000.00		
Site work [$]	630,000.00		
Machines	**Initial Investment [£]**	**Dollar-British Pound Exchange Rate [$/£]**	**Initial Investment [$]**
Bale breaker	5,620,000.00	1.46	8,205,200.00
Flake washing plant (includes granulating, drying, and washing)	9,444,000.00		13,788,240.00
LDPE-PP-extruder	1,422,000.00		2,076,120.00
Metering bin	150,000.00		
Additional Equipment			**Initial Investment**
Rolling stock (e.g., front-end loader) [$]			50,000.00
Total investment costs [$]			**26,069,560.00**

Table 8.26 Economic Analysis of Optimization II for Plastic Recycling Facility (PRF): Additional Operating and Maintenance Costs

Personnel Salaries per year	No. per Shift	Cost per Person per Year [$]		Shifts per Day		Total Costs [$]
Sorting and bale breaking	6	30,000.00		3		540,000.00
Flake washing	2	30,000.00				180,000.00
LDPE-PP extrusion	2	30,000.00				180,000.00
Waste processing	2	30,000.00				180,000.00
Equipment operators	4	35,000.00				420,000.00
Machines: Maintenance Costs		**Investment costs [$]**		**Maintenance [%]**		**Maintenance Costs [$]**
		24,069,560.00		5		1,203,478.00
Machines: Operating Costs	**Electricity Consumption [kWh/t]**	**Electricity Price [$/kWh]**	**Water Consumption [L/t]**	**Water Price [$/L]**	**Tons per Year [t]**	**Total Costs [$]**
Bale breaker	8.00	0.0996	0.00	0.0040	15,000	11,952.00
Flake washing plant	350.00		1.80			523,006.99
LDPE-PP extrusion	275.00		0.40			410,873.78
Metering bin	1.50		0.00			2,241.00
Rolling Stock: Operating Costs	**Diesel Consumption [L/t]**	**Waste per Year [t]**		**Diesel Price [$/L]**		**Diesel Costs per Year [$]**
Rolling stock	10.00	15,000		0.5807		87,097.57
Yearly operating and maintenance costs [$]						**3,738,649.33**
Overall operating and maintenance costs (10 yrs) [$]						**37,386,493.32**

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Rudolph · Kiesel · Aumnate

Understanding Plastics Recycling

This book shows the true and often-underestimated market potential of plastics recycling, with analysis from economic, ecological, and technical perspectives. It is aimed at both technical and non-technical readers, including decision makers in material suppliers, plastic product manufacturers, governmental agencies, educators, and anyone with a general interest in plastics recycling.

An overview of waste handling systems with a focus on the U.S. market is provided. Different methods of waste handling are compared from both economic and ecological perspectives.

Since plastic waste recycling is essential from an ecological point of view, common strategies and new approaches to both increase the recycling rate and improve recycling economically and technically are presented. This includes processing and material properties of recycled plastics.

Finally, a worldwide outlook of plastic recycling is provided with analysis of additional worldwide markets, encompassing highly developed, fast-developing, and less developed countries.

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