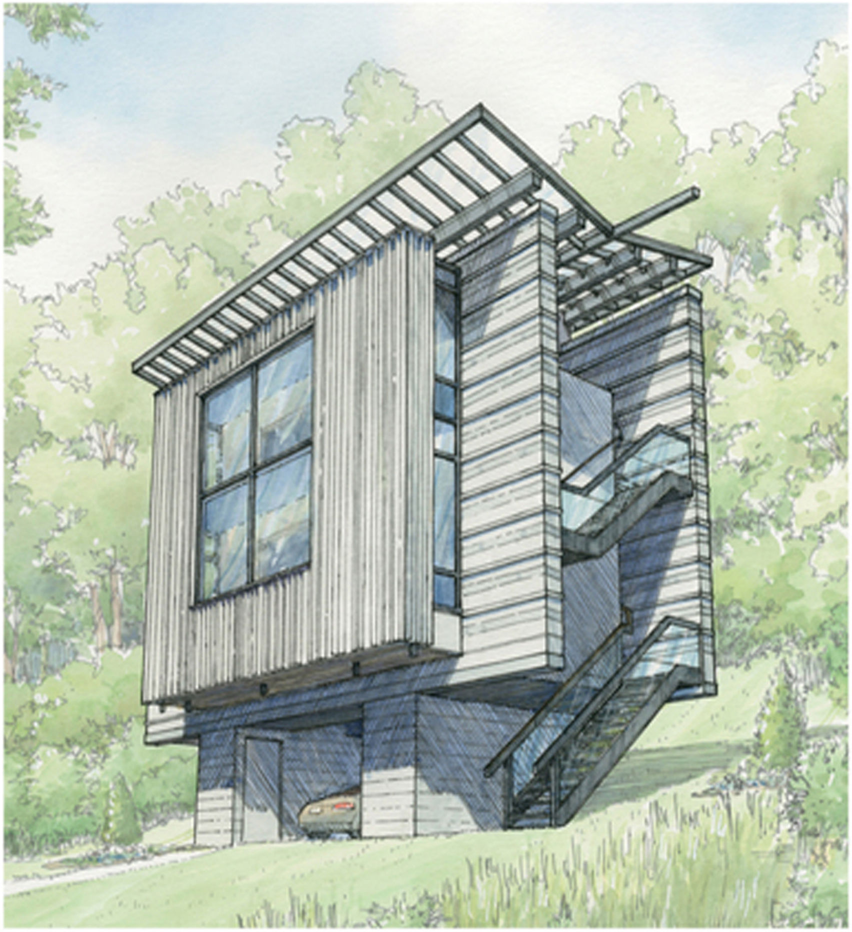
SUN, WIND & LIGHT

architectural design strategies

third edition



MARK DeKAY and G. Z. BROWN

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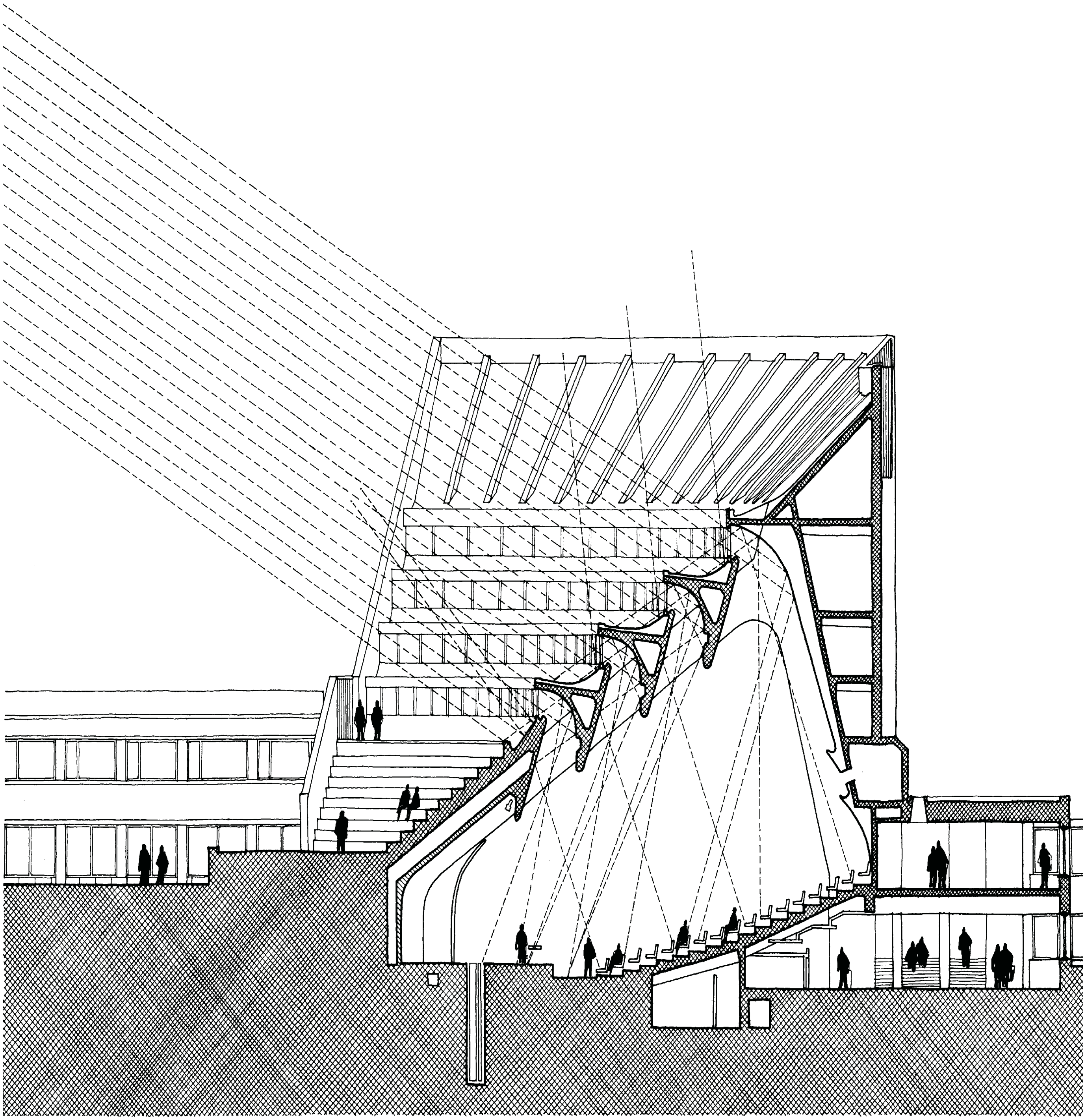

SUN, WIND & LIGHT

ARCHITECTURAL DESIGN STRATEGIES

third edition

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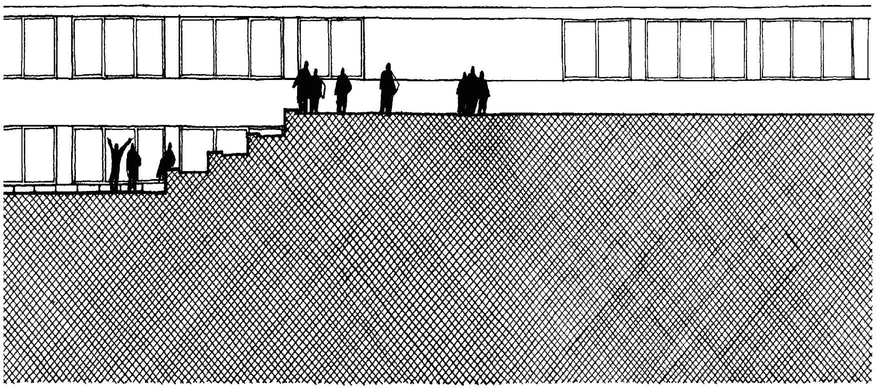

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FOR MY LOVING WIFE SUSANNE

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Contents Overview

WHAT'S IN THE *SWL PRINTED*

WHAT'S IN THE *SWL ELECTRONIC*

SWL Printed Contents

abbreviated*

* All of the *SWL Printed* material is also included in electronic format in *SWL Electronic*.

SWL Electronic Contents

abbreviated*

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* All of the *SWL Printed* material is also included in electronic format in ⌿ *SWL Electronic.*

** Strategies designated as "in *SWL4*" will appear in their fully developed form in the 4th edition.

Alphabetic Contents

of Strategies, Techniques, Bundles, Synergies and High-Performance Assessments

KEY

A = Analysis technique

B = Bundle

P = High-performance assessment

S = Synergy

No prefix = Design strategy

Preface

Purpose and evolution of *Sun, Wind & Light*

The purposes of this third edition of *Sun, Wind & Light (SWL)* are aligned with those outlined in the first edition preface: to help architectural designers who are not energy experts understand the energy consequences of their most basic design decisions. With this information they can then use energy issues to generate form rather than seeing them simply as limits that must be accommodated. Furthermore, this new edition is meant to provide designers with the preliminary design tools and strategies to meet and exceed the Architecture 2030 energy and carbon targets.

SWL has expanded in this edition from 109 to 150 Analysis Techniques and Design Strategies. It helps architects to design net-zero energy buildings by assisting them in creating sustainable designs based on site forces of sun, wind and light. *SWL* addresses issues of how to heat with the sun, cool with the wind and earth, light with the sky and make power with renewable energy. *SWL* serves both design professionals and students of design.

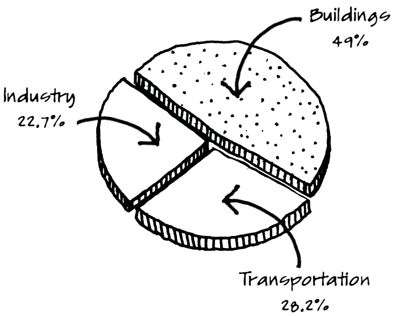
The new edition is not simply an update. Instead, it is a complete redesign and a mapping of the knowledge of preliminary phase net-zero energy design. Key to this new approach are three new methods:

1) The **Design Strategy Map method**, which allows us to map existing design strategies, identify missing strategies and reveal their hierarchical 'vertical' scalar structure.
2) The method of **Strategy Bundles** reveals the synergistic interrelationships among the strategies and issues.
3) A third approach, the **Design Decision Chart,** uses a design question-driven method for selecting design strategies and linking them together into **Bundles.**

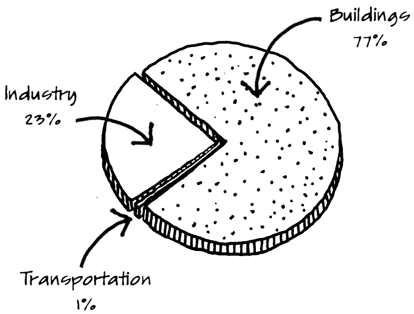
Finally, we combine all these methods and resources into a **searchable electronic resource**, ⌁ *SWL Electronic*, accessible in numerous ways not possible in print.

In addition to the new knowledge structure and new ways of navigating and representing the knowledge, we have also added 9 new bundle spreads, 7 synergies, 15 new design strategies, 4 new analysis techniques, 6 high-performance building assessment techniques, numerous concise design strategies and favorite design tools. Each has an average of 5 illustrations for approximately 225 new illustrations.

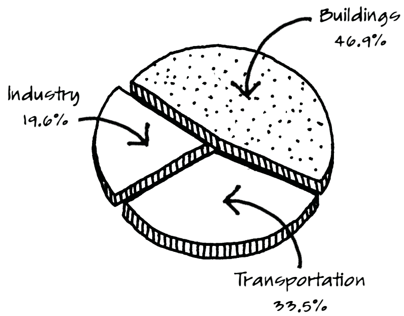
Sun, Wind & Light is one of the only sources to fundamentally integrate the formal language of architectural design with the discipline of building science. Climatic forces are important in architecture because a building's



U.S. Energy Consumption by Sector



U.S. Electricity Consumption by Sector



U.S. CO_2 Emissions by Sector

response to climate is directly related to its energy consumption, and because climate is a powerful local context giving designers a means of regional expression and place making. We are delighted that *SWL* has become a standard in courses on sustainable or low-energy design across the world. Uniquely among its peers, it bridges the worlds of engineering and architecture by connecting form and energy flows.

Organizational changes in the third edition

Veteran *SWL* users will notice that the work has been radically reorganized. The entire contents of the second edition is now located on the companion ⌿ *SWL Electronic*. The printed book, which we will refer to in the text as *SWL Printed*, is almost entirely new material, with the addition of selections and condensations of some of our favorite design strategies and design tools. The Analysis Techniques, which came first in *SWL2,* have been moved to the back of the sequence, partly to emphasize the importance of design thinking and strategies. The work now moves in *SWL Printed* from more general systems of navigation to the energy design process to associations of strategies in the bundles and finishes with new techniques for net-zero and carbon-neutral buildings. In ⌿ *SWL Electronic* the sequence moves from large- to small-scale design strategies, and finally to the detailed, more quantitative analysis techniques. Gone is the separate section for "Strategies for Supplementing Passive Systems." In general the distinction between passive and active systems is more useful conceptually than in practice, where most buildings are a combination of the two. Therefore the "supplemental" strategies have been folded into their appropriate sequence within the 'design strategies' section. Most of these more mechanically-oriented strategies fall into the scale of building parts.

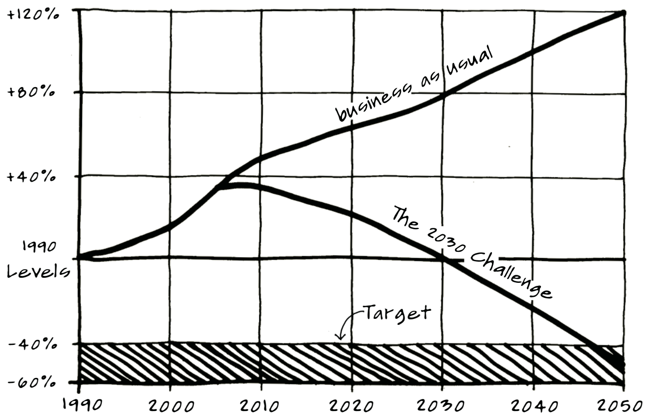
A new intention: reversing building emissions

In addition to the general purpose outlined above, this third edition's intent is focused on the potential impact of this work for one of the most significant issues of our time. As we have gained experience as authors, teachers and design consultants, we have become even more committed to sustainable design, more aware of the urgency of its discipline and more radical in our ambitions for architecture.

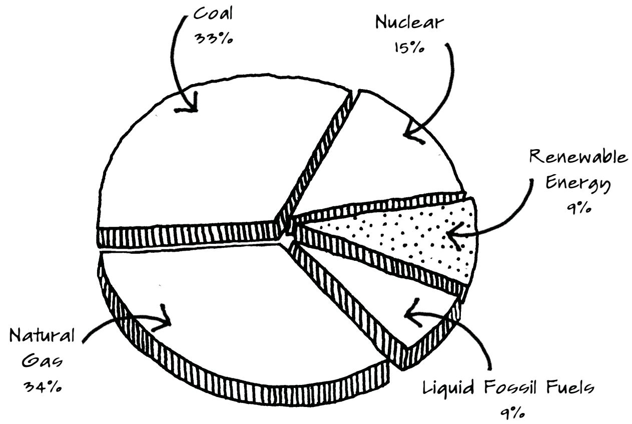
This new edition sets out two additional purposes:

1) **To map the knowledge base** of preliminary climatic design via new theoretical frameworks
2) **To provide accessible methods for net-zero energy design** with the intent of contributing to the massive effort by the building community to reduce greenhouse gas emissions from the building sector to pre-1990 levels by 2030.

The Architecture 2030 organization has made it unmistakably clear that the building community has a historic opportunity to turn around the North American



U.S. Building Sector CO_2 Emissions



Building Energy Consumption by Fuel Type, 2010

contribution to global climate change by meeting targets for fossil fuel reduction (and thus greenhouse gas reductions) leading to all new buildings being designed to *carbon-neutral performance standards by the year 2030*. Beyond this is the more ambitious goal of a site net-zero energy building, one which *produces as much renewable energy on site as it consumes*. Therefore, this edition sets as its task to help designers effectively begin the net-zero energy design process by selecting strategies that use site energy resources to reduce energy loads and produce green power, the two sides of the net-zero equation.

Building on *SWL*'s precedent of quick tools for schematic and preliminary design, *strategic tools* have been created that help the designer identify networks of related design strategies in support of net-zero design, along with *quick calculation methods* that can be done in a matter of minutes without expensive expert energy consultants. As in the previous editions, whenever possible these quantitative techniques have been presented in graphic ways that visually reveal (the audience is architects after all) the relationships among the most important variables and those variables that most influence architectural form.

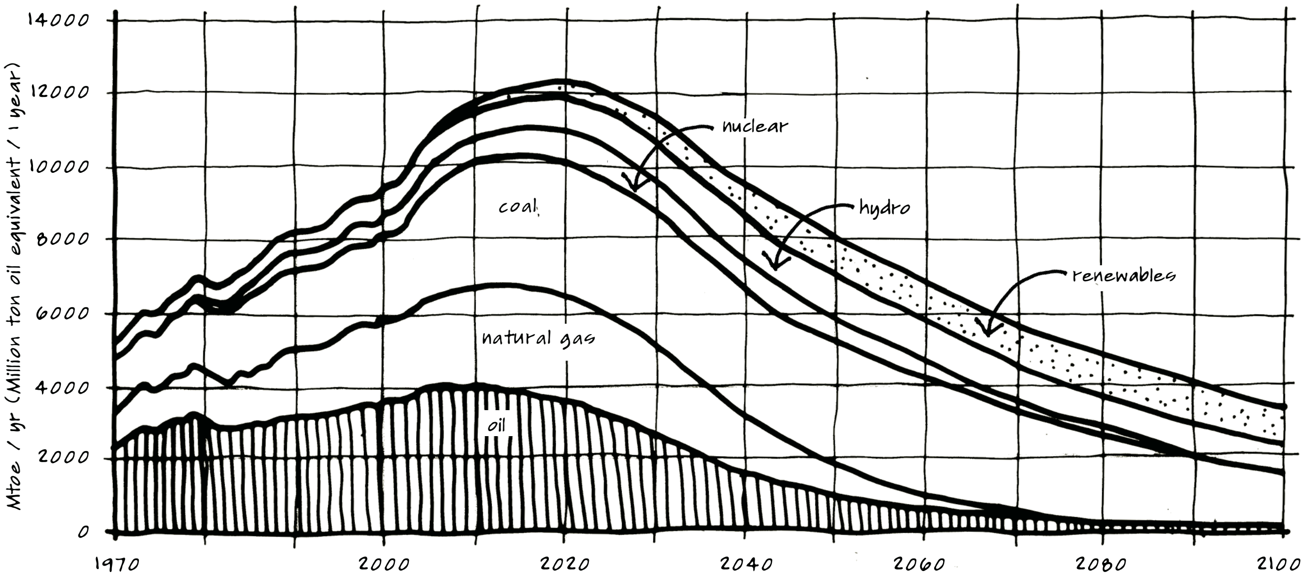
In the second edition introduction, it was noted that while fossil fuel resources are finite, the capability of natural systems to absorb society's wastes may be an even more stringent limit:

> *While saving energy has a high social benefit because it slows the depletion of finite reserves of fossil fuels, it is equally important in reducing the pollution caused by the extraction and burning of these fuels, and therefore in reducing acid rain, the potential for global climate change, and the localized ecological impact of practices such as strip coal mining. (SWL2)*

The three graphs from Architecture 2030 (previous page) show the significant contribution that buildings make to energy use and carbon emissions. Buildings are responsible for 49% of **U.S. Energy Consumption by Sector**, a dramatic 77% of **U.S. Electricity Consumption by Sector** and 47% of **U.S. Carbon Dioxide Emissions by Sector**. Globally, these percentages for buildings are even greater. According to Architecture 2030:

> *By the year 2035, approximately three-quarters (75%) of the built environment will be either new or renovated. This transformation over the next 30 years represents an historic opportunity for the architecture and building community to make the changes necessary to avoid dangerous climate change.* (Architecture 2030, 2011)

The graph of **U.S. Building Sector CO_2 Emissions** (previous page) shows projections for two paths. In the "business as usual" scenario, buildings continue current energy use and fossil fuel trends and become an increasing part of the global climate change problem. In the second, "The 2030 Challenge" scenario, radically reduced



World Energy Production, 1970-2100

fossil fuel targets are aggressively implemented, buildings reverse their CO_2 emissions to pre-1990 levels by 2030 and continue to reduce overall CO_2 emissions into the second half of the 21st century, even when accounting for projected growth in the building stock. This trend would have the effect of eliminating the need for all coal-fired power plants in the U.S., a dramatic impact on the country's responsibility for climate change!

Buildings built today outlive their energy sources

The graph of **Building Sector Energy Consumption by Fuel Type** shows the mix of fuels used in 2010 by buildings in the U.S. (Architecture 2030, 2011). Fossil fuels combine to provide 76% of building energy. Not only is the burning of these fuels responsible for producing greenhouse gases, but each of the three fossil fuels is predicted to reach its peak production and begin to decline by 2030 or before, both raising architecture's contribution to climate change and requiring a dramatic society-wide shift to alternative sources of energy.

Peak oil is the date when maximum global petroleum extraction was reached, after which production declines. U.S. oil production peaked in 1970. Since the 1970's, total new oil and gas discoveries have declined every year and domestic production has declined every year. Globally, the world's crude oil production peaked in 2004 (Inman, 2010; IEA, 2010).

US *peak natural gas* production was in 1973; new discoveries have raised production in recent years, but prices have risen as a result of increased demand for natural gas for electricity production. Most new power plants burn natural gas and relatively few new coal plants have been built in recent years. One-third of global energy comes from natural gas and demand is rising steadily. Estimates on global peak natural gas vary from the present to 2030.

In contrast to earlier predications of centuries-long supplies of coal, predictions are now much less optimistic for the date of *peak coal*. In 2007, the German think tank Energy Watch Group analyzed each country's coal reserves and production, concluding “global coal production [will] peak around 2025 at 30% above present production in the best case”(Energy Watch Group, 2001).

Paul Chefurka (2007) has done an excellent job of assembling projections of various fuel sources, as shown in the graph of **World Energy Production,** which predicts *world peak energy* (for all fuels) occurs somewhere around

2020 and declines in all fossil fuels over the rest of the century.

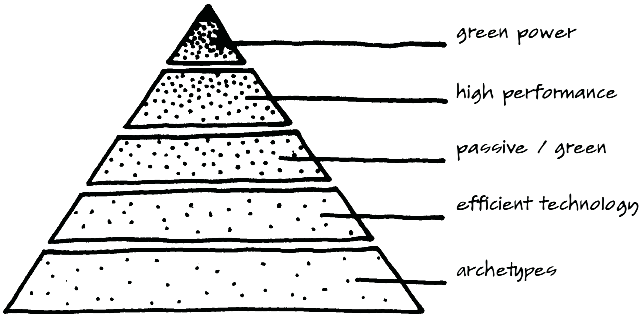
If we continue on the business-as-usual path for energy use in buildings, then the most likely scenario is for oil use in buildings (only 9% currently) to decline, while first natural gas and then coal-fired energy use in buildings will increase, exacerbating current greenhouse gas and climate change trends.

However, *there is a clear alternative to ongoing increases in demand and fossil fuel use for the building industry: the path of design*.

The design path can radically reduce energy consumption by buildings and end our dependency on fossil fuels for buildings. Using current knowledge and available technologies, ASHRAE has produced a series of *High-performance Building Design Guides* with targets of 30% and now 50% reduction from their own energy performance standards. These are prescriptive guides for different building types, with requirements varying by climate, which do not even employ passive design strategies. Such prescriptive requirements depend on specifications for efficiency of the building envelope and mechanical systems. Such efficiency measures are *out of order* in two ways:

- They miss the critical early steps toward net-zero energy buildings that architectural design provides. They focus only on what engineers do and miss what architects do.
- They are necessary but not sufficient to reach a *responsible* net-zero energy building that does not depend on high levels of renewable energy.

Sun, Wind & Light takes the approach that green power systems, such as photovoltaics and wind generation, are the most expensive and appropriately the last stage in a sequence of the **Hierarchy of Strategies for Net-Zero Building Design**, as shown in the diagram. The design strategies in *SWL3* run across these stages, but are centered in the lower three levels *where the design of buildings drives performance*. The diagram shows five levels of consideration. Each can be thought of as engaging Climate, Use, Design and Systems—fundamental perspectives that we will introduce later in Part II's section on "Buildings and Energy Use."



Hierarchy of Strategies for Net-Zero Building Design

Although these levels can be thought of in a sequence, and some design processes may proceed from larger questions to more detailed decisions, or from more formal to more technological questions, the sequence of consideration may be varied and the pyramid is not intended to imply a strict sequence. Instead, the way to think of these levels of concern is that each higher level depends on the lower level. For example, while it is conceptually possible to have a huge PV system (producing a high level of green power) to supply a poorly designed building with large energy loads, it is neither prudent nor rationally elegant. In the early days of the passive movement in architecture, proponents debated "mass and glass" vs. "light and tight" or "passive" vs. "active" approaches. The hierarchy of strategies transcends these polarities with a way of thinking and designing that integrates them while also providing a linkage between architecture and engineering logics.

The hierarchy suggests solving the energy design problem with the lowest level of technology possible and the least cost strategies, while also substituting embodied intelligence in architectural form for hardware.

The net-zero energy equation in a building can be solved in many different ways, however there are elegant and inelegant ways to reach net zero. There are ways that give all of the power and profits to utilities, green power equipment corporations, HVAC manufacturers and engineers, and there are ways that employ the power of architectural design to reduce the need and magnitude

of these other players. Ethical distinctions of significant degree characterize these various approaches.

The hierarchy says that it is better to use site design to reduce the environmental stresses on buildings and to provide access to desired climatic resources to solve a portion of the energy problem *before* using building design to overcome what the building does not need to do. There is no point in designing a solar-heated or naturally ventilated building unless it is a low-load building to begin with. The hierarchy calls us to design effective passive systems for heating, cooling and lighting to radically reduce loads *before* designing and specifying a highly efficient HVAC system. Essentially, an efficient heating system with 25% of the load is better than an efficient system that has to be four times as big or run four times as many hours per year. When the first three levels are done well, the conventional heating or cooling system can sometimes be completely eliminated (such as in the PassiveHaus), what the Rocky Mountain Institute refers to as "tunnelling through the cost barrier." The hierarchy says that *after* loads are thoroughly minimized by considering Design, Climate and Use at levels 1–3, then high-performance Systems become appropriate and a careful consideration of their integration with the passive systems can minimize the net loads of the building. Only then does making one's own electricity on-site make sense.

This bucks some current trends toward large surface areas of glass, double envelope buildings that attempt to reclaim the morality of the Miesian aesthetic, and wildly expensive demonstration projects covered in photovoltaics, looking forward to a time of cheap power-producing building surfacing. Such projects are bought at a high financial price, a high cost in embodied energy and carbon and in overall environmental impact. PVs, while yielding no emissions in producing their energy, do not come without an environmental cost. Indeed, even high-tech glass window walls with their metal frames have similar issues.

Perhaps the best argument for reclaiming the path of architectural design as the essential core of the energy design process is that it results in simpler buildings affordable to more of the world's burgeoning population. High-performance, high-technology buildings that ignore the fundamental levels of the net-zero energy design hierarchy are expensive, even when the technology used is "green."

Over the decades, as buildings have become more complex, architects have ceded much of their responsibility over energy use in buildings to energy consultants or engineers. For a series of reasons, design and performance, what Lance Lavine calls, "mechanics and meaning in architecture," in his book of the same name, have been isolated into separate professions, logics and methods. While architects definitely have a role in the upper two levels, and these levels have significant design implications for buildings, it is in the lower three levels where architects find their voice as those who configure space and form.

When architects claim the power of the design path in shaping the form of sustainable high-performance buildings, then rich human experiences of nature and its forces of sun, wind, light, earth, water and living things will be present. Further, when the entire spectrum of the hierarchy is passionately engaged by designers, these rich experiences have the potential to develop into meaningful cultural communications, into a symbolic language that places us into relationship with nature. Frank Lloyd Wright often spoke of the integral nature of design, the interconnection of forms, ideas and expression from the site to the details, as for example, embodied in Unity Temple. By engaging all five levels of this hierarchy, designers can aspire to a similar kind of continuity of expression about the relationship between humans and their designed artifacts, along with their context in Nature. The widespread cultural adoption of net-zero design may ultimately depend on such an aesthetic and cultural expression that only competent and conscious designers can manifest.

Level of Archetypes

The *level of archetypes* is the level of basic architectural design where issues of siting, orientation, location, shape, proportion and surface to volume ratio are considered, along with the neighborhood or urban fabric context of building groups that set the pattern for access to sun, wind and light. This third edition introduces a new set of

neighborhood-scale design strategy bundles (configurations of strategies) that includes COOLING NEIGHBORHOOD, SOLAR NEIGHBORHOOD, NEIGHBORHOOD OF LIGHT and INTEGRATED URBAN PATTERN. These are considerations nowhere to be found in any high-performance building standards. In *SWL3,* many of the design strategies address these archetypes, such as SHARED SHADE, SOLAR ENVELOPES, BREEZY OR CALM STREETS, MIGRATION, EAST–WEST PLAN, DEEP SUN and ROOMS FACING THE SUN AND WIND. Additionally, at this fundamental level designers consider a range of zoning and room organization strategies that set the possibilities for what comes next. These include strategies such as DAYLIGHT ZONES, COOLING ZONES, HEATING ZONES, BORROWED DAYLIGHT, BUFFER ZONES, and so on.

This first level insures access to sun, wind and light, the formation of favorable outdoor microclimates, a good bioclimatic site location, and a preliminary building organizations that will work well for energy when more detailed and complex strategies are employed.

Level of Efficient Technology

The *level of efficient technology* is a prerequisite to the design of passive systems. For example, the European *PassiveHaus* standard is essentially a heating season envelope performance standard driven by efficient envelope technology. To use the relatively low grade (temperature difference) energy of the sun as a winter heat source, the building must have a low rate of heat loss so that a small supply of heat can meet the load. Similarly, in summer, a building with a high rate of heat gain from its internal loads and through the building skin will be difficult if not impossible to cool with natural forces. Consider the analogy of a bathtub in which the water level can be kept high with the drain open or closed. The open drain is like a building with high heat loads; it requires a large supply, with the tap wide open. When the drain is closed, the tap can be closed with only an occasional need to add small amounts of hot water to offset the trickle that escapes the imperfect drain seal. This is like a solar building with a tight envelope and a low heat loss rate; it can be heated with a relative trickle of energy from the sun.

SWL3 addresses this need for efficient buildings with strategies and analysis techniques such as EQUIPMENT HEAT GAIN, ELECTRIC LIGHTING HEAT GAIN, VENTILATION OR INFILTRATION GAIN AND LOSS, SKIN THICKNESS, WINDOW AND GLASS TYPES, EXTERIOR SURFACE COLOR and EXTERIOR SHADES. Also introduced in this edition is the strategy bundle RESPONSIVE ENVELOPE, which helps to sort out the complexities present when designing high-performance envelopes. Prescriptive envelope standards are often good at improving performance using this level. Although many of the decisions about envelope performance are detailed, and thus tend to come later in the design process, *SWL3* helps the designer make general typological choices up front about the performance needed even if the specific choice about the actual elements specified comes later.

Level of Passive Design

Much of *Sun, Wind & Light* helps designers with the *level of passive design*, in which the building is configured to consciously heat itself with the sun, light itself with the sky and cool itself with the wind and other natural forces. Given neighborhood, site and building massing solutions addressed at level one of *archetypes* and given an efficient envelope that reduces heat gain and loss insured by level two *efficient technology,* passive design becomes possible.

This is the level in which the designer can engage the various passive solar heating systems, such as DIRECT GAIN ROOMS, SUNSPACES, THERMAL STORAGE WALLS and so on, along with the details of these systems, such as THERMAL MASS, SOLAR APERTURES and MASS SURFACE ABSORPTANCE. This edition also introduces whole-building scale bundles including PASSIVE SOLAR BUILDING, PASSIVELY COOLED BUILDING, DAYLIGHT BUILDING and OUTDOOR MICROCLIMATE.

With respect to daylighting, the passive design level engages a series of strategies that bring light supplied by the design decisions made at previous levels to the scale of rooms and building parts, such as DAYLIGHT ROOM GEOMETRY, SIDELIGHT ROOM DEPTH, DAYLIGHT APERTURES and DAYLIGHT REFLECTING SURFACES. Similarly, passive cooling systems can be selected and designed at this level. Examples include CROSS-VENTILATION ROOMS, STACK-VENTILATION ROOMS, NIGHT-COOLED MASS, EVAPORATIVE COOLING TOWERS,

VENTILATION APERTURES and DOUBLE SKIN MATERIALS.

SWL3 deals less with the two upper levels in the hierarchy, both because it focuses on preliminary design and because it focuses more on architectural issues than on engineering issues. *SWL* does, however, address these levels as they intersect preliminary design and assumptions needed for preliminary phase estimation of net-zero performance.

Level of High-Performance

The *level of high-performance* engages both sophisticated and efficient HVAC systems and their integration with architectural design and with passive systems. Strategies include ELECTRIC LIGHTING ZONES, MIXED MODE BUILDINGS, HEAT PUMPS, MANUAL OR AUTOMATED CONTROLS, MECHANICAL SPACE VENTILATION and so on.

Level of Green Power

In the current edition, we address the *level of green power* in strategies for PHOTOVOLTAIC WALLS AND ROOFS and for SOLAR HOT WATER, along with their associated analysis techniques. Both of these upper levels and the whole hierarchy of strategies for net-zero buildings are supported by a set of high-performance buildings assessment techniques designed to help users design and evaluate net-zero and carbon-neutral buildings. These include ENERGY TARGETS, ANNUAL ENERGY USE, NET-ZERO ENERGY BALANCE, ENERGY USE INTENSITY, EMISSIONS TARGETS and CARBON-NEUTRAL BUILDINGS.

New content in the third edition

In terms used by Paul Erlich, environmental impact in the form of greenhouse gas emissions is driven by energy use, and energy use is driven by energy demand. Energy demand can be thought of as being driven by three factors:

- *Population* (which continues on its exponential increase, passing 7 billion this year)
- *Affluence,* which is the volume of goods and services that a person or society expects (such as how many miles we drive or how many square feet we live in)
- *Technology,* which is the efficiency with which a given good or service is delivered (such as how much energy it takes us to stay warm or how much material it takes to span a roof)

Of these three drivers, design affects population little, if at all. However, design does impact both affluence and technology. Design is responsive to the demands and expectations of culture, but it is also in a dialogue with culture. Design can follow demand or create demand. It can be seen as a mere service, shifting responsibility to the client for its magnitude, such as the size of a building, or the comfort criteria expected. Consider a given need like a library that might be housed with a large building, or, with more effective design thought, could be accommodated in a much smaller building; a designer may take a proactive role with clients defining comfort criteria, occupancy schedules and so on, in the context of energy and environmental consequences. Particularly in its programming and pre-design stages, design reaches deep into the assumptions that drive culture and the variable of affluence.

A colleague who is a sustainability architect-analyst once told of a client who came to him and wanted to make sure that the 18,000 ft^2 (1672 m^2) house he had planned would use 50% less energy than conventional design. The architect said, “That's easy, why don't you simply build a 9,000 ft^2 house?” Nowhere in LEED or any other high-performance green guidelines or criteria will you find criteria for building size. According to the codes and standards, if you want to build 9,000 ft^2 (836 m^2) per person in your new house, that is fine, so long as you meet the energy criteria on a per unit area basis. When design meets environmental ethics such cultural insanity can be overcome.

New analysis techniques have been added to address some of these embedded assumptions in the process of building design. New techniques such as ADAPTIVE COMFORT CRITERIA, ENERGY PROGRAMMING and LOAD-RESPONSIVE SCHEDULING, along with new Synergies, including ENERGY CONSCIOUS OCCUPANTS. Some of the simplest and most cost effective strategies involve lowering the thermostat, turning on a ceiling fan to allow a higher summer temperature, scheduling to avoid peak cooling hours or changing

the corporate dress code to respond to the seasons. These may seem like nonnegotiable cultural practices, but they have real financial and environmental impacts, and as it turns out, they are practices we have collectively created only relatively recently.

Much of this book is bout the relationship between energy use and architectural form at a range of scales. This edition fills in some of the holes in *SWL* as a knowledge base, thanks to students and clients.

New building groups scale content can be found in strategies to support a NEIGHBORHOOD OF LIGHT in the form of DAYLIGHT DENSITY and DAYLIGHT BLOCKS. The CLIMATIC ENVELOPES strategy helps designers create building massing that admits both winter sun and daylight all year, and in some cases creates summer shade with the help of the SHADOW UMBRELLA strategy.

The older *SWL2* strategy BALANCED URBAN PATTERNS, which addressed combinations of strategies for heating and cooling issues in different climates, has been incorporated into a new strategy bundle, INTEGRATED URBAN PATTERNS.

Two **zoning strategies** have been added: PERIODIC TRANSFORMATIONS, in which space is "switched" depending on seasonal or daily conditions (such as when a "thermal enclave" is created); and MIXED MODE COOLING, a strategy that recognizes the hybrid nature of many buildings as using both passive and mechanical strategies. The older strategy HEAT-PRODUCING ZONES has become HEATING ZONES to cover a wider range of rooms and activities that impacts heating. This is paired with the related COOLING ZONES, for designing to meet the overheated season.

SWL3 adds several **new daylighting design strategies** and makes several modifications to previous ones. The older ATRIUM has become ATRIUM BUILDING to address the planning and design options for a building's organization, while the sizing tools for the atrium itself have been spun off into a new TOPLIGHT ROOM strategy. SKYLIGHT BUILDING helps the designer with single-story rooms lighted with skylights, an issue not addressed in *SWL2*. DAYLIGHT ROOM GEOMETRY treats the room design as a lighting fixture.

Strategies at the scale of building parts for OPEN ROOF STRUCTURE and DAYLIGHT ROOF address how to bring more light through the roof assembly and roof structure, along with how to configure clerestories and monitors in roof systems. Guidance for the effect of arranging daylight apertures on daylight distribution is developed in the WINDOW PLACEMENT strategy.

Revisions to the ventilation strategies have updated the *SWL2* strategies of CROSS-VENTILATION and STACK-VENTILATION to become CROSS-VENTILATION ROOMS and STACK-VENTILATION ROOMS, which aligns them better with other room-scale design strategies that focus on room characteristics for a given issue. The aperture sizing tools previously found in these strategies are now located in a single VENTILATION APERTURES strategy that parallels the related SOLAR APERTURES and DAYLIGHT APERTURES.

Strategies for thermal or fresh air and distribution fill gaps from the second edition. Two strategies have been added to address the need to store heat or to use radiation as a means of delivering heat or cool. MOVING HEAT TO COLD ROOMS is useful when the designer needs to move heat from where it is collected (usually rooms with an equatorial orientation) to rooms that cannot collect their own heat. When rooms are adjacent, the CONVECTIVE LOOPS strategy helps insure the passive air distribution will work properly. In many buildings, MECHANICAL HEAT DISTRIBUTION is helpful in distributing passively generated heating or cooling, and can be used with both passive and active sources. Preliminary design guidance for the critical issue of controls is given in MANUAL OR AUTOMATED CONTROLS.

An expanded treatment of thermal storage and radiant distribution can be found in the significant expansion of the THERMAL MASS strategy to include sizing for not only direct masonry and water thermal mass in the room, but also remote and indirect masonry thermal mass coupled by convection, along with new sizing for phase change materials. A relatively detailed strategy on MASS ARRANGEMENT has been added to address where to put mass to be most effective for heating or cooling.

A series of new analysis techniques fill in a few holes and add an entire section called High-Performance Assessments. To design for daylighting, one can now begin with DAYLIGHT DESIGN FACTOR to set design targets.

The **emphasis on net-zero energy design** in this current edition has necessitated a series of six additional analysis techniques. These begin with setting ENERGY TARGETS AND EMISSIONS TARGETS. One request received from users on numerous occasions is for a simple ANNUAL ENERGY USE calculation technique. Therefore, in this edition there are techniques for calculating the building's ENERGY USE INTENSITY and comparing it to targets. Finally, the new techniques are completed with NET-ZERO ENERGY BUILDINGS and CARBON-NEUTRAL BUILDINGS evaluation.

Acknowledgements

We would like to gratefully acknowledge the people who have been most helpful in making this third edition possible. The scope of such an undertaking as *SWL* was a constant source of amazement to the many people involved over many years in the production of the current edition. Such a work is the product of a team involving two authors, several staff and multiple generations of students at two universities over the course of twelve years. Without them *SWL3* would literally not have been possible.

Gary Coates at Kansas State University wrote an excellent student workbook with a series of exercises used in his classes. His work has been influential in developing improvements to many of the strategies and analysis techniques and has provided a thorough testing of the material over a period of more than a decade. Many of the improvements suggested by his students and errors found in the second edition have been incorporated or corrected in this edition. Gary was also the impetus and inspiration for the section on "Navigation by Climate," which began with a list of second edition strategies that he organized according to their applicability for different climates and for achieving a range of energy goals in that climate. His sustained enthusiasm for *SWL* continues to be a gift, and his selfless collegiality a rare exemplar.

Susanne Bennett was involved in many aspects of the project, including editing all of the *SWL Printed* and *SWL Electronic* pages, collaborating on grant writing and managing the project finances and the GreenVision research studio. Her volunteer commitment to the project and the possibility of its contribution to the discipline being fulfilled has been extraordinary. She deserves special acknowledgment for such partnership in the collective effort to sustain the level of unreasonableness needed to complete the work.

Many student assistants worked on this project. At the University of Tennessee, student research assistants Sushant Verma and Mahamadou Diarra updated the tables and many of the references from *SWL2*. Mahamadou had the arduous task of recovering text from the legacy Adobe Table software and recreating all of the *SWL2* tables in InDesign; he also completed many of the icons for individual strategies, building on the earlier work of David Timmerman. Myles Trudell, Paul Butts, Allison Luan and Stephen Collins worked on early versions of many *SWL3* strategies and *SWL2* revisions, tested applications of the tools and generated the first versions of the design strategy maps. Paul's initial draft and diagrams served as the basis for what became the strategy for MOVING HEAT TO COLD ROOMS.

Sushant Verma updated and converted the *SWL2* layout files done in Adobe PageMaker 6 to PageMaker 6.5 and then to the current version of Adobe InDesign CS. He worked diligently to refine the final versions of the design strategy maps, a very complex graphic design task. He also became a test case for developing the first structure for a bundle, using his design for a house in New Orleans to study the RESPONSIVE ENVELOPE bundle. Joleen Darragh and Jona Shehu found many examples of bioclimatically designed buildings for the *Climate Context* reports found on *SWL Electronic*; and Joleen helped with updating text for the *SWL2* strategies in InDesign.

Kelly Arnold, Emma Gill and Jennifer Nguyen contributed to this edition's illustrations. Dede Christopher contributed her substantial skills to the cover illustration and to numerous others, especially the more complex perspective views in the new edition. Jared Eisenhower and Reid Cimala dedicated their summer to completing the illustrations. Jared and Reid both mastered the now arcane techniques of hand-drawn ink on mylar, contributing the majority of the new hand illustrations. Jared worked on numerous digital illustrations, too. Reid deserves special thanks for his commitment to the quality of the final

product and his mastery of all aspects of the production. Jordan Etters joined the GreenVision team in the final months, adding his substantial graphic skills to complete the remaining digitally generated graphics. All three of these students, still undergraduates, formed a team exhibiting the highest level of professionalism. Their commitment to excellence and their perseverance to complete the work both shows clearly in the product and predicts a bright professional future for each.

The project was also funded in part by a generous grant from John Wiley & Sons, who agreed to let us design the book, do the layouts and all of the illustrations, and simply deliver to them a finished product ready for publication. The AIA's Upjohn Initiative Award contributed substantially towards the development of the "New Knowledge Structure for Net-Zero Energy Design" as embodied in the design strategy maps, the bundles and the energy design process, including the new net-zero design decision chart. This funding was in part matched by the University of Tennessee College of Architecture and Design and by the University of Oregon Department of Architecture. Support for illustrations was provided by a small grant from the UT Humanities Initiative Book Subvention Awards and by matching funds from the College of Architecture and Design.

Some of the data used in the appendix and included in *SWL Electronic* have been borrowed from work supported by the Hay Fund of the Renewable Energy Institute at Cal Poly, San Luis Obispo, a portion of which appeared in the appendix of *SWL2*. Early work on the theory of Design Strategy Maps and Bundles was supported by a generous grant from the Graham Foundation, who also supported illustrations for *SWL2* in an earlier grant. Further, early development of the Design Strategy Maps concept explored their structure at larger scales of green infrastructure and was supported by a grant from the Boston Society of Architects.

The excellent Sun, Wind & Light hand lettering font used in the illustrations was created by vLetter from original hand lettering (www.vletter.com).

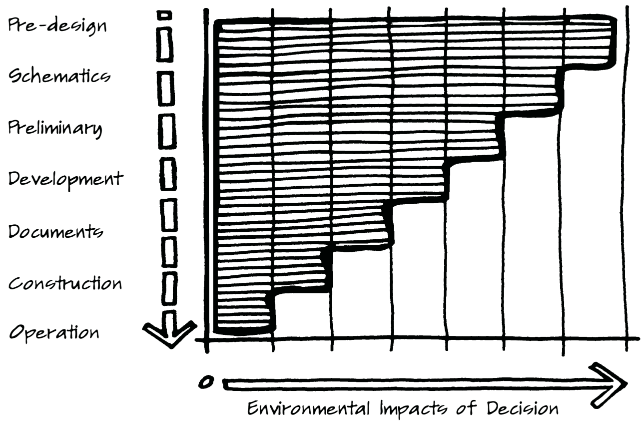
From Charlie at the University of Oregon: I would like to acknowledge the people who helped in the creation of this edition of *SWL*. In particular, Gwynne Mhuireach was invaluable in preparing and organizing new content. All of my colleagues and students working in the Energy Studies in Buildings Laboratory gave graciously of their time and effort testing experimental concepts.

Many of the new ideas introduced in this book resulted from discussions with architects and other design professionals during energy-efficiency design assistance projects. My knowledgeable associates at Solarc Architecture and Engineering, Inc. helped to refine some of the tools developed for this edition. Conversations with the architects at SRG Partnership seeded a number of ideas and were instrumental in generating concepts that would resonate with design professionals. SRG Partnership also generously provided photos and drawings to illustrate the new Synergies.

Introduction

Premise

A basic premise of this book is that most decisions that affect a building's energy use occur during the pre-design, schematic or preliminary design stages of the project as the diagram, **Front Loaded Sustainable Design** indicates. Furthermore, the effort required to implement those decisions at the beginning of the design process is small compared to the effort that would be necessary later on. Therefore, if energy issues are going to receive an appropriate level of consideration at the beginning of the design process, an effective strategy is to present them in a way that is useful to the designer and fits with other things the designer is considering at that time. At first, the designer works primarily in a synthesis mode, bringing ideas together, rater than in an analysis mode. Therefore, information and problem analysis in *SWL* is presented in a way that is generative of architectural form and that helps the designer understand how the forms generated by energy concerns fit with forms generated by other architectural issues. The schematic design stage is one in which things proceed very rapidly, involving experimentation with many ideas and combinations of ideas. The considerations are broad and conceptual rather than detailed and fine. Therefore, information in *SWL* is accessible and quick to use.



Front Loaded Sustainable Design

The authors anticipate that the users of this book will have some background in energy issues and techniques, so the book is not meant to be a complete, self-sufficient reference or textbook; nor is it meant to be a primer that is read from cover to cover. These considerations have had a profound effect on the character of this book. The information presented is at a rule-of-thumb or design guideline level. Its intention is to give only general ideas about architectural elements and their size and relationship to other elements. Precision of the information is sacrificed somewhat so that speed of use may be

increased. The approximation methods are founded on certain assumptions about the elements under consideration. *Make sure to read carefully the text that accompanies each tool and identifies its assumptions.* If those assumptions do not apply to the considerations of the moment, then the approximations probably won't either. So, along with the speed of use comes a certain need for caution, though no more so than with many of the other concerns in the schematic stage. It is important to realize that to *develop and detail* a design based on the ideas in this book, the designer must also go to other sources and use more sophisticated tools.

Most of the ideas in this book are presented in a format of a few pages. Each spread contains a statement of the idea, a brief explanation of the phenomenon and its architectural implications, and an illustration of how the idea has been used elegantly by other architects. The brevity is aimed at increasing speed of use, and the illustrations are a means of helping the designer translate ideas into architectural form.

Limits of scope

Readers will understand that this book deals primarily, though not exclusively, with mixed heating and cooling climates like those within the contiguous United States. Many of the design strategies will be useful in other climates, but there is a distinct bias towards those that address the changing nature of mixed climates rather than the more consistent needs of extremely hot or cold regions. However, beginning with the second edition, the range of coverage has been extended wherever possible to cover latitudes from the equator to the poles, and coverage of topics applicable to Canada and Alaska has been added in many strategies.

The strategies often use language for northern latitude sun positions, with southern latitude references given parenthetically, for example, "(N in SH)" means north in the Southern Hemisphere. Alternatively, we use the terms *equator-facing* and *polar-facing* (or simply *equatorial* or *polar*) to apply to both sites in both hemispheres. Many of the strategies assume a sun position to the south of the building that stays low in the winter sky. These assumptions may be inappropriate for regions near the equator, so, use with caution.

Some strategies address an important consideration of how passive design strategies are best integrated with more conventional electrical and mechanical systems in buildings. This integration is complex, especially in large buildings, and could easily fill a book by itself. The intention is to identify recurring considerations, like how to extend the heat storage capacity of passive systems, and to explain their potential architectural impact, not to give detailed methods for designing or sizing HVAC systems.

Organization of the *SWL* resources

This edition of *SWL* is organized in two complementary parts:

1) *SWL Printed*, which offers multiple navigation tools, describes how to use *SWL* and presents the energy design process, including the new Design Decision Charts, along with the spreads for the new Strategy Bundles and new High-Performance Buildings techniques.
2) *SWL Electronic* includes all of the *SWL Printed* content, the Detailed Design Strategies and Detailed Analysis Techniques, plus a rich collection of appendices, including extensive climate data and the *SWL Tools* zero-energy spreadsheet.

While Part VIII and Part IX are found only in *SWL Electronic, SWL Printed* is organized into Part I, "Navigation"; Part II, "Using *Sun, Wind & Light*"; Part III, "Synergies"; Part IV, "Bundles"; Part V, "Favorite Design Tools, condensed"; and Part VI, "Favorite Design Strategies, condensed."

In Part I, "Navigation," *SWL Printed* is organized in several ways to help the user find a particular piece of information. First, there are several tables of contents: a short and a long version for both *SWL Printed* and for *SWL Electronic*. The short "Abbreviated Contents" list all of the synergies, bundles, techniques and design strategy names for quick reference. These are most useful when one is already familiar with the book. In addition to the names, the "Detailed Contents" give action statements under their major headings and subheadings so that in a few minutes

one can get a feeling for what is covered in the entire book.

New to *SWL* is the “Alphabetical Contents,” which is a speedy way to find the location of a synergy, bundle, strategy or technique if you already know its name. The “Navigation Matrix” is a graphic way to select and locate strategies by a combination of scale and energy topic (heating, cooling, lighting, ventilation or power).

The tool, “Navigation by Design Strategy Maps,” helps identify strategies that may be related to a strategy the designer is already using or considering. It is organized by a nine-level system of increasing complexity. The knowledge structure of the Design Strategy Maps is covered in greater detail in the “Navigation” section.

The book is indexed in multiple ways: using a conventional “Subject Index,” identifying the designers of the examples and the examples themselves in the “Designers and Precedents Index,” and indexing selected tables and graphs in the “Design Tools Index.” After you’ve read about an idea it will be easy to retrieve.

SWL Electronic reproduces the 8.5 x 11 landscape format pages, now printable, from *SWL2* with corrections, updates and many new strategies and techniques. It is divided into two main parts: Part VIII, “Detailed Design Strategies,” and Part IX, “Detailed Analysis Techniques.”

Part VIII, “Detailed Design Strategies” is the heart of *SWL Electronic* content. It is the section that designers will find the most useful while formulating concepts for a project. The design strategies are organized into sections first in terms of scale: Building Groups, Buildings and Building Parts. This helps a designer understand a particular principle, like sun movement, at a scale of consideration that is similar to the project.

Part IX, “Detailed Analysis Techniques,” plays a crucial but supporting role to the first part. These techniques serve the designer in three ways:

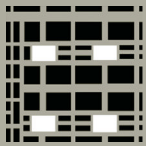
- *Defining the context of the problem* by understanding the sun, wind and light resources of a particular site and climate
- *Understanding the nature of the design problem itself:* Are the issues about heating, cooling or daylighting? How do the problems change over the day and from season to season, and how are they affected by changes in the building’s form and envelope construction? With this information the designer can form an idea of what kinds of strategies are likely to be important.
- *Evaluating the success of the design* at meeting net-zero energy, lighting or emissions targets

The “Glossary” section provides definitions for technical terms used in the text. All of the appendices are located in *SWL Electronic* and “Appendix A” includes climate data organized by city and keyed to the technique or strategy where the data is needed. That way, most of the information required to design in a particular place can be found in one location. The appendices also include more general climate data that is not specific to a particular city, such as data in the form of maps.

The multiple organizations of design knowledge

For many years researchers have been exploring how to organize design knowledge and, in particular, how to organize knowledge about designing with energy. It turns out that there is no one perfect organizational system that suits every purpose and every individual's orientation. While print requires that a particular linear organization be used, *SWL* also provides many ways via contents and indices, Design Strategy Maps, the Design Decision Chart and Strategy Bundles to arrive at which strategies to use and how to access them. Locating the bulk of the content on *SWL Electronic* also allows searching functions not possible in the printed book.

Organization by scale and complexity. As in *SWL1 and SWL2*, the primary organization of strategies is by three scale groupings: *Groups of Buildings* (anything larger than a single building), *Buildings* and *Building Parts.* These can be extended from an architecture-centric logic to include the domain of landscape architecture. Thus, the scale of Groups of Buildings also includes the scale of *Site* and the space between and around building groups and complexes, whatever it may be called. The scale of *Buildings* includes the land and site, the scale of the *Grounds* of an individual building, while the scale of *Building Parts* includes landscape and living elements, termed the scale

SCALE	DESIGN COMPONENTS
 **Groups of Buildings / Sites** L9 Neighborhoods L8 Urban Fabric L7 Urban Elements	• Streets Parking Transit Roads Bikeways Walks • Buildings • Open spaces Shaped Space (plazas, squares) Green Space (parks, habitat, conservation land) • Landform (topography) • Water • Infrastructure
 **Buildings / Grounds** L6 Whole Building L5 Room Organizations L4 The Room	• Rooms Subspaces (alcoves, activity areas) Cores (serving spaces) • Courtyards (outdoor rooms, gardens, porches) • Circulation (paths, indoor streets, corridors, stairs) • Transitional Space (in-between space, entrances, arcades)
 **Building Parts / Planting** L3 Building Systems L2 Elements L1 Materials	• Walls (including partitions) • Floors • Roofs • Windows • Foundations • Trees • Vines • Ground cover • Systems • Distribution • Controls • Lighting • Machines

DESIGN CHARACTERISTICS

• Size	• Organizations, Modular
• Shape	• Organizations, Stacked
• Enclosure	• Organizations, Staggered
• Orientation	• Organizations, Radial
• Increment	• Organizations, Gridded
• Location	• Organizations, Combined
• Edges	• Organizations, Sectional
• Use/Occupancy	• Organizations, Differential
• Linkages	• Organizations, Thin
• Layers	• Organizations, Thick
• Type	• Organizations, Zoned
• Color	• Organizations, Elongated
• Texture	• Organizations, Networked
• Material	• Organizations, Nodal
• Switching	• Organizations, Compact
• Cycles	• Organizations, Clustered
• Configuration	• Organizations, Dispersed
• Organizations, Open	• Organizations, Hierarchical
	• Organizations, Interwoven

DESIGN ISSUES

• Heating	• Ventilation	• Emissions
• Cooling	• Daylighting	• Power

Elements of the SWL Knowledge Structure

of *Planting*. In this edition each grouping is subdivided into three subcategories to form a *nine-level hierarchical spectrum of complexity*. The logic of this system are explained in detail in Part I, "Navigation." Essentially, following systems theory, elements or strategies at any lower level help to build strategies at the next higher level. For example, Level 2 *Elements* such as windows, are made of Level 1 *Materials* like glass and wood. Level 2 windows combine with other elements to make Level 3 walls, while combinations of Level 3 walls, floors and roofs combine to make a Level 4 *Room* and so on. The compete sequence is shown in the table **Elements of the *SWL* Knowledge Structure.** Within the scalar organization, which is also an organization based on complexity, the strategies are organized by *architectural elements*, such as streets, blocks, rooms, windows and walls, and by their

design characteristics and the relationships among those elements, such as size, shape, layers and zones. Every design strategy is defined by a relationship among its elements. This approach was used because architectural elements are the common denominator of the issues under consideration at the scheming stage. They are what the designer manipulates to develop a design concept. For example, when considering the role of windows, the designer can find heating, cooling and daylighting strategies organized together under the categories of window orientation, size, location and shape. These strategies can be considered together and with other non-energy window considerations, such as view or display.

At the scale of building groups, the elements of streets, buildings and open spaces are primarily used. In a complete set of design elements for neighborhood and urban design a longer list that includes all the major elements present in a site plan is required. Streets are allowed to stand in for all circulation at this scale. For issues beyond energy and climate, more distinctions are required, but the basic framework is still valid and expandable, as shown in the table.

At the scale of buildings, the primary elements are rooms and courtyards. For simplicity, *rooms* cover all types of rooms and *courtyards* stand for all types of outdoor occupied spaces. Massing and volume are not elements in themselves; in this way of thinking, they are patterns resulting from the organization of the elements, rooms and courtyards. Although not found necessary for the issues in *SWL3*, the components at this scale also include *circulation,* because a basic pattern of room organization most often consists of rooms served by circulation and the space of circulation itself. The basic distinction is between rooms as indoor space and courtyards as outdoor space, but it seems evident that *transitional space* is present in many buildings and plays an increasingly important climatic role in both cold climates and hot climates. While each category can be further differentiated, the current framework is shown in the table.

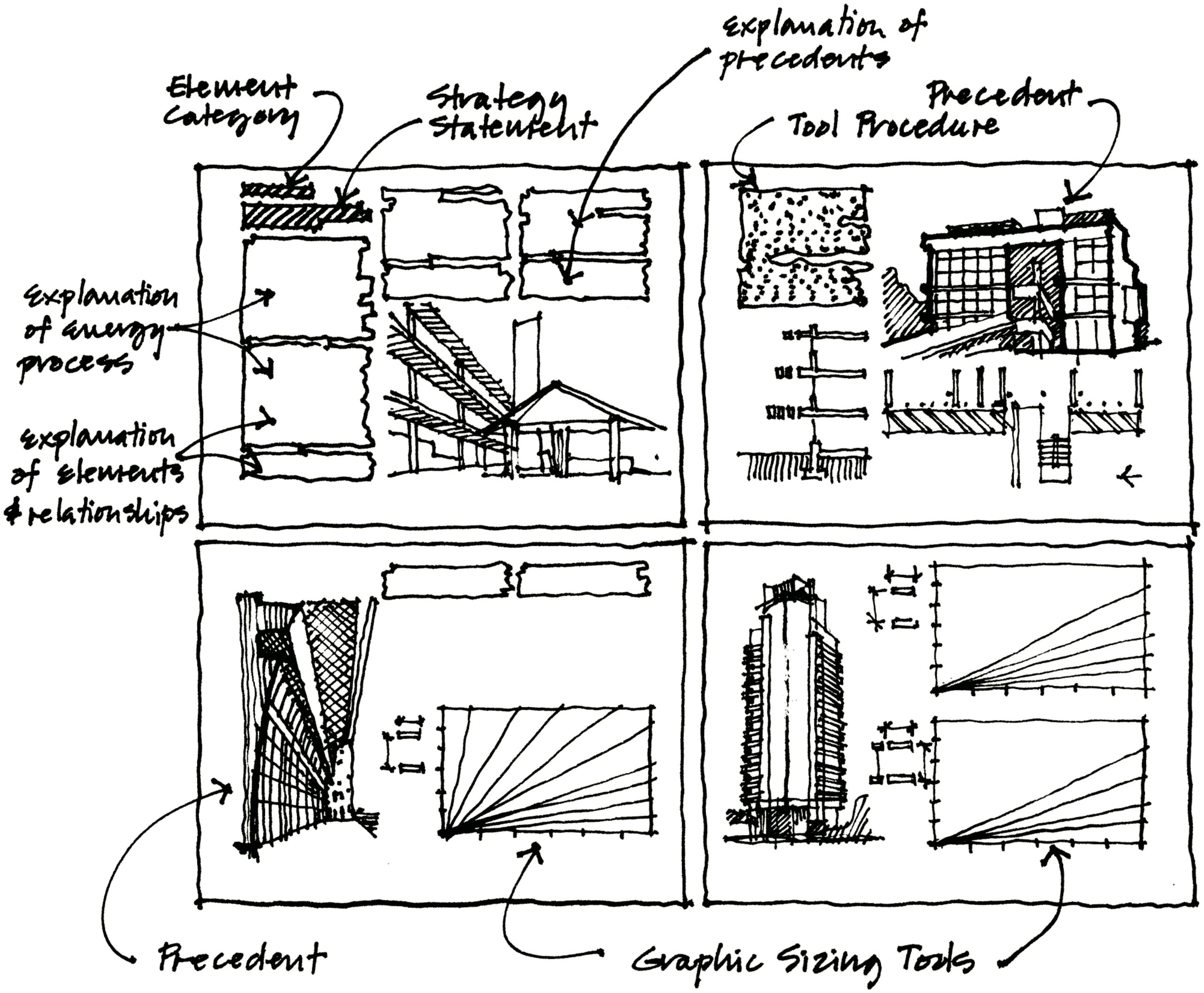
At the scale of building parts, the architectural components used in *SWL3* are primarily walls, floors, roofs and windows, but also ducts and plenums, machines, storage elements, etc. If the issues of this work were more structural in nature, such elements might be expanded to include columns, beams, footing and trusses. For landscape strategies, the elements become trees, vines, ground cover, etc. A partial list of design components at this scale is given in the table.

Organization by design characteristics. If a design strategy is defined by the relationship among its constituent design components, as are listed in the table **Elements of the *SWL* Knowledge Structure** for different scales, then the design characteristics specify the nature of the relationship among the elements. Often this relationship has a magnitude expressed in terms of size or proportion. At other times the relationships are patterns of organization that might occur in the same configuration but at different scales. Relationships can express either quantity or pattern or both.

Each strategy in *Sun, Wind & Light* is located at a particular scale and level of complexity; it is also expressed in terms of the components it addresses and how these components are related to each other in terms of specific characteristics. The list of the characteristics that are used is by no means exhaustive and will expand over time as needed.

Organization by design issue. Each strategy in *SWL3* is also categorized by its impact on an energy issue or topic. In the scope of this work, the issues are heating, cooling, daylighting, ventilation, emissions and power. Ventilation, by which is meant the provision of fresh ventilation air to building interiors (in contrast to ventilation with outdoor air for space cooling) is new to this edition. Some strategies, such as SOLAR APERTURES or DAYLIGHT ENVELOPE address a single issue, while others such as CLIMATIC ENVELOPE and SEPARATED OR COMBINED OPENINGS address several or even all of the issues simultaneously.

As a general framework for design knowledge these issues could be expanded to a wider range of objective issues (material resources, pollution, water, air quality, habitat, etc.) for both environmental issues and



Anatomy of a Sun, Wind & Light Design Strategy

non-environmental issues. Conceivably there is also no reason that the issues and intentions might not be expanded to include subjective issues of beauty and human experience, thus linking pleasure and performance. The issues within the scope of *SWL3* are given in the table.

Anatomy of a *Sun, Wind & Light* design strategy

The organizational structure described in the preceding pages is embedded in the header of each design strategy. For example, the header for the ATRIUM BUILDING design strategy looks like this:

Rooms and Courtyards: Shape and Enclosure

33 An *ATRIUM BUILDING* with a glazed or unglazed light court within can provide light to surrounding interior rooms. [daylighting]

The scale/level of complexity, given in the contents and page footer is *Buildings/Level 5, Room Organizations*. The design components in this case are *Rooms and Courtyards*. The design characteristics are *Shape and Enclosure,* which are also given in the footer. The name of the strategy, *Atrium Building,* is formatted in all caps, italicized and made a part of the bold formatted *action statement*. Each strategy's action statement is followed by a design issue that it concerns, shown in brackets; in this case the issue is *daylighting*.

Each design strategy is intended to support designers at making important schematic-level design decisions about the form or organization of building groups, sites, buildings or building elements. Each gives the following:

- a short *statement* of the strategy in the header
- a paragraph or more of *explanation* of its energy-related phenomenon
- an *example* of how the strategy has been used in an elegant way by another architect in buildings of high design quality
- a *tool* that helps to make a design decision such as size, shape, organization, color, material, etc.

Within the strategy statements, the discussion of the illustration, such as the **Larkin Building** by Frank Lloyd Wright, is given in bold type and the sizing rule-of-thumb or other design guideline or instruction are ***highlighted in bold italics*** so that they can be easily found. Within the text, sources that contain a more detailed explanation of the idea or the example are identified by author and date in the form of: (Author, date). These sources frequently aren't the original source but are a convenient place to find more information. A complete citation for all sources mentioned in the text can be found in the bibliography.

Part I
NAVIGATION

The knowledge contained in *Sun, Wind & Light* can be accessed in many ways. Because it is structured in a modular way (as Synergies, Bundles, Design Strategies and Techniques) and because there are many ways that these "parts" can be related to each other and combined into larger design patterns, there are several means offered to access the content and to determine which components the designer wants to employ.

One can take any of several perspectives on the knowledge contained in *SWL*. The design strategies can be accessed in terms of name, scale, complexity, design components, energy issue or climate. Each reveals or discloses something that a different viewpoint does not. Each perspective also conceals something that a different view may not. No approach to access, structure or navigation is necessarily better or worse. Each may appeal to a different individual designer's learning style, temperament, design process or worldview. Each approach to organization has its strengths and weaknesses, so in this edition, designers can select which is appropriate for his or her uses.

In previous editions, the contents were organized only by scale and architectural element, a means that made sense to the authors because we thought that it was important to emphasize the relationship among heating, cooling and daylighting at the scale of particular design components, such as windows. All of the design strategies for windows were grouped together, and if the designer's concern that day was designing windows, everything in the book about windows was located on adjacent pages. The drawback to this organizational method was that if a designer was interested in only one issue, such as daylighting, considered across a range of scales and design components, it was more difficult to find the applicable design strategies.

Because there is so much content, most of the new information is in *SWL Printed* and all the new information, including what is printed here plus over 700 additional new and revised pages, is located in *SWL Electronic*. Several kinds of tables of contents are included. In *SWL Electronic,* one will find reproduced all of these navigation instruments from the printed book, plus searchable and printable electronic versions of all of the content.

For additional ways to find what you need in *Sun, Wind & Light*, see:

Sun, Wind & Light also contains multiple indices. Each index directs the reader to content in both *SWL Printed* and *⌁ SWL Electronic*.

Navigation Matrix

by Scale and Energy Topic

The Navigation Matrix on the following pages organizes all of the Synergies, Bundles, Design Strategies and Techniques in *Sun, Wind & Light* by scale and energy topic. Find on the vertical axis the three scale groupings, *Groups of Buildings, Buildings* and *Building Parts*, which apply to the bundles and design strategies, plus the category of *Analysis & Evaluation* [Techniques], which often relates to multiple scales. On the horizontal axis are the categories of energy topics that the Synergy, Bundle, Strategy or Technique helps the designer consider. The topics include, *Heating, Cooling, Ventilation, Daylighting* and *Power* and combinations of these.

Each of the knowledge modules in *SWL* is listed with its sequential number. Synergies are designated S1, S2, S3, etc. Bundles are listed as B1, B2, etc. Both are shown in ***bold type.*** Design Strategies are listed as 1, 2, 3, etc. Analysis Techniques are numbered A1, A2, A3, etc. and the new High-Performance Buildings assessment methods are labeled P1, P2, P3, etc. This follows the naming conventions in the text and in the other navigation instruments.

Strengths

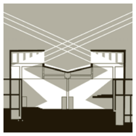
- Useful for finding the strategies or bundles that operate at a particular scale
- Helpful for finding design guidance on a particular energy topic, such as daylighting
- Useful for finding strategies that may be related by scale and topic(s) to a strategy the designer is already considering
- Helps understand the range of strategies that apply to particular topics

Weakness

- Does not reveal the scalar or complexity of relationships among strategies
- Implies but does not specify the relationships between energy topics

	HEATING 	COOLING 	COOLING & VENTLILATION 	HEATING & COOLING 	
ANALYSIS & EVALUATION 	A3 Solar Radiation	A26 Shading Calendar		A1 Sundial A2 Sun Path Diagram A4 Wind Rose A5 Wind Square A6 Air Movement Principles A7 Site Microclimates A13 Adaptive Comfort Criteria	A16 Occupancy Heat Gain A17 Electric Lighting Heat Gain A18 Equipment Heat Gain A21 Skin Heat Flow A22 Window Solar Gain A24 Bioclimatic Chart A25 Earth Contact A27 Total Heat Gains & Losses
BUILDING GROUPS  L7-L9	**B3 Solar Neighborhood** 8 Gradual Height Transitions 11 Winter Courts 12 Neighborhood Sunshine 15 Solar Envelopes 18 Tall Building Currents 20 East-West Elongated Building Groups	**B2 Cooling Neighborhood** 2 Shared Shade 9 Interwoven Buildings & Planting 10 Interwoven Buildings & Water 16 Shadow Umbrella 22 Green Edges 23 Overhead Shades	1 Converging Ventilation Corridors 19 Dispersed Buildings	3 Topographic Microclimates	7 Loose/Dense Urban Patterns 21 Wind Breaks
BUILDINGS  L4-L6	**B7 Passive Solar Building** 28 Heating Zones 36 East-West Plan 37 Deep Sun 39 Moving Heat to Cold Rooms 42 Convective Loops 48 Direct Gain Rooms 49 Sunspaces 50 Thermal Storage Wall 51 Thermal Collectors	**B6 Passively Cooled Building** 54 Night Cooled Mass 59 Shady Courtyards	26 Cooling Zones 27 Mixed Mode Cooling 30 Permeable Buildings 44 Cross-Ventilation Rooms 45 Wind Catchers 46 Evaporative Cooling Towers 53 Stack-Ventilation Rooms	**B8 Outdoor Microclimates** **S5 Thermal Sailing** 24 Migration 29 Buffer Zones 32 Locating Outdoor Rooms 34 Clustered Rooms	40 Stratification Zones 52 Roof Ponds 58 Breezy/Calm Courtyards
BUILDING PARTS  L1-L3	70 Well Placed Windows 80 Breathing Walls* 81 Solar Reflectors 84 Solar Apertures 102 Mass Surface Absorptance	61 Water Edges 63 Layer of Shades 91 External Shading 92 Internal & In-between Shading 105 Double Skin Materials	69 Ventilation Openings Arrangement 86 Ventilation Apertures 96 Mechanical Space Ventilation	60 Mass Arrangement 62 Insulation Outside 74 Skin Thickness 75 Thermal Mass 76 Earth Edges 77 Radiant Surfaces	89 Movable Insulation 94 Rock Beds 95 Mechanical Mass Ventilation 100 Heat Pumps 104 Exterior Surface Color

Heating & Ventilation

HEATING, COOLING & VENTILATION	HEATING, COOLING & DAYLIGHTING	COOLING & DAYLIGHTING	DAYLIGHTING	POWER	
					
A12 Temperature & Humidity A23 Vent./Infiltration Gain & Loss A28 Balance Point Temperature A29 Balance Point Profile	**S1 Climate Resources** **S2 Occupants Behaviors** A14 Energy Conscious Programming A15 Load-Responsive Scheduling A32 Energy Use Intensity A33 Emissions Targets*		A8 Sky Cover A9 Daylight Availability A10 Daylight Obstructions A11 Design Daylight Factor	A19 Electric Loads A20 Hot Water Loads A30 Energy & Pollution Targets A31 Annual Energy Use A34 Net-Zero Energy Balance A35 Carbon-Neutral Building*	**ANALYSIS & EVALUATION** 
17 Breezy/Calm Streets	**B4 Integrated Urban Patterns** **S3 Resource-Rich Environments** 5 Climatic Envelopes		**B1 Neighborhood of Light** 4 Daylight Density 6 Glazed Streets 13 Daylight Blocks 14 Daylight Envelopes		**BUILDING GROUPS**  **L7-L9**
43 Rooms facing the Sun and the Wind	**S4 Spatial Zoning** 25 Periodic Transformations		**B5 Daylight Building** 31 Borrowed Daylight 33 Atrium Building 35 Thin Plan 38 Skylight Building 41 Daylight Zones 47 Toplight Room 55 Daylight Rm Geometry 56 Glare-Free Rooms 57 Sidelight Room Depth		**BUILDINGS**  **L4-L6**
71 Sympathetic HVAC 72 Mechanical Heat Distribution 97 Ducts & Plenums 98 Earth–Air Heat Exchangers 99 Air–Air Heat Exchangers	**B9 Responsive Envelope** **S6 Multivalent Design** **S7 Active Tailored System** 67 Separated or Combined Openings 87 Air Flow Windows 106 Window & Glass Types 101 Man/Auto Controls **also Emissions*	88 Light Shelves 90 Daylight Enhancing Shades	64 Reflected Sunlight 65 Open Roof Structure 66 Daylight Roof 68 Window Placement 73 Electric Light Zones 82 Low Contrast 83 Skylight Wells 85 Daylight Apertures 93 Task Lightning 103 Daylight Reflecting Surfaces	78 Photovoltaic Walls & Roofs 79 Solar Hot Water **also Emissions*	**BUILDING PARTS**  **L1-L3**

Navigation by Design Strategy Maps

Key Points

- Strategies are organized in levels of complexity.
- Less complex/smaller scale strategies help build larger strategies.
- Every strategy has a context.
- More complex/larger strategies organize patterns of smaller strategies.
- A full range of complexity levels is necessary for a whole and complete environment.

Strengths

- Helps identify relationships and link strategies across scales
- Helps designers look vertically at the set of strategies needed to be effective
- Identifies strategies that may be critical to the success of another strategy or upon which a given strategy may depend
- Provides a graphic overview of the whole knowledge base of *SWL*

Weaknesses

- Only really helpful if the designer knows the essence of several strategies already
- Best for advanced users; may be opaque for beginners
- Requires user to understand the rules for relationships among strategies that are behind the graphics

The nested hierarchy of the Design Strategy Maps

The Design Strategy Maps are one way to look at the structure of the knowledge base of net-zero energy design and climatic design. They show the relationships latent in the many design strategies in *Sun, Wind & Light*. They organize the design strategies into a nested, lattice-like hierarchical network.

The organization of the Design Strategy Maps is based on the idea that each strategy is *both a whole and a part*. Each strategy organizes and is made up of strategies at a lower order of complexity and a smaller scale. Each strategy also has a context, which is another larger, more complex strategy.[1]

The second idea embodied in the Design Strategy Maps is that this nesting of strategies within strategies can be associated with *levels of scale,* where each larger scale exhibits an increase in complexity. The spectrum of complexity is organized in a system of nine levels, from materials to regions, as shown in **Levels of Complexity for Design Strategy Maps**.

1 The structure of the maps is based on observations about the relationships of parts and wholes first formally identified in general systems theory and later in ecological hierarchy theory. An informal version was employed by Alexander, et al, in *A Pattern Language* (1977). Wilber (2000) articulated the logics of such systems structures that apply to many knowledge domains in what he calls "the twenty tenets."

GROUPS OF BUILDINGS [Sites]
- L9 Neighborhood
- L8 Urban Fabric
- L7 Urban Elements

BUILDINGS [Grounds]
- L6 Whole Buildings [Plot]
- L5 Room Organizations
- L4 The Room [Garden]

BUILDING PARTS [Landscape Parts]
- L3 Building Systems [Landscape Systems]
- L2 Elements [Plantings]
- L1 Materials

Levels of Complexity for Design Strategy Maps

- L9 Neighborhoods: **NEIGHBORHOOD OF LIGHT**
- L8 Urban Fabrics: **CLIMATIC ENVELOPES**
- L7 Urban Elements: **DAYLIGHT ENVELOPES**
- L6 Whole Buildings: **DAYLIGHT BUILDING**
- L5 Room Organizations: **THIN PLAN**
- L4 The Room: **SIDELIGHT ROOM DEPTH**
- L3 Building Systems: **WINDOW PLACEMENT**
- L2 Elements: **DAYLIGHT APERTURES**
- L1 Materials: **WINDOW & GLASS TYPES**

Levels of Complexity: examples at each level for SWL daylighting strategies(one possible example)

Using this logic of parts and wholes, an architectural *Element [L2]*, such as a window, is made up of and cannot exist without its constituent *Materials [L1]*, such as glass and wood. *L2 Elements* help to build larger, more complex strategies at the level of *L3 Building Systems,* such as walls, roofs and floors. In turn, *L3 Building Systems* are configurations of *L2 Elements*. Similarly, *L4 Rooms* are configurations of *L3 Building Systems;* while *L5 Room Organizations* are made up of *L4 Rooms,* and *L6 Whole Buildings* are combinations of *L5 Room Organizations*. Each increase in complexity proceeds in this way, a nested hierarchy of spatial order.

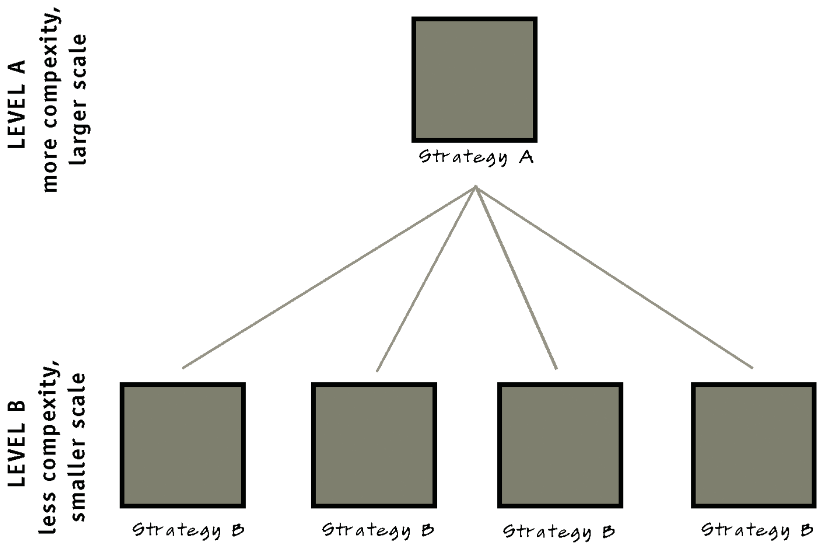
Of course, this is only one way to look at the order of parts and wholes. One could generate a system with more fine gradations or one with fewer levels. However, this is a system that seems to fit the common logics that designers use and the ways the profession speaks of the components and scales in buildings, such as the way rooms and courtyards are organized to make buildings and the way materials are organized into building assemblies like walls and roofs. It is about the simplest system of levels that accounts for all of the physical elements of design and how one can empirically observe parts combining to form larger patterns.

The hypothesis of this ordering system is that these relationships among scales are necessary for a *whole and complete* built environment and that, in most cases, strategies at several scales are needed for a particular strategy to function well and for the building as a system to work. Without this kind of scalar continuity of the strategies used in a building design, an entire architectural idea, such as the idea of a building as a lighting fixture for daylight, *may* break down and fail.

The example of daylighting

One route (there could be many) through the full hierarchy for a building and context designed for daylight is shown in the above **Levels of Complexity: examples at each level for *SWL* daylighting strategies**.

As an example, the SIDELIGHT ROOM DEPTH [L4] strategy says that the depth of a room with windows on only one side should be no more than 2.5 times the height of the window head to achieve an acceptable ratio of light between the windows and the back of the room. It is based on the configuration of relationships among sun, sky, window, room geometry, surface reflectance and human visual perception. If this pattern is extended to a consideration of a building plan, it generates another strategy, called THIN PLAN [L5]. By this pattern, the plan thickness of any part of a sidelighted building should not exceed 6–7 times the window head height (if an internal electrically lighted zone for circulation is allowed) or 5 times the window head height if good daylight is to reach to every room.



Diagrammatic Relationships Among Strategies in the Design Strategy Maps

If we then jump to the neighborhood scale, a similar pattern emerges when we intersect these articulated thin plan buildings with a city grid, DAYLIGHT BLOCKS [L7], which helps build DAYLIGHT DENSITY [L8] (For more complete relationships, see the **Design Strategy Map: Building Group Scale**). The NEIGHBORHOOD OF LIGHT strategy, at level 9, helps to organize the smaller level 8 patterns of DAYLIGHT DENSITY and CLIMATIC ENVELOPES, which, in turn, organizes both DAYLIGHT ENVELOPES and SOLAR ENVELOPES at level 7, strategies that guide urban building massing to insure access to light and sun.

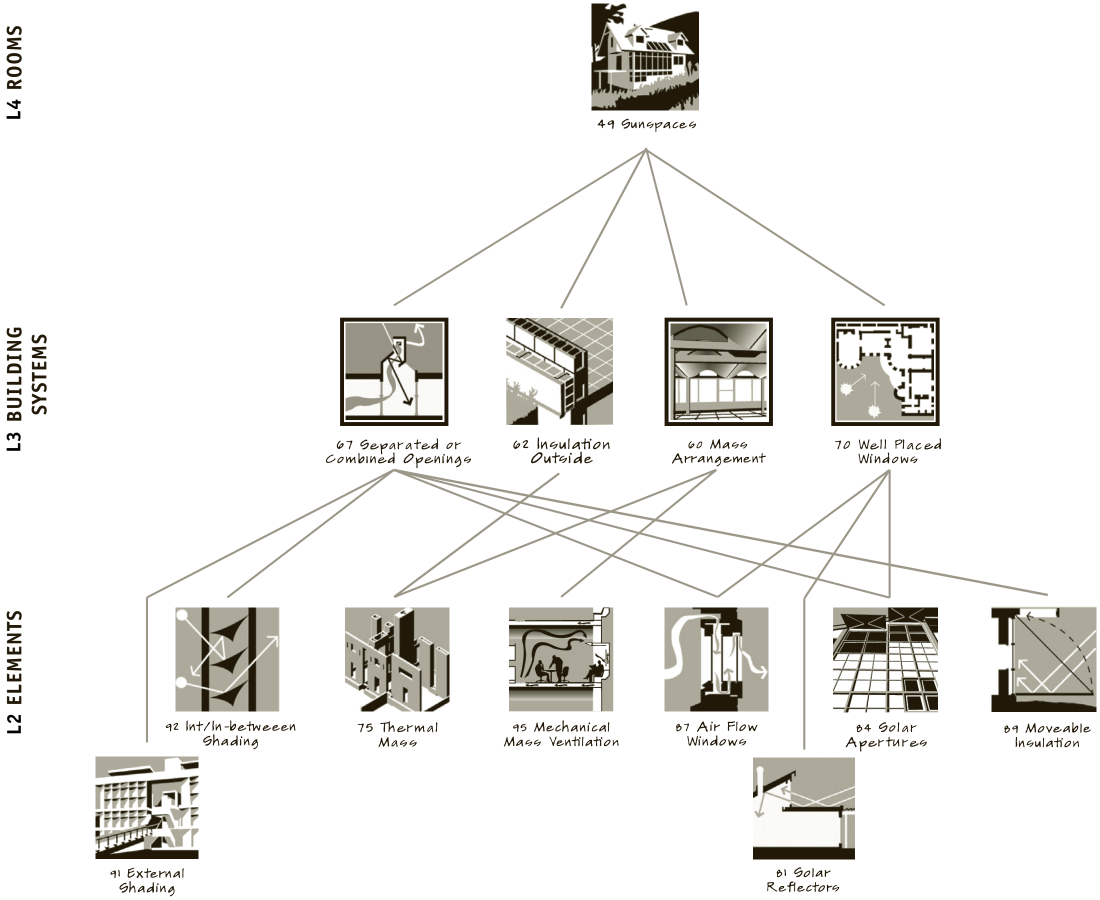
It is also easy to demonstrate that poor daylighting will result if a building lacks all strategies at a particular level. For example, in the case daylight example, if the WINDOW AND GLASS TYPE [L1] is not transmissive enough, or the DAYLIGHT APERTURES [L2] too small, the WINDOW PLACEMENT [L3] too concentrated or unilateral, the ROOM DEPTH [L4] too deep or the plan too thick (not a L5 THIN PLAN), daylight goals cannot be met. Similarly, if the large-scale strategies do not create the synergy necessary to bring sufficient daylight to the edge of the building, daylight design success at the building scale is highly improbable.

Like all the tools in *SWL,* the maps don't specify exactly what form to design or exactly what strategies to combine. What the Design Strategy Maps do suggest is a way to touch all the bases and check whether or not an important strategy has been overlooked. A successful design for a DAYLIGHTED BUILDING in a context that makes daylighting possible will employ one or more of the *SWL* daylighting design strategies at each of these levels of complexity. Most often, there are several strategies available at each level. Of course, not every building will typically employ every possible strategy.

What the links and levels mean

Consider for example two strategies, A and B, as shown in **Diagrammatic Relationships Among Strategies in the Design Strategy Maps.** In general, if Strategy A is shown above Strategy B in the Design Strategy Maps, then the following relationships are usually observed in the form given in the statements, but not vice versa. These are multiple ways to say the same thing:

- A is the *whole* of which B is a *part.*
- A helps to *organize* B or the *pattern of* Bs.
- A enfolds or contains or *includes* B.
- A is an immediate *context* of B. B is *nested within* A.



Sunspace Strategy and Related Strategies of Lower Complexity

- B *can exist* without A, but A *cannot exist* without B (or some B; not all possible Bs are identified in *SWL3*). So, if all the Bs are destroyed, A is also destroyed. A needs B (or at least one B) to exist.
- A is *enhanced* by B.
- The character of A is the *configuration of relationships* between Bs.
- A *transcends but includes* B.
- The deeper the A (more nested levels), the lower its population. There are more Bs in the world than As.
- A is *more complex* than B.
- B can usually participate in multiple As.

An A design strategy can then be considered to be a higher, more inclusive, deeper design strategy than B. The principles above hold generally to be true, although every variation of the list may not seem to apply to an individual strategy.

An excerpt from the map

To see the structure with more clarity, an excerpt from the maps is shown in the graphic **Sunspace Strategy and Linked Strategies of Lower Complexity**. A sunspace is a type of solar heating system in which the collection and storage for the building or a zone of the building are concentrated in one space. The SUNSPACE can be thought of as a configuration of a conserving envelope, a concentrated

amount of thermal mass and glazing properly located and sized. The diagram suggests that four L3 Building System strategies, when configured properly, are needed to generate the larger strategy SUNSPACE. Without windows, mass and an insulated envelope, the room will not be a sunspace.

In a typical sunspace design, the heat is collected via windows, which are concentrated on the equatorial facade while smaller glazing is placed on other orientations to reduce heat loss [WELL-PLACED WINDOWS]. These sun-collecting windows can serve the single purpose of heat collection, but most often, some will have to also serve for ventilation [SEPARATED OR COMBINED OPENINGS]. Similarly, the openings in the interior mass wall can serve the single purpose of ventilation between the sunspace and the adjacent rooms, or they may also be enlarged to admit light to the rooms. The mass and its location [MASS ARRANGEMENT] are critical to the sunspace's success. It works best with a mass floor, a masonry wall dividing the sunspace and the heated rooms, and often, either additional thermal storage in the form of water containers in the space or as remote storage. The mass then has to be located with its surfaces exposed to the sunspace interior and with its INSULATION ON THE OUTSIDE to keep from losing the captured heat. If a designer is working on creating a sunspace, the links between the sunspace and the L3 strategies help remind the designer to consider these critical elements.

Each L3 Building Systems strategy is linked to one or more L2 Elements strategies. For example, the mass arrangement strategy helps find the best locations for THERMAL MASS and NIGHT-COOLED MASS. The sunspace designer might be thinking only of winter heating when deciding on the size and location of the mass, but the links remind him to also consider the summer night-cooled mass. The MASS ARRANGEMENT strategy configures the elements of thermal storage. Similarly, the INSULATION OUTSIDE strategy configures the insulation in SKIN THICKNESS and the thermal mass in the wall or roof. It is composed of them. If INSULATION OUTSIDE is an A level strategy, then THERMAL MASS and SKIN THICKNESS are its Bs.

Remember that the Design Strategy Maps show potential linkages and a large set of strategies from which the designer can select. All the strategies will not be used in one building. The sunspace, for example, will in all likelihood, not use all of the strategies that are linked to it at lower levels. For example, both EXTERNAL SHADING and INTERNAL OR IN-BETWEEN SHADING are linked to SEPARATED OR COMBINED OPENINGS and from there to SUNSPACE. The sunspace might use only one of these. Some strategies, such as SOLAR REFLECTORS and AIR FLOW WINDOWS, can be considered optional refining strategies. Some designs may use them and others will not.

Thinking in terms of both analysis and context

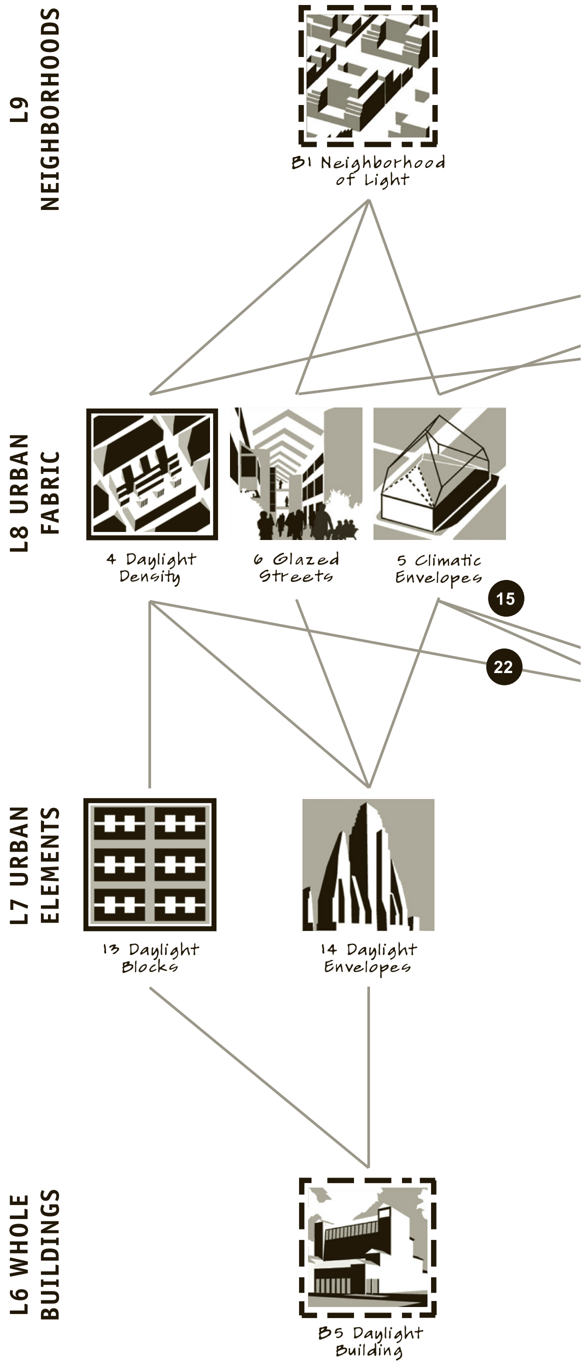
Form is often conventionally understood in architectural terms as the pattern that configures parts within the whole. Many, if not most, ways of understanding these formal patterns involve techniques of analysis that break down, dissect or deconstruct the larger whole into its constituent elements or their fundamental arrangements and relationships. The *analytic method* is a valid approach, from which one can learn much about buildings. It can be thought of as moving from higher to lower levels of complexity in the maps. Analysis is true and correct in that it describes one portion or aspect of design, however, alone it is incomplete and insufficient in two ways:

1) The *emergent qualities* unique to the whole are never found via analysis, only those qualities found in the parts.
2) Atomistic analysis misses *how the whole is simultaneously a part* of something larger.

The *yin* of analysis's *yang* is *holism and contextualism*. To understand anything as a whole, one has to look for what is unique to the whole and not found in the parts. The *contextual method* looks for the larger whole to which a part contributes. One way this is often done in design is by mapping the pattern that defines the whole, that is representing the *relationships* among the parts. In addition to breaking it down, one can understand the whole by placing it within its larger, containing context where it becomes a part of a whole larger than itself.

In architectural terms, designers can think of a building's form as both a product of its constituent parts, the internal "order within" and at the same time, as a product of its external context-based order, the "order without." This logic applies at every scale of design. Instead of form alone, consider thinking of the more inclusive idea of "place-form," which is a multitiered nesting of part, whole and context. From this perspective, every whole at every level is made up of parts. Such things with their whole/part nature are known in systems theory as *holons*. A hierarchy of nested holons is a *holarchy*. *SWL3* terms these spatial holons "design strategies."

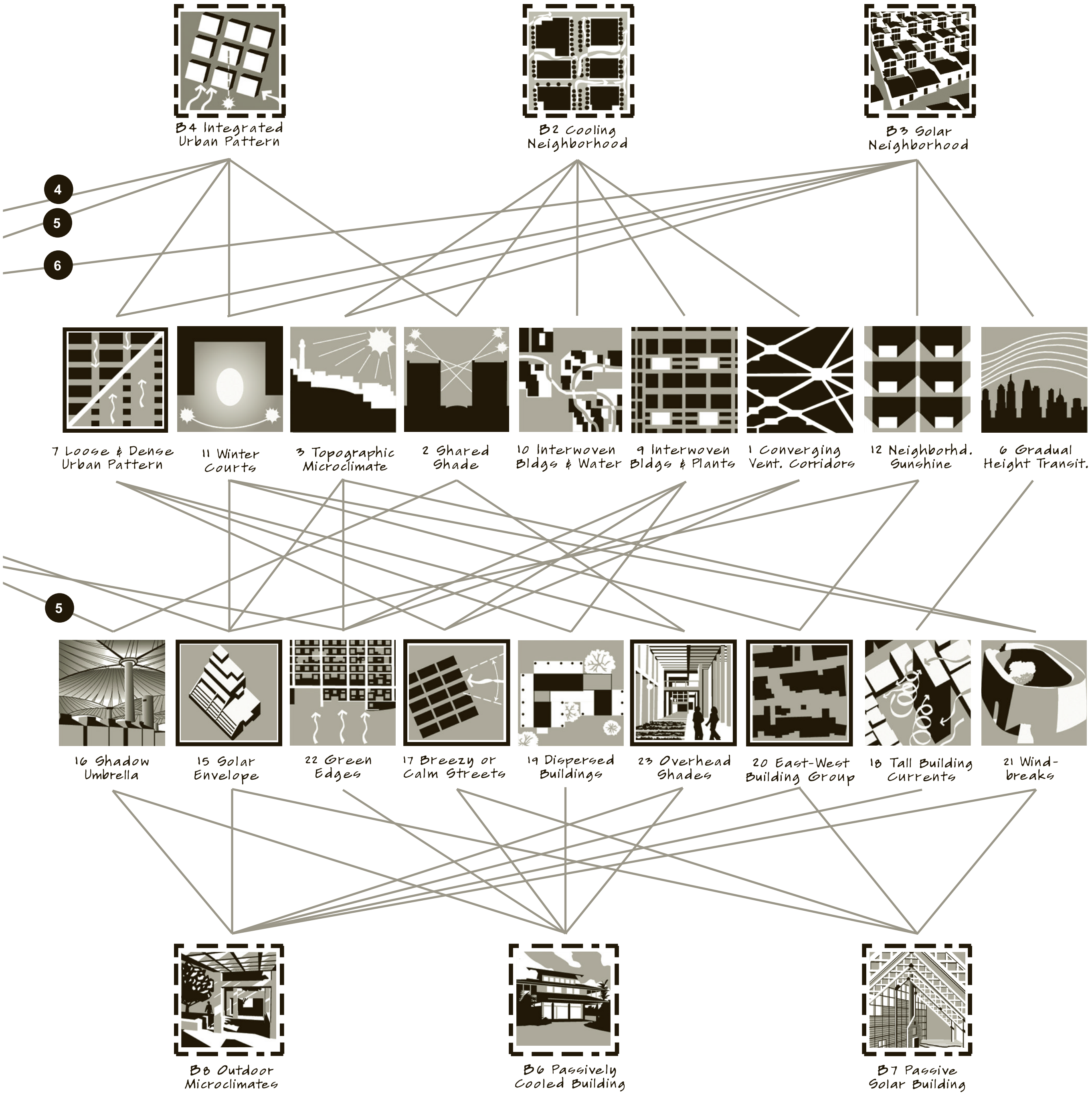
The **Design Strategy Maps** reveal the most significant of these nested complexity relationships among the design strategies in *Sun, Wind & Light,* though more connections could, of course, be drawn and more strategies could be added. At the scales of Building Parts, there are definitely important relationships not revealed in this edition of the maps. The Design Strategy Maps address only one very significant kind of relationship and make no attempt to illustrate all possible relationships among strategies. Finally, it is clear that the *SWL* collection of strategies is incomplete and that the knowledge base keeps expanding!



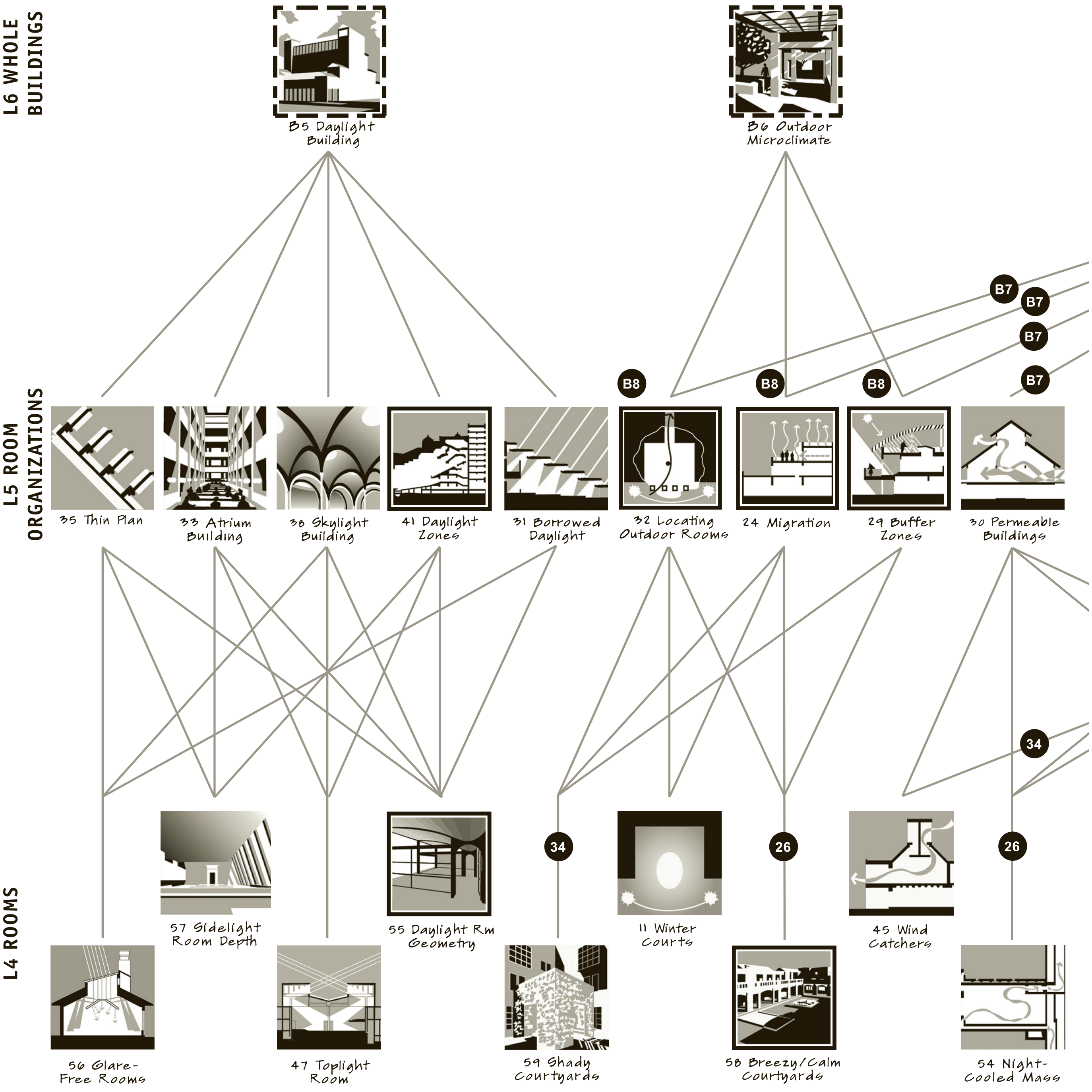
Bundles

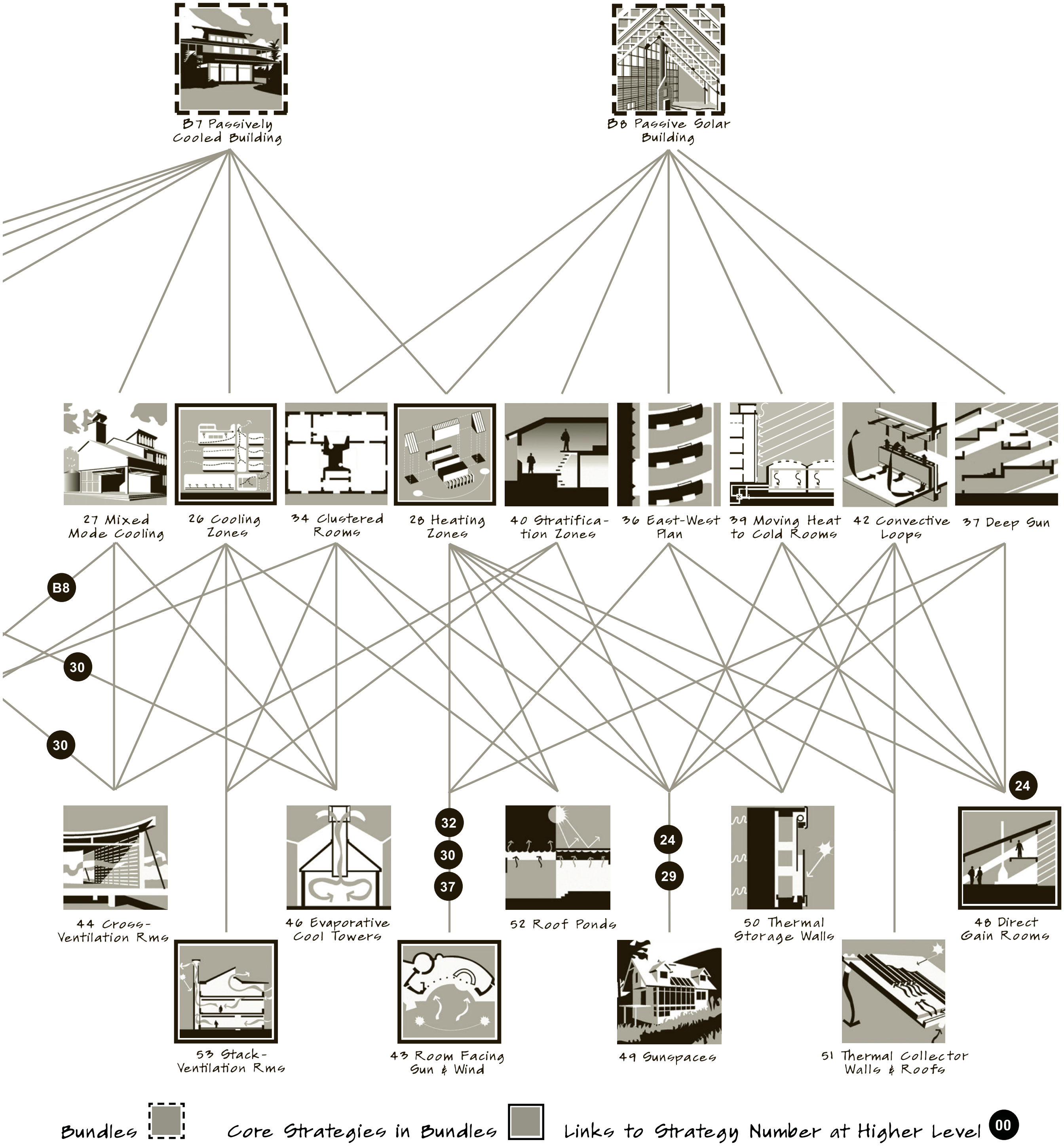
Core Strategies in Bundles

Links to Strategy Number at Higher Level 00

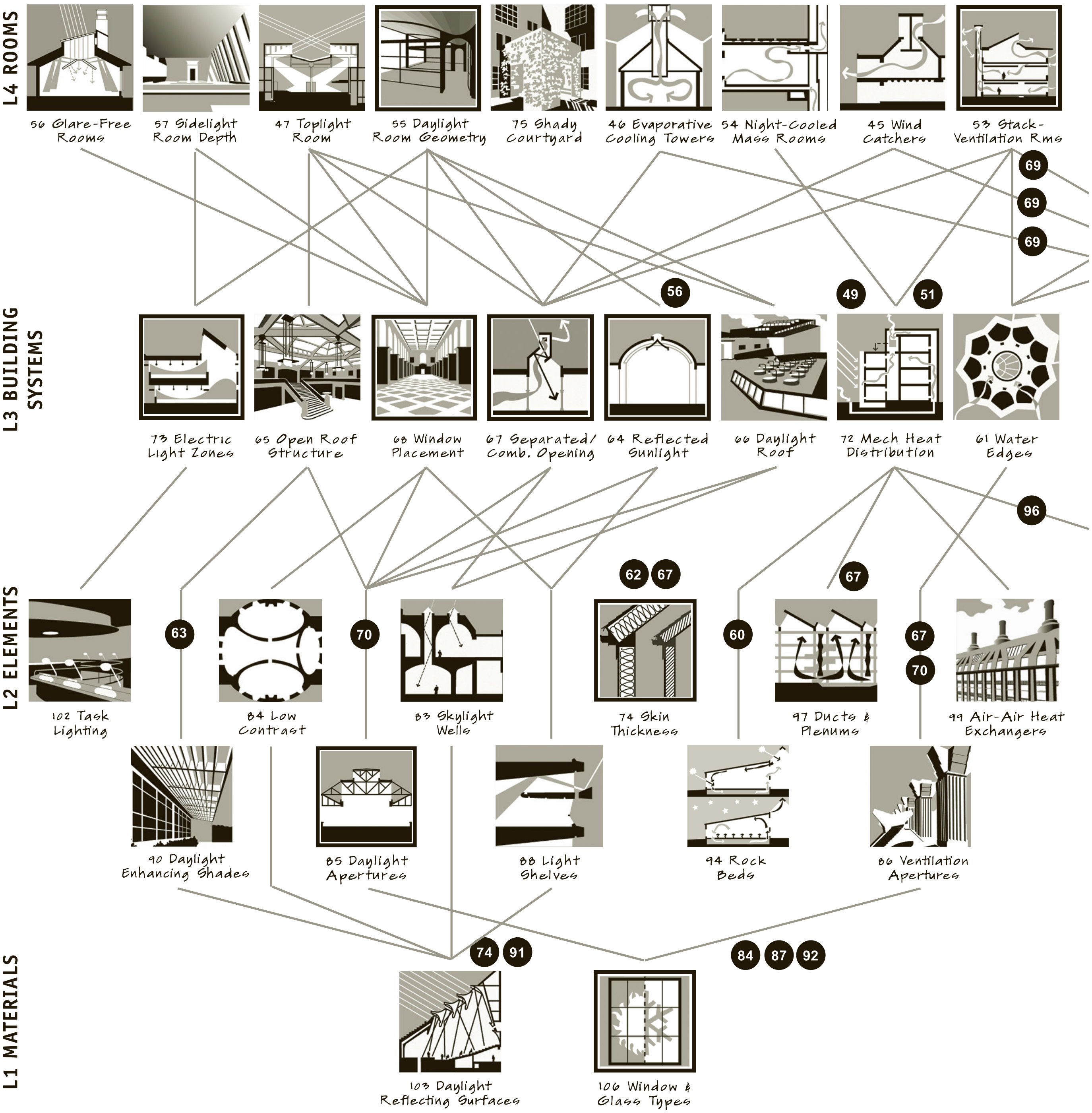


DESIGN STRATEGY MAP, Building Groups Scale

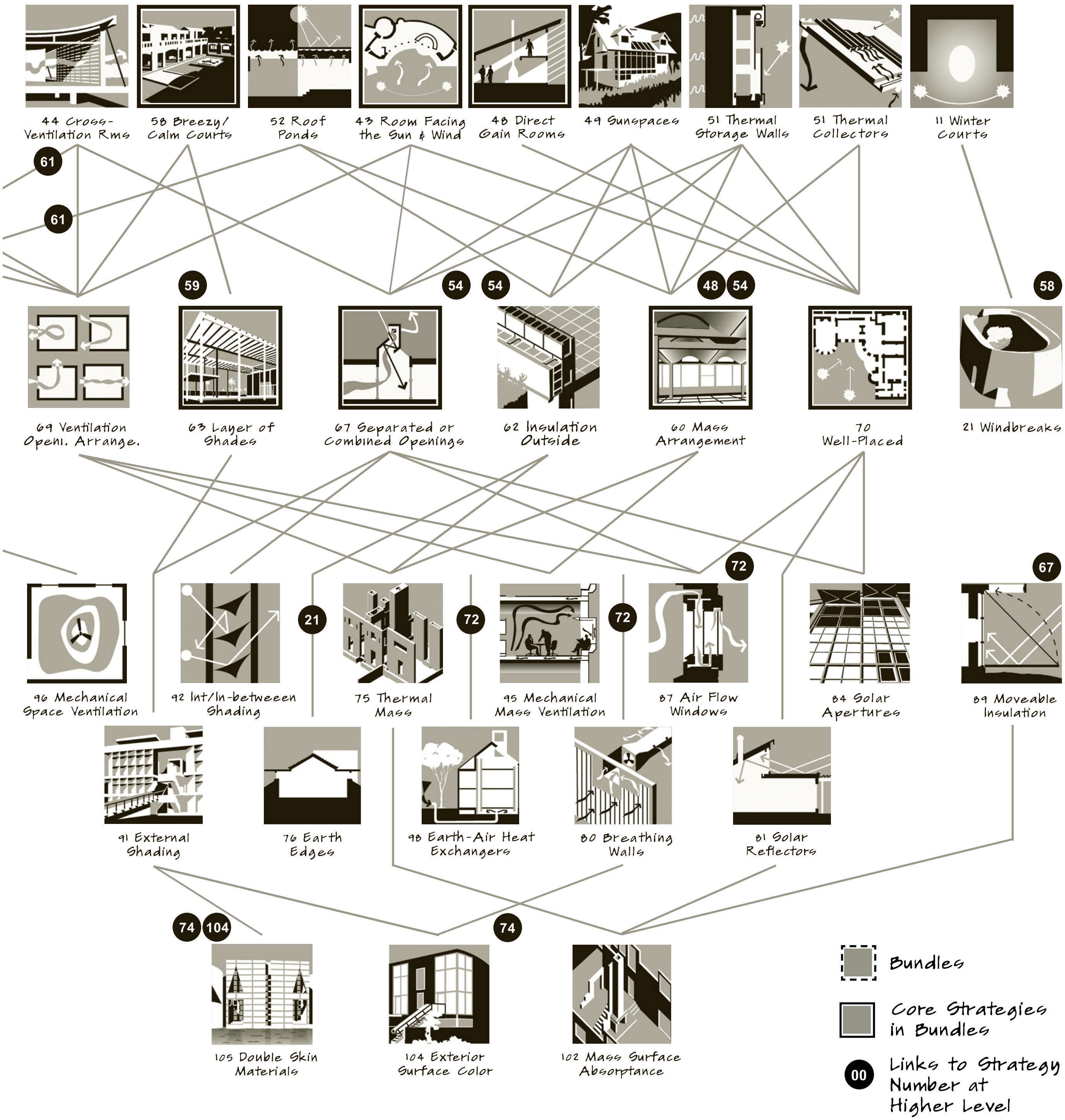

L6 WHOLE BUILDINGS
B5 Daylight Building
B6 Outdoor Microclimate
L5 ROOM ORGANIZATIONS
B7
B7
B7
B7
B8
B8
B8
35 Thin Plan
33 Atrium Building
38 Skylight Building
41 Daylight Zones
31 Borrowed Daylight
32 Locating Outdoor Rooms
24 Migration
29 Buffer Zones
30 Permeable Buildings
34
L4 ROOMS
34
26
26
57 Sidelight Room Depth
55 Daylight Rm Geometry
11 Winter Courts
45 Wind Catchers
56 Glare-Free Rooms
47 Toplight Room
59 Shady Courtyards
58 Breezy/Calm Courtyards
54 Night-Cooled Mass



B7 Passively Cooled Building
B8 Passive Solar Building
27 Mixed Mode Cooling
26 Cooling Zones
34 Clustered Rooms
28 Heating Zones
40 Stratification Zones
36 East-West Plan
39 Moving Heat to Cold Rooms
42 Convective Loops
37 Deep Sun
B8
30
30
24
32
30
37
24
29
44 Cross-Ventilation Rms
46 Evaporative Cool Towers
52 Roof Ponds
50 Thermal Storage Walls
48 Direct Gain Rooms
53 Stack-Ventilation Rms
43 Room Facing Sun & Wind
49 Sunspaces
51 Thermal Collector Walls & Roofs
Bundles
Core Strategies in Bundles
Links to Strategy Number at Higher Level
00



 DESIGN STRATEGY MAP, Building Parts Scale


44 Cross-Ventilation Rms
58 Breezy/Calm Courts
52 Roof Ponds
43 Room Facing the Sun & Wind
48 Direct Gain Rooms
49 Sunspaces
51 Thermal Storage Walls
51 Thermal Collectors
11 Winter Courts
61
61
59
54
54
48
54
58
69 Ventilation Openi. Arrange.
63 Layer of Shades
67 Separated or Combined Openings
62 Insulation Outside
60 Mass Arrangement
70 Well-Placed
21 Windbreaks
72
67
21
72
72
96 Mechanical Space Ventilation
92 Int/In-betweeen Shading
75 Thermal Mass
95 Mechanical Mass Ventilation
87 Air Flow Windows
84 Solar Apertures
89 Moveable Insulation
91 External Shading
76 Earth Edges
98 Earth-Air Heat Exchangers
80 Breathing Walls
81 Solar Reflectors
74
104
74
105 Double Skin Materials
104 Exterior Surface Color
102 Mass Surface Absorptance
Bundles
Core Strategies in Bundles
00
Links to Strategy Number at Higher Level

Bundle variations based on climate

One fundamental context used in *SWL* is the building's climatic region. Except for daylighting, most design strategies can be divided into heating or cooling or both heating and cooling; a few are only applicable to hot-humid or hot-arid conditions. All of the daylighting strategies can be used to some degree in any climate. Three basic climate categories are designated for strategies and bundles of strategies:

- **Cold (C)**
- **Hot–Humid (H–hu)**
- **Hot–Arid (H–ar)**

A combination of climate and internal gains can account for much in determining appropriate energy strategies for preliminary design. The table **Bundle Variations by Climate and Internal Gains** shows how the three fundamental climate variations can be adapted to cover a wide variety of building situations. In general, a building with high internal gains, known as internal-load-dominated (ILD), such as a conventional sealed office building that does not make significant use of daylighting, has a lower balance point and more need for cooling than a similar building with low internal gains, known as skin-load-dominated (SLD), such as the one you might design using *SWL*. The ILD building will act like a building in a hotter climate and have greater needs for shading, cooling, etc. Similarly, because it has no envelope and no internal gains, an outdoor space will have conditioning needs more like a climate a step cooler than that of a SLD building.

The table's "center of gravity" assigns the basic climate types to an SLD building in a climate as typically perceived. For example, the table shows the Cold climate (C) in a cold, heating-dominated climate, like Duluth, Minnesota, Zone 6A and a Hot-Humid climate (H–hu) in a hot humid, cooling-dominated climate, like Miami, Florida, Zone 1A. For climate zone designations, see the **Maps of International Climate Zones** (following spread and larger versions in Appendix D).

The designation "H2" or "C2" means that the basic climate type conditions are exacerbated and that the dominant heating or cooling emphasis drives the climatic design responses even more than a condition with a designation of H or C. For example, an SLD building in a cold climate has a climate type designation of C. An outdoor room, which is more subject to the outdoor condition and has no internal loads, shifts to a C2 designation, meaning that it has a more intense cold condition to address. Similarly, an ILD building with large internal gains in a hot

Navigation by Climate

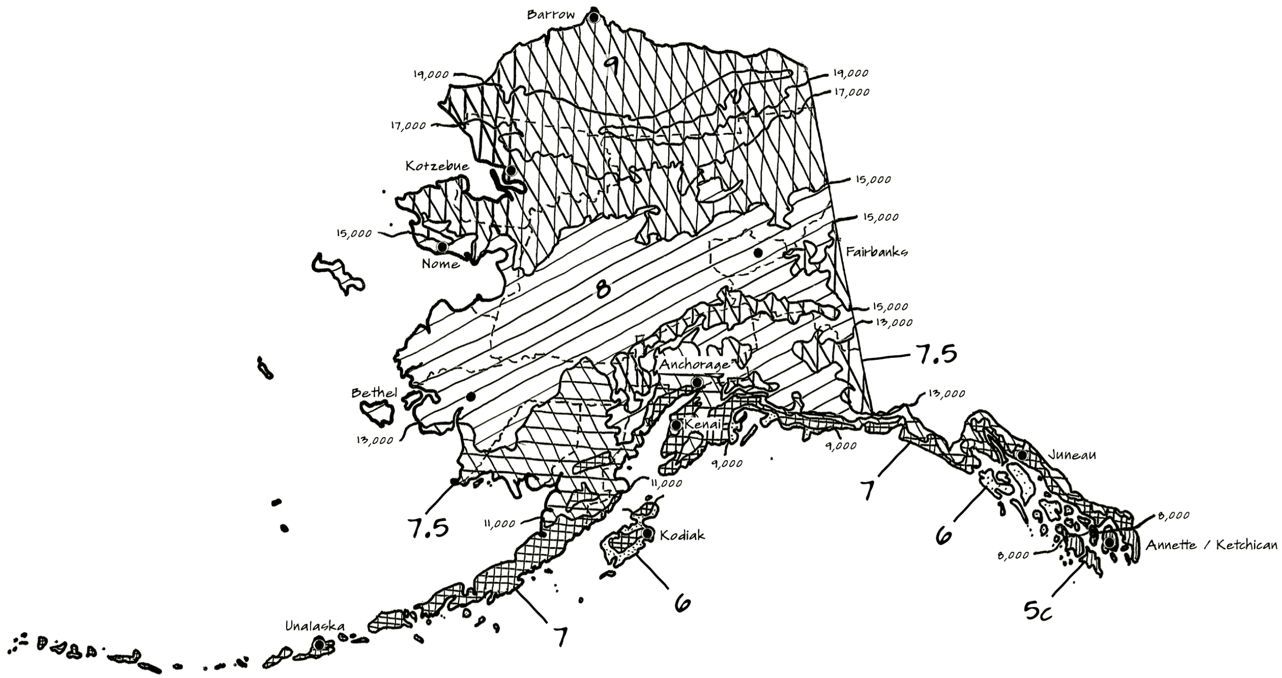
CLIMATE	PERCEIVED CLIMATIC CONDITION	ILD/THICK BUILDING	SLD/THIN BUILDING	OUTDOOR ROOMS
COLD	Heating Dominated	C + H-hu C + H-ar	C	C2
MIXED	Combined Heating & Cooling	H–hu H–ar	C + H–hu C + H–ar	C
HOT HUMID	Cooling Dominated: Humid	H2–hu	H–hu	C + H–hu
HOT ARID	Cooling Dominated: Arid	H2–ar	H–ar	C + H–ar
		HIGH INTERNAL GAINS	**LOW INTERNAL GAINS**	**NO INTERNAL GAINS**

Bundle Variations by Climate and Internal Gains

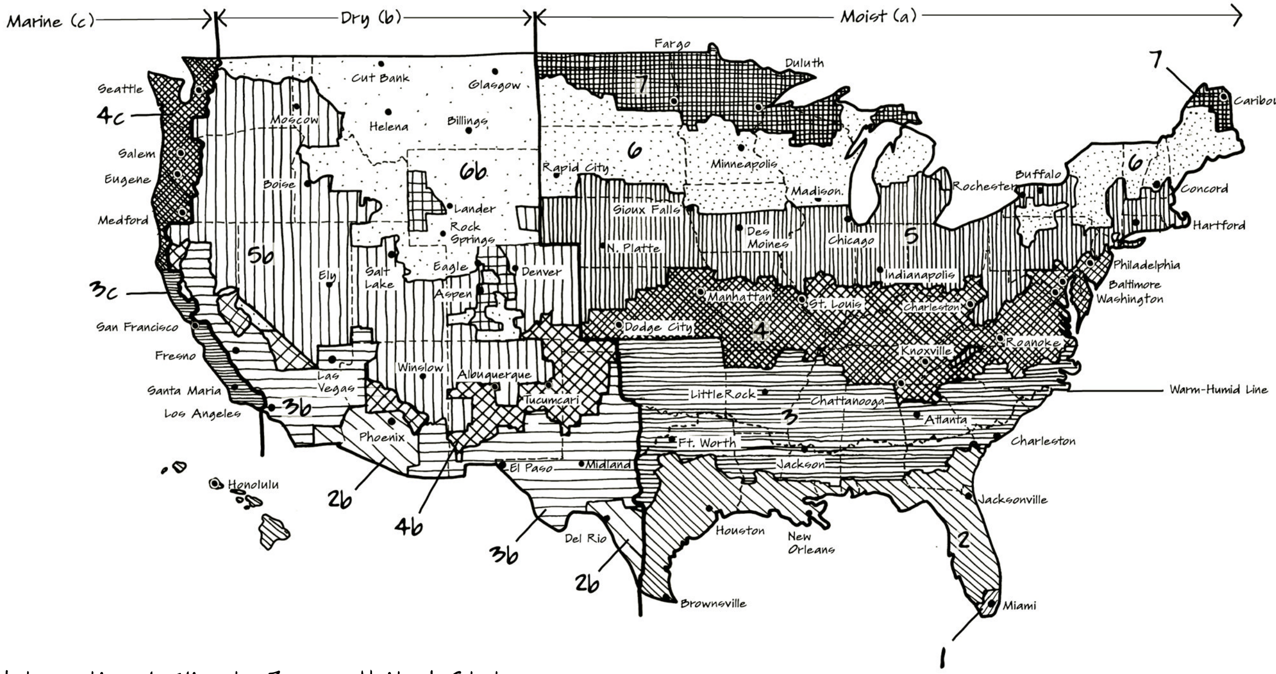
ILD = Internal-Load-Dominated; SLD = Skin-Load-Dominated; C = Cold Bundle; H = Hot Bundle; ar = arid; hu = humid
H2 = very hot, heavily cooling dominated; C2 = very cold, heavily heating dominated
Thick Building = a building with a low percentage of passive zones (see text)
Thin Building = a building with a high percentage of passive zones (see text)

arid (H–ar) climate may need cooling all the time. (H2–ar)

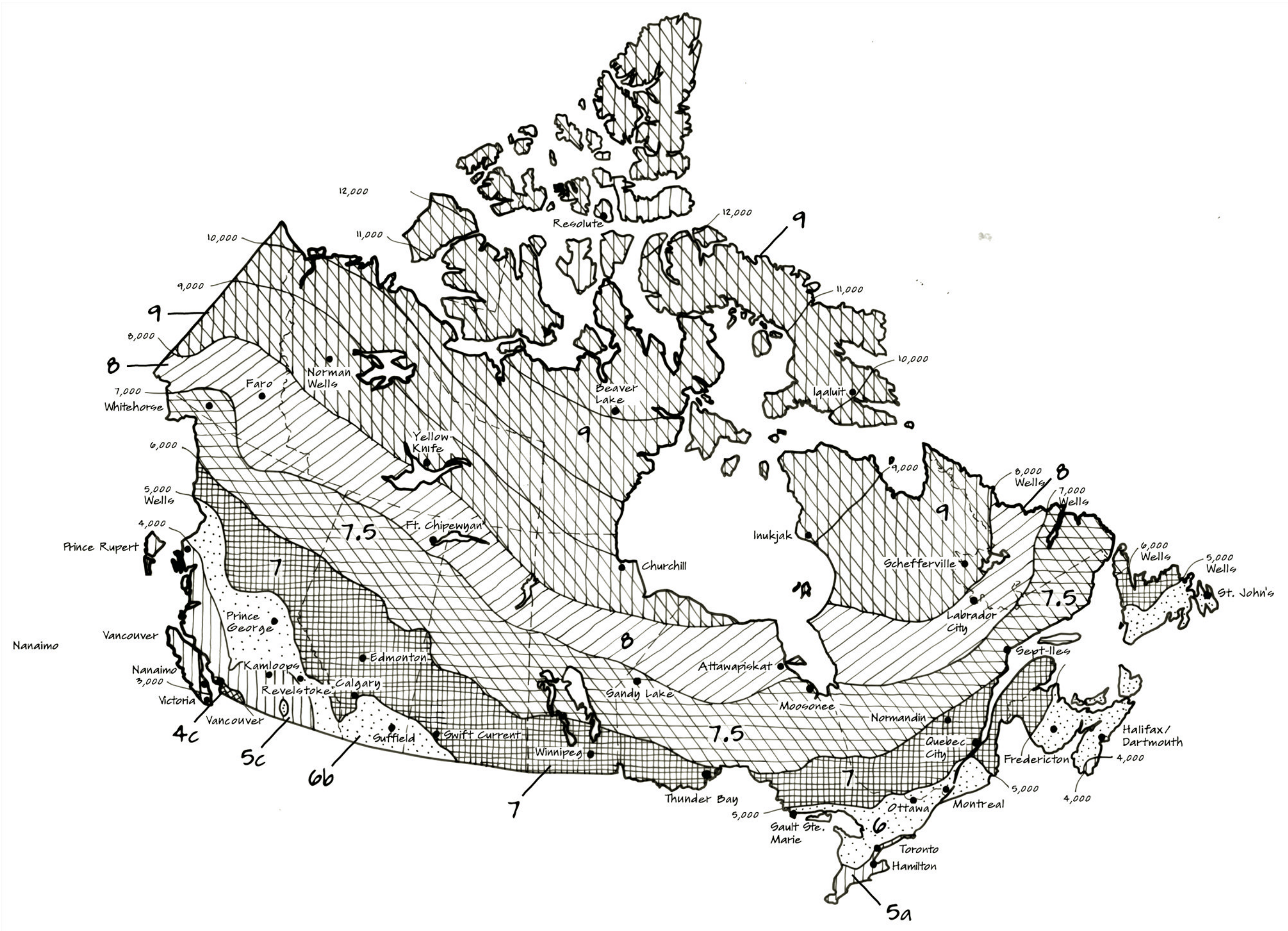
Most climates in North America are mixed climates, that is, their buildings require both heating and cooling for some periods of the year. For buildings with some combination of heating and cooling, the designer can use design strategies or bundles from both the Cold and one of the Hot climate groups. Remember that it is not just the climate that determines the need for heating or cooling but rather the combination of Climate + Use + Design (for more on this, see "Buildings and Energy Use" in Part II). This combination of factors drives the building's BALANCE POINT TEMPERATURE and BALANCE POINT PROFILE.



International Climate Zones, Alaska



International Climate Zones, United States



International Climate Zones, Canada

Marine (C) definition: Locations meeting all four of the following criteria:

1. Mean temperature of the coldest month between 27°F (-3°C)
2. Warmest month mean < 72°F (22°C)
3. At least four months with mean temperatures over 50°F (10°C)
4. Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through march in the Northern Hemisphere and April through September in the Southern Hemisphere.

Note: Larger versions of these maps are located in Appendix D of *SWL Electronic*

Dry (B) definition: Locations meeting the following criteria:

1. Not marine and
2. $P < 0.44 \times (T - 19.5)$ [IP units]
3. $P < 2.0 \times (T + 7)$ [SI units]

where:

P = annual precipitation in inches (cm) and

T = annual mean temperature in °F (°C).

Moist (A) definition: Locations that are not marine and not dry. (ASHRAE, 2007, Appendix B)

CLIMATE ZONE			IP Units, DD °F	SI Units, DD °C
VERY HOT	Humid	1A	> 9000 CDD50	> 5000 CDD10
	Dry	1B		
HOT	Humid	2A	6300–9000 CDD50	3500–5000 CDD10
	Dry	2B		
WARM	Humid	3A	4500–6300 CDD50	2500–3500 CDD10
	Dry	3B		
	Marine	3C	< 4500 CDD50 and < 3600 HDD65	< 2500 CDD10 and < 2000 HDD18
MIXED	Humid	4A	< 4500 CDD50 and 3600-5400 HDD65	< 2500 CDD10 and 2000-3000 HDD18
	Dry	4B		
	Marine	4C	3600–5400 HDD65	2000–3000 HDD18
COOL	Humid	5A	5400–7200 HDD65	3000–4000 HDD18
	Dry	5B		
	Marine	5C		
COLD	Humid	6A	7200–9000 HDD65	4000–5000 HDD18
	Dry	6B		
VERY COLD		7	9000–10800 HDD65	5000–6000 HDD18
SEVERE COLD		7.5	10800–12600 HDD65	6000–7000 HDD18
SUBARCTIC		8	12600–14400 HDD65	7000–8000 HDD18
ARCTIC		9	> 14400 HDD65	> 8000 HDD18

International Climate Zones, definitions

Outdoor conditions that drive envelope and solar loads are determined by the Climate. See CLIMATE RESOURCES. The Use factors set internal comfort criteria, occupancy schedules and rates of internal heat gain. See OCCUPANT BEHAVIORS. The building's form regulates envelope heat loss and gain, the amount of sun collected through windows or blocked by shading and so on.

The table shows the basic climate categories used to classify strategies in *SWL*. Individual design strategies are all too broad to be associated with a single climate zone. Many are too broad to be limited even to one of the 3 basic climate types. Instead, many strategies address a range of conditions from mild to extreme. For example, the tools in SOLAR APERTURES relate sun-facing solar glazing to annual solar savings fraction (SSF) for a range of climates from hot-humid climates like Zone 1A, Miami, Florida—which still has a short heating season—to very cold climates like Zone 7B Edmonton, Alberta.

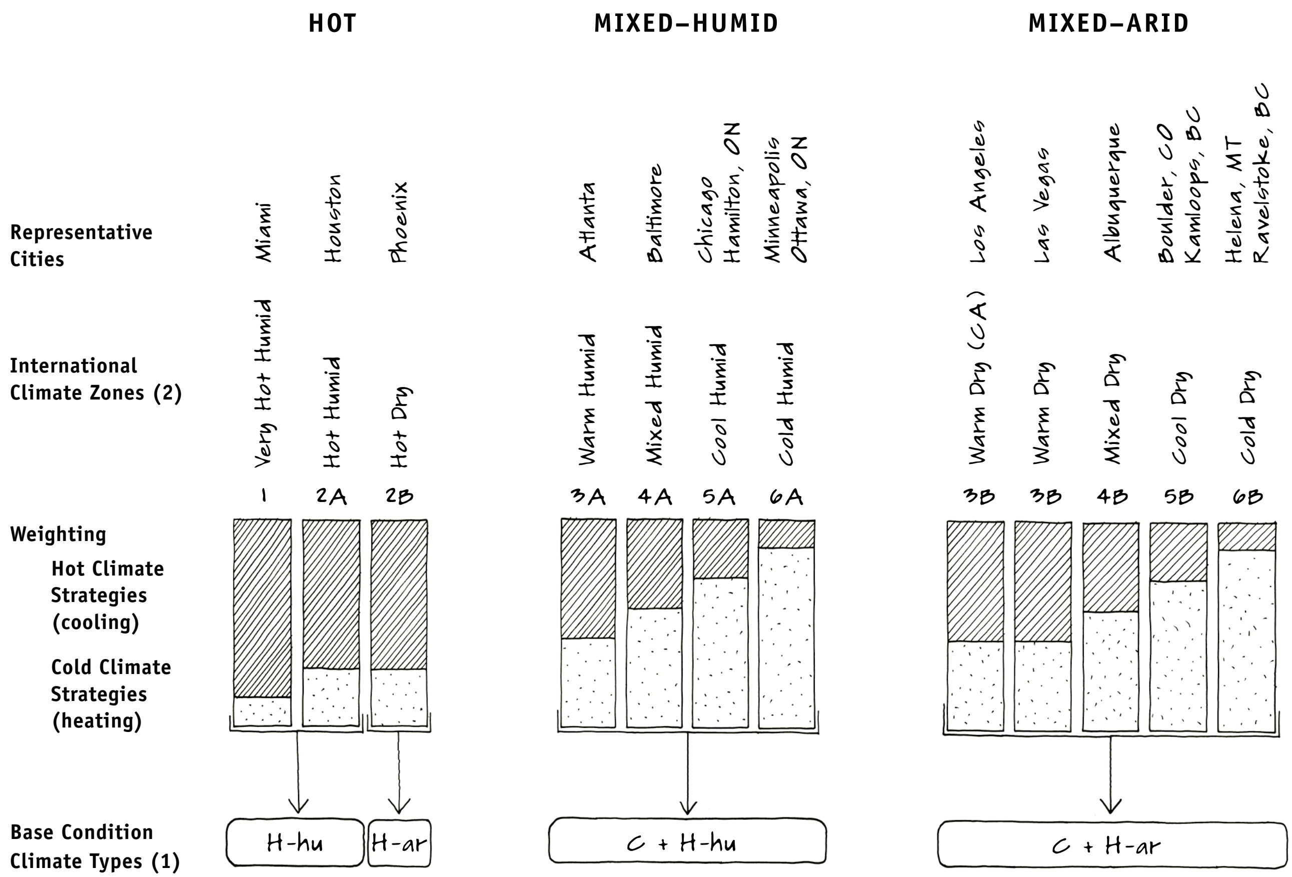
The climate zone numbers in the maps and diagrams are from the **International Climate Zones** *definitions*, and representative cities are for the climate zones in the United States. Cities in Zones 1–7 and 8 are those that have been selected by the U.S. Department of Energy based on where the most people live in that zone; therefore, they are not always the cities with statistically typical climate conditions within the zone itself. Zone 7.5 has been added to *SWL* as a subdivision of Zone 7. This follows zones proposed by Canada. Zones 9 and 10 are subdivisions of Zone 8 because the heating degree day variation in Zone 8 as defined by ASHRAE is actually equivalent to several other zones combined. Zones 7.5, 9 and 10 are exclusive to *SWL*.

To select strategies and bundles appropriate to a building's climate:

1) ***Find the climate zone for your building site*** using the **Maps of International Climate Zones** (United States, Alaska or Canada).
2) ***Select the base climate condition*** from **Climate Zones and Their Priorities for Heating and Cooling Strategies** (next spread).
3) ***Modify your base climate zone using the table of* Bundle Variations by Climate and Internal Gains,** (two spreads back), if required, depending on whether you are designing an ILD building, an SLD building or an outdoor room.
4) ***Select a new equivalent climate zone,*** if you are designing an ILD building or an outdoor room. From your base climate zone condition, if required, move in the Hot direction (left) or the Cold direction (right). From the diagram, **Climate Zones and Their Priorities for Heating and Cooling Strategies,** (next spread) read the recommended weighting of Hot (cooling) vs. Cold (heating) strategies.
5) ***Select appropriate Synergies, Design Strategies and Analysis Techniques.*** Using these weightings as priorities, refer to **Strategies by Climate and Energy Intentions** (two spreads forward).

Of course, not every strategy on the list must be used and an energy intention may still be achieved by employing various combinations.

6) ***Use the weightings to create custom bundles*** from a mix of strategies drawn from hot and cold variations. See the section, "Making Your Own Bundles" in Part IV, "Bundles." Some strategy bundles are differentiated by climate. When selecting among them, use the same steps above to determine your equivalent climate zone.



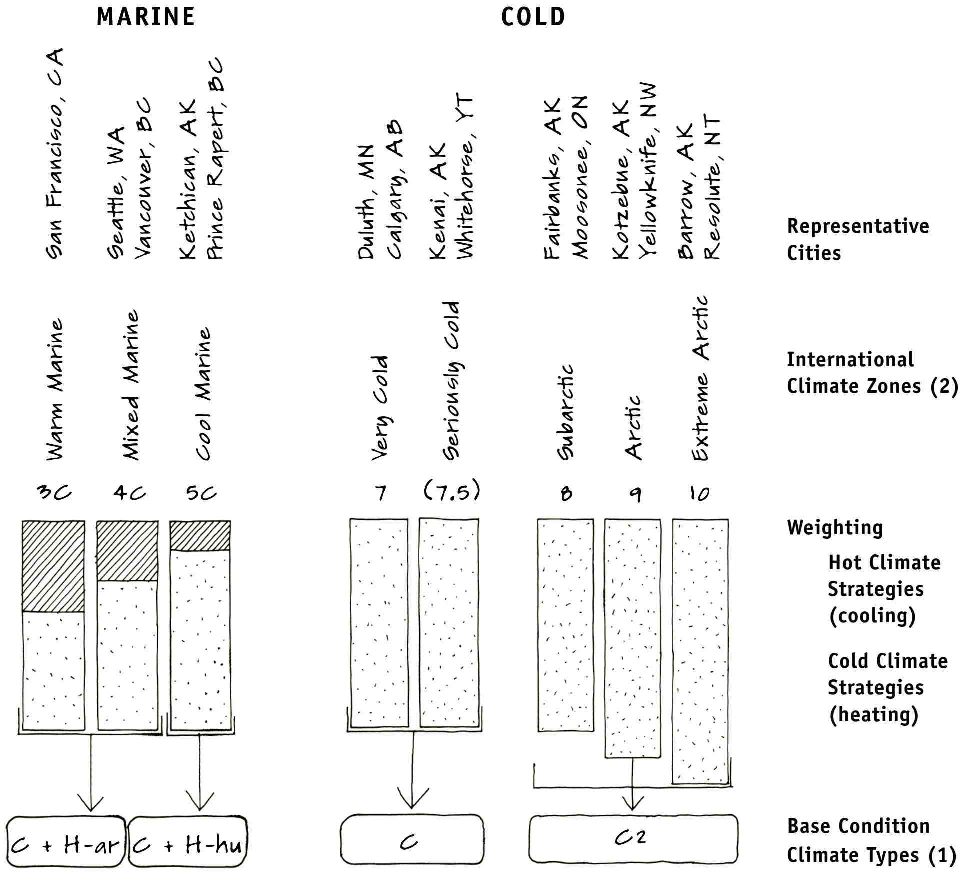
Climate Zones and Their Priorities for Heating and Cooling Strategies

(1) For SLD / Thin Plan Buildings, Outdoor Rooms (no internal gains), or ILD / Thick Buildings priorities will shift. See "Bundle Variations by Climate and Internal Gains."

(2) See International Climate Zone Maps for United States, Alaska, and Canada.

The table of **Strategies by Climate Type and Energy Intentions** on the following pages divides strategies into groups based on their potential applicability to All Climates, or to the climate conditions of Cold, All Hot, Hot–Humid, or Hot–Arid. Each climate type has a set of energy intentions relative to Sun, Wind, Daylight, Temperature, Moisture, or combinations of these (Multiple Forces). Daylighting strategies apply to all climates. Within each of these climate force categories the table shows a series of energy intentions designated as S1, S2, S3, etc. for Sun; M1, M2, M3, etc. for Moisture, and so on. Beneath each **bold intention statement** are strategies that can be used to address its issue.

Some strategies help to achieve more than one energy intention, so the user will find these repeated. Like all of the *SWL* navigation aids, the advice is general and different strategies or combination of strategies can often achieve the same end.



Climate Zones and Their Priorities for Heating and Cooling Strategies

Strategies by Climate Type and Energy Intentions

ALL CLIMATES

SYNERGIES

S1 Climate Resources
S2 Occupant Behaviors
S3 Resource-Rich Environment
S4 Spatial Zoning
S5 Thermal Sailing
S6 Multivalent Design
S7 Tailored Active Systems

BUNDLES

B1 Neighborhood of Light
B4 Integrated Urban Patterns
B5 Daylight Building
B7 Outdoor Microclimates
B9 Responsive Envelope

HIGH-PERFORMANCE METRICS

p1 Performance targets.
A30 Energy Targets
A33 Emissions Targets
A11 Design Layout Factor
84 Solar Apertures
p2 Assess energy performance
A27 Total Heat Gains & Losses
A31 Annual Energy Use
A32 Energy Use Intensity
A34 Net-Zero Energy Balance
p3 Assess emissions perform.
A35 Carbon-Neutral Building

WIND

w1 Control infiltration.
A4 Wind Rose
A23 Ventilation/Infiltration Gain and Loss
21 Windbreaks
76 Earth Edges
70 Well-Placed Windows
w2 Admit controlled fresh air ventilation.
A23 Ventilation/Infiltration Gain and Loss
67 Separated or Combined Openings
80 Breathing Walls
87 Air Flow Windows
98 Earth–Air Heat Exchangers
99 Air–Air Heat Exchangers

SUN

s1 Collect sun for service hot water.
A20 Hot Water Loads
79 Solar Hot Water
s2 Collect sun for producing electricity.
A19 Electric Loads
78 Photolotaic Walls/Roofs

MOISTURE

m1 Allow vapor to dry inward/outward.
m2 Remove excess moisture by ventilation.
A12 Temperature and humidity [*SWL4*]
A24 Bioclimatic Chart
44 Cross-Ventilation Rooms
53 Stack-Ventilation Rooms
69 Ventilation Openings Arrangement
86 Ventilation Apertures
96 Mechanical Space Ventilation

MULTIPLE FORCES

f1 Preserve access to on-site resources.
A7 Site Microclimates
5 Climatic Envelopes
f1 Provide a range of thermal conditions.
A14 Energy Programming
24 Migration
25 Periodic Transformations
26 Cooling Zones
27 Mixed Mode Cooling
28 Heating Zones
40 Stratification Zones
f3 Passive design; use efficient equipment.
71 Symphatic HVAC [*SWL4*]
100 Heat Pumps [*SWL4*]
101 Manual or Automated Controls
26 Cooling Zones
27 Mixed Mode Cooling
28 Heating Zones

DAYLIGHT

d1 Preserve daylight access on the site.
A9 Daylight Availability
A10 Daylight Obstructions
4 Daylight Density
13 Daylight Blocks
14 Daylight Envelopes
d2 Capture daylight architecturally.
A8 Sky Cover
A11 Design Daylight Factor
6 Glazed Streets
31 Borrowed Daylight
33 Atrium Building
35 Thin Plan
38 Skylight Building
47 Toplight Room
55 Daylight Room Geometry
66 Daylight Roof
67 Separated or Combined Openings
68 Window Placement
85 Daylight Apertures
d3 Reflect daylight deep into interiors.
57 Sidelight Room Depth
65 Open Roof Structure
66 Daylight Roof
83 Skylight Wells
88 Light Shelves
103 Daylight Reflecting Surfaces
d4 Admit reflected or diffuse light to reduce heat gains.
A1 Sundial
A2 Sun Path Diagram
A26 Shading Calendar
64 Reflected Sunlight
88 Light Shelves
90 Daylight Enhancing Shades
106 Window and Glass Types
d5 Provide a range of lighting conditions.
A14 Energy Programming
25 Periodic Transformations
31 Borrowed Daylight
41 Daylight Zones
95 Task Lighting
101 Manual or Automated Controls
d6 Control glare.
56 Glare-Free Rooms [*SWL4*]
64 Reflected Sunlight
82 Low Contrast
88 Light Sleeves
106 Window and Glass Types
d7 Integrate daylight and electric light.
41 Daylight Zones
73 Electric Light Zones
93 Task Lighting
101 Manual or Automated Controls

COLD CLIMATES

BUNDLES

B3 Passive Solar Neighborhood
B7 Outdoor Microclimates
B8 Passive Solar Building

SUN

s3 Preserve site solar access.
A7 Site Microclimates
12 Neighborhood Sunshine
15 Solar Envelopes
18 East–West Elongated Building Groups

s4 Admit sun when there's a heating load at night.
A3 Solar Radiation
A29 Balance Point Profile
36 East–West Plan
37 Deep Sun
43 Rooms Facing Sun/Wind
48 Direct Gain Rooms
49 Sunspaces
50 Thermal Storage Wall
51 Thermal Collector Walls and Roofs
52 Roof Ponds
67 Separated or Combined Openings
82 Solar Reflectors
84 Solar Apertures
106 Window and Glass Types

s5 After passive design, collect sun for active heating.
51 Thermal Collector Walls and Roofs

MULTIPLE FORCES

f4 Create a warmer outdoor microclimate.
A7 Site Microclimates
3 Topographic Microclimates
7 Loose/Dense Urban Patterns
8 Gradual Height Transitions
11 Winter Courts
18 Tall Building Currents
21 Wind Breaks
24 Migration
32 Locating Outdoor Rooms
58 Breezy/Calm Courtyards

WIND

w2 Admit controlled fresh air ventilation.
89 Breathing Walls

w3 Block cold wind.
A4 Wind Rose
A5 Wind Square
A6 Air Movement
3 Topographic Microclimates
7 Loose/Dense Urban Patterns
11 Winter Courts
21 Windbreaks
34 Clustered Rooms
76 Earth Edges
70 Well-Placed Windows

w4 Decrease interior air velocity.
75 Thermal Mass
77 Radiant Surfaces [*SWL4*]

TEMPERATURE

t1 Decrease allowable interior temperature.
A13 Adaptive Comfort Criteria
A14 Energy Programming
A16 Occupancy Heat Gains
A24 Bioclimatic Chart
24 Migration
29 Buffer Zones
40 Stratification Zones

t2 Shift schedules to avoid peak cold.
A15 Load Responsive Scheduling

t3 Increase/concentrate internal heat generation.
A18 Equipment Heat Gain
A16 Occupancy Heat Gain
A17 Electric Light Heat Gain
28 Heating Zones

t4 Block heat loss through the envelope.
A21 Skin Heat Flow
A25 Earth Contact
A27 Total Heat Gains/Losses
21 Windbreaks
29 Buffer Zones
34 Clustered Rooms
70 Well-Placed Windows
74 Skin Thickness
76 Earth Edges
89 Movable Insulation
104 Exterior Service Color
106 Window and Glass Types

t5 Store daytime heat for use at night.
50 Thermal Storage Wall
52 Roof Ponds
60 Mass Arrangement
62 Insulation Outside
75 Thermal Mass
77 Radiant Surfaces [*SWL4*]
94 Rock Beds
102 Mass Surface Absorptance

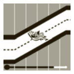
t6 Move heat to storage or where needed.
39 Moving Heat to Cold Rooms
42 Convective Loops
72 Mechanical Heat Distribution
97 Ducts and Plenums
95 Mechanical Mass Ventilation

Strategies by Climate Type and Energy Intentions

ALL HOT CLIMATES

BUNDLES

B2 Cooling Neighborhood
B6 Passively Cooled Building
B7 Outdoor Microclimates



TEMPERATURE

t7 Increase allowable interior temperature.
A24 Bioclimatic Chart
A13 Adaptive Comfort Criteria
A14 Energy Programming
A16 Occupancy Heat Gains
24 Migration
29 Buffer Zones
40 Stratification Zones
96 Mechanical Space Ventilation

t8 Shift schedules to avoid peak heat.
See daylight strategies (All Climates)
A14 Energy Programming
A15 Load-Responsive Scheduling

t9 Decrease/isolate/disperse internal heat genneration
A18 Equipment Heat Gains
A16 Occupancy Heat Gains
A17 Electic Lighting Heat Gain
26 Cooling Zones

t10 Block heat gain and allow heat loss through envelope when indoors is hotter than outdoors.
A21 Skin Heat Flow
A25 Earth Contact
29 Buffer Zones
74 Skin Thickness
76 Earth Edges
89 Movable Insulation
104 Exterior Surface Color
106 Window and Glass Types

t11 Store heat when it's too hot to ventilate.
A24 Bioclimatic Chart
A25 Earth Contact
A27 Total Heat Gains and Losses
52 Roof Ponds
54 Night-Cooled Mass
60 Mass Arrangement
62 Insulation Outside
75 Thermal Mass
77 Radiant Surfaces [*SWL4*]
76 Earth Edges
94 Rock Beds
95 Mechanical Mass Ventilation

t12 Move coolth to storage or to where it is needed.
72 Mechanical Heat Distribution
97 Ducts and Plenums
95 Mechanical Mass Ventilation

WIND

w5 Preserve wind access on the site.
A4 Wind Rose
5 Wind Square
A6 Air Movement Principles
1 Converging Ventilation Corridors
3 Topographic Microclimates
7 Loose/Dense Urban Patterns
17 Breeezy Streets
19 Dispersed Buildings

w6 Admit outside air when it's not too hot for cooling.
A4 Wind Rose
A24 Bioclimatic Chart
A27 Total Heat Gains and Losses
26 Cooling Zones
27 Mixed Mode Cooling
30 Permeable Buildings
43 Rooms Facing Sun and Wind
44 Cross-ventilation Rooms
45 Wind Catchers
53 Stack Ventilation Rooms
58 Breezy Courtyards
67 Separated or Combined Openings
69 Ventilation Openings Arrangement
86 Ventilation Apertures
96 Mechanical Space Ventilation

w7 Block wind when it's too hot for cooling.
21 Windbreaks
58 Breezy/Calm Courtyards

w8 Increase interior air velocity.
69 Ventilation Openings Arrangement
86 Ventilation Apertures
96 Mechanical Space Ventilation

MULTIPLE FORCES

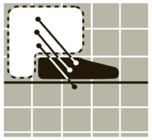
f5 Create a cooler outdoor microclimate.
A7 Site Microclimates
A24 Bioclimatic Chart
9 Interwoven Buildings and Planting
10 Interwoven Buildings and Water
16 Shadow Umbrella
22 Green Edges
23 Overhead Shades
24 Migration
32 Locating Outdoor Rooms
58 Breezy/Calm Courtyards
59 Shady Courtyards

SUN

s6 Block sun when outside temp. is above the balance point.
A1 Sundial
A2 Sun Path Diagram
A22 Window Solar Heat Gain
A26 Shading Calendar
A29 Balance Point Profile
2 Shared Shade
29 Buffer Zones
63 Layer of Shades
59 Shady Courtyards
90 Daylight Enhancing Shades
91 External Shades
92 Internal and In-Between Shades
106 Window and Glass Types
105 Double Skin Materials

s7 Use sun to enhance stack-ventilation.
53 Stack-Ventilation Rooms

HOT–ARID CLIMATES



MOISTURE

m3 Add moisture to indoor air (humidify).
46 Evaporative Cooling Towers
71 Sympathetic HVAC [*SWL4*]

m4 Add moisture to ventilation air.
99 Air–Air Heat Exchangers
98 Earth–Air Heat Exchangers

m5 Use evaporative cooling when it's too hot for other cooling strategies.
10 Interwoven Buildings and Water
46 Evaporative Cooling Towers
34 Clustered Rooms
61 Water Edges

HOT–HUMID CLIMATES

MOISTURE

m6 Remove moisture from indoor air.
71 Sympathetic HVAC [*SWL4*]

m7 Remove moisture from ventilation air.
99 Air–Air Heat Exchangers

m8 Avoid creating additional humidity.
Avoid these strategies:
10 Interwoven Buildings and Water
46 Evaporative Cooling Towers
61 Water Edges

Part II

USING *SUN, WIND & LIGHT*

Designers seeking to produce net-zero and peak-zero, net-positive energy buildings require an understanding of what causes buildings to use energy as well as how to harness the energy design process by integrating multiple design strategies.

The first section of Part II, “Using *Sun, Wind & Light*,” illustrates and explains the basic components and relationships of an integrated design process for “**Buildings and Energy Use**.”

The second section introduces the **Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings.** This chart guides designers through a decision-making process that leads to seven generalized Synergies, which are in turn supported by a range of design Strategies and Bundles of strategies that can help buildings achieve maximum performance. An overview of the chart's structure is given first, followed by the chart itself, then an example and finally, suggestions for remembering seven synergies that answer each question set in the chart.

Buildings and Energy Use

Building loads and energy use

Modern buildings use energy to power equipment and provide occupants with comfortable conditions. Over half of the energy consumed by buildings is used to meet heating, cooling, ventilation and lighting loads (U.S. DOE, 2012). The diagram **Influence of Climate, Use and Design** (next spread) shows the primary determinants of these loads.

Climate is the set of external factors (temperature, relative humidity, radiation, wind patterns, etc.) that affect building loads.

Use comprises the operational characteristics associated with a building's program and occupants. How a building is used is critical to the magnitude and timing of the loads, since loads tend to follow people.

Design includes all aspects of a building's form, organization, parts and materials over which a designer has control.

Load reduction strategies

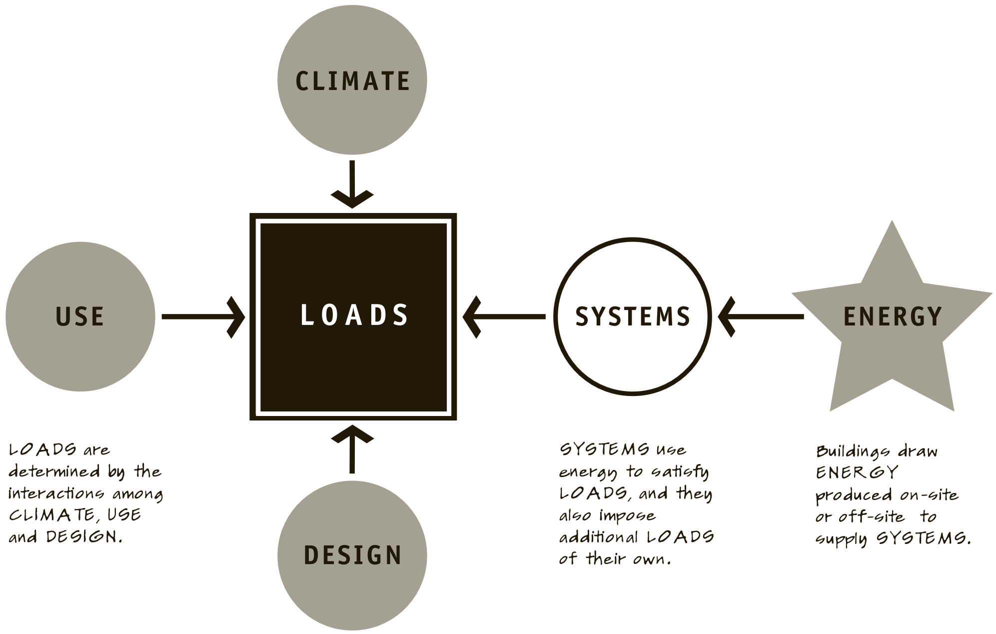
In the effort to save energy, the first conventional response is often to improve the efficiency of the mechanical and electric lighting systems (e.g., changing from T-12, a historically common fluorescent lamp, to more efficient T-8 lamps). However, if the loads are reduced with passive strategies *before* the systems efficiency is improved, greater reductions in energy use can be achieved, along with a reduction in the size and initial cost of the systems. This is shown in the diagram **Load Reductions Minimize Energy Produced** (next spread).

Interactions among Climate, Use and Design provide key opportunities for load reduction strategies. For example, NIGHT-COOLED MASS is a passive Design strategy used to reduce or eliminate cooling loads. It works most effectively in climates where nighttime temperatures drop below the upper limit of the occupant comfort zone and when the internal gains created by the Climate and Use of the building are small enough to be absorbed by the thermal mass.

Reducing loads to a minimum makes it possible to use on-site energy production strategies to meet the remaining demands of any necessary mechanical, lighting or electrical systems, resulting in a *net-zero* or *peak-zero, net-positive* building.

Net-zero and net-positive EUI buildings

Energy use intensity (EUI) is a common metric used to quantify and compare the operational energy consumed

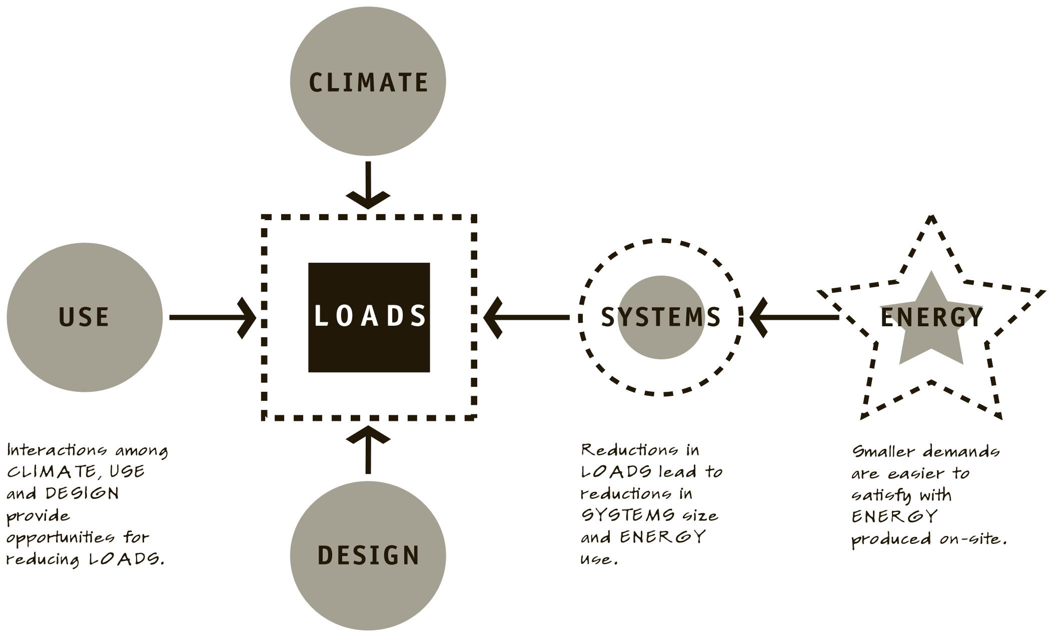


Influence of Climate, Use and Design

by buildings. The EUI measures the amount of energy required by a building on a per unit area basis and is calculated by dividing the total annual energy use by the total floor area of the building. The EUI can be weighed against a building's *energy production intensity* (EPI), an estimate of the energy that is generated within the site's boundaries based on available climate resources for photovoltaic panels, wind turbines or other renewable power generation methods employed in the design. Regardless of the power generation method used or fuel type consumed, all production units are converted to annual kBtu/ft^2 (or annual kWh/m^2) so that equivalent comparisons can be made between buildings and across different fuel types. Using these two metrics, we can view the energy demand versus energy production as a spectrum where an *energy balance index* (EBI) is equal to EPI minus EUI:

Energy Balance Index =
Energy Production Intensity – Energy Use Intensity

Conventional buildings have a negative EBI value, since they draw power from off-site in order to satisfy thermal, lighting and plug loads. A zero value for EBI means that demand equals supply, indicating a building that is net zero. A *net-zero energy building* is defined as one that produces as much energy as it consumes during a given time period (Torcellini et al., 2006), usually calculated on an annual basis. In *SWL*, "net zero" always refers to a *site* net-zero building [see definitions in NET-ZERO ENERGY BALANCE]. An even more efficient building would produce at least as much energy as it consumes at *any* point in time (including at its peak load hour), resulting in *more* energy generation than consumption at all other off-peak times; it would have a positive value on the EBI scale. This

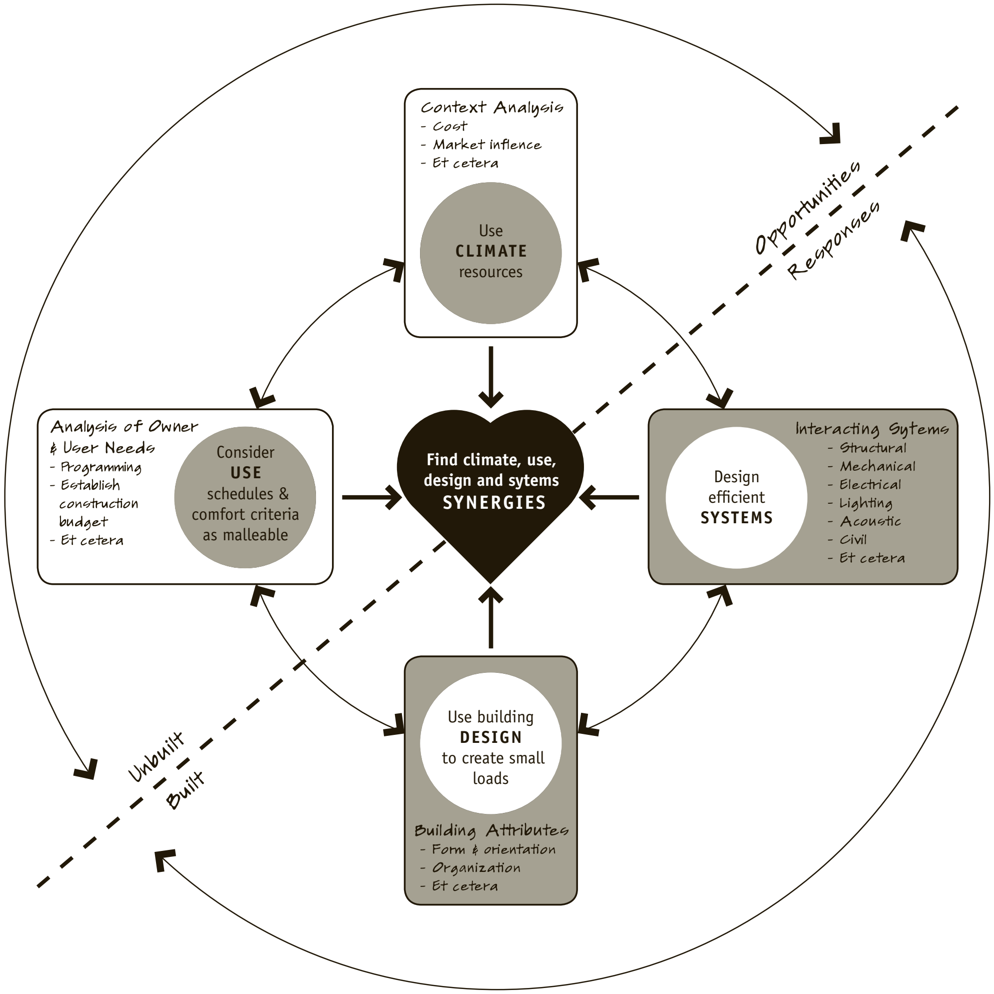


Load Reductions Minimize Energy Produced

would be referred to as a *peak-zero, net-positive* building. Other buildings might have an annual positive EBI and therefore be considered *net-positive,* yet still import energy to handle their peaks.

Integrated design

Integrated design is both a theoretical approach to creating more sustainable buildings and a practical method for the actual work of designing and constructing buildings: "In the creation of the built environment, integrated design is the synthesis of climate, use loads and systems to achieve a more comfortable and productive environment for the occupants, and a building that is more energy-efficient than current best practices" (Brown and Cole, 2006). At its heart, integrated design is an iterative search for synergies between two or more aspects of a project that can create benefits greater than the sum of those resulting from individual design decisions. Integrated design occurs in the context of the many considerations that are part of any design project—including structural systems, project budget, security and code requirements—and provides a lens through which to view these factors. Collaboration among project stakeholders throughout the design and construction process increases the likelihood that synergies will be found and implemented in the project.



Integrated Design Process

The **Integrated Design Process** diagram reorganizes the components of preceding diagrams to show the iterative nature of the design process and it defines the lens through which each component can be viewed. Climate, for example, could be considered either a positive or negative influence on the project. The integrated design lens urges designers to view Climate as a resource. Likewise, the Use of the building (e.g., schedules and comfort criteria) could be viewed either as a fixed requirement or, according to the integrated design lens, as a malleable element that can be influenced by the building design. The diagram also groups the components according to conceptual similarities. Climate and Use are paired together because they are the two aspects of the design process that define the problems and opportunities of the project. They also share the attribute of being "unbuilt," or lacking a physical form, in contrast to both Design and Systems, which constitute the designer's "built" responses

to the Climate and Use pair. The outermost arrows represent the iterative process of viewing opportunities and designing responses, while the inner circular arrows show the iterative search for synergies among two or more of the components.

Using synergies to achieve net-zero and peak-zero, net-positive performance

Since certain characteristics are common to most buildings—they exist within a climate, they are designed, they get used, they create an indoor environment and they have structure—a handful of cardinal concepts can be distilled that constitute synergies in the relationships among Climate, Use, Design and Systems. The seven Synergies presented in the next section can serve to guide the designer from the beginning of each project towards specific strategies that take advantage of these synergies, ultimately making it easier to achieve net-zero and peak-zero, net-positive buildings.

For example, a synergy that exists between Use and Climate is that energy-conscious occupant behaviors can reduce peak heating, cooling and lighting loads. A specific instance of this synergy is the high level of climate responsiveness exhibited by occupants of Pueblo Acoma, near Albuquerque, New Mexico, where MIGRATION within the building occurs according to outdoor conditions. In contrast, many conventional buildings are operated in ways that directly conflict with climate, such as offices in warm climates that have peak occupancy and solar and equipment loads during periods of high temperature.

Design Decision Chart

for Net-Zero and Peak-Zero, Net-Positive Buildings

The Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings helps designers make decisions early in the design process. It provides a method for linking a small number of memorable design concepts, or Synergies, with Bundles and individual Strategies.

Synergies, as described in the previous section, are fundamental concepts based on relationships among Climate, Use, Design and Systems. They are designated in the chart and in the table of contents by a capital letter *S* preceding each synergy number.

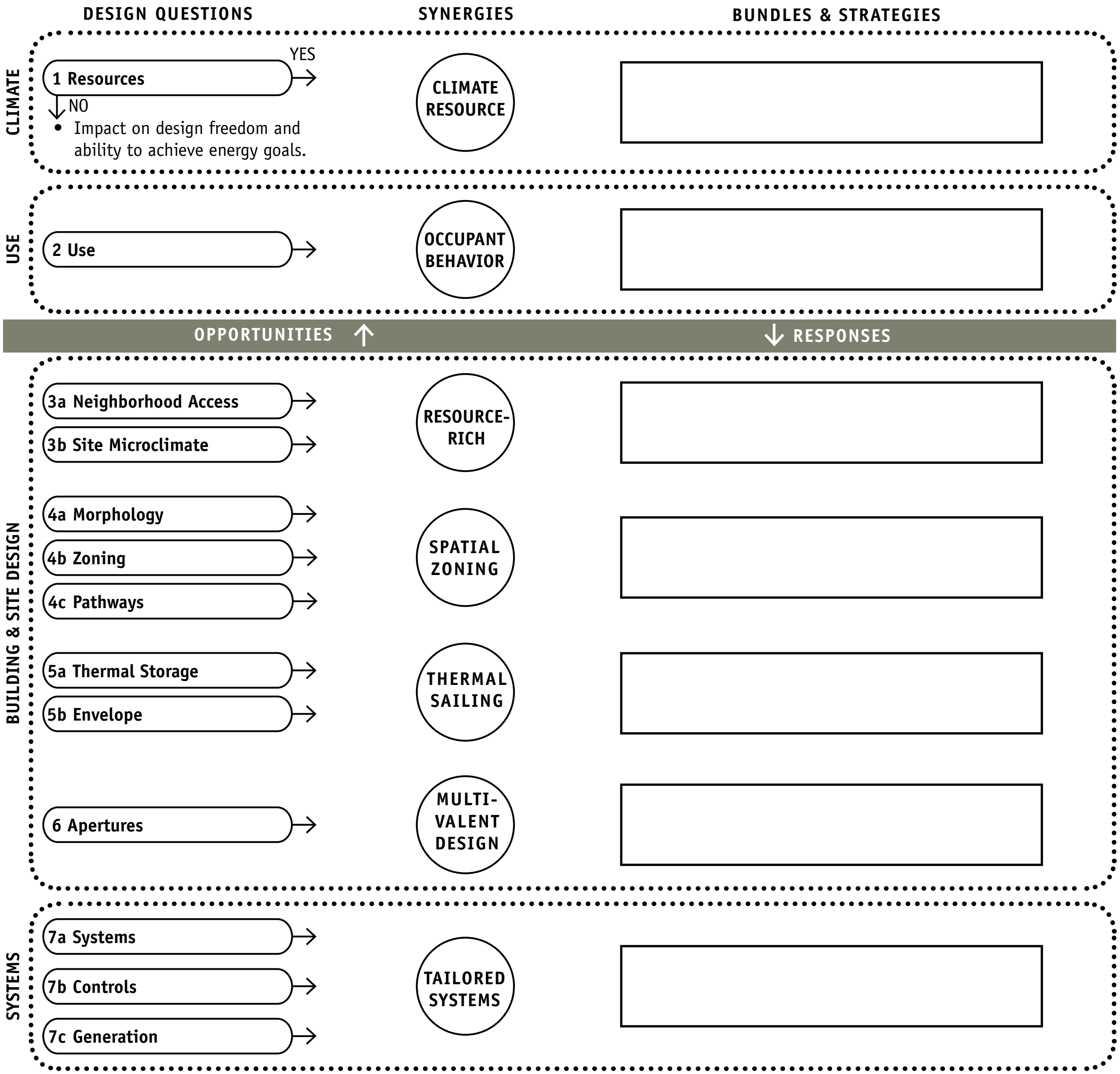
Bundles are sets of related strategies that work together to resolve commonly occurring design problems. They are defined and detailed further in Part IV, "Bundles," where "Some Fundamental Bundles" are offered. Bundles are designated in the chart and in the table of contents by a capital letter *B* preceding each bundle number.

Design Strategies are generalized solutions to recurring design problems that connect architectural form to performance in ways that allow for design flexibility. All of the Strategies can be found in ⚡*SWL Electronic,* and a few of the most commonly used Strategies are located in Part V, "Favorite Design Tools," and in Part VI, "Favorite Design Strategies." Strategies are designated in the chart and table of contents simply by a number and capital letter preceding it.

Analysis Techniques enable the designer to understand, before the building is designed, how the building is likely to use energy, what the climate is like and which architectural design strategies are appropriate. They are designated in the chart and in the table of contents by a capital letter *A* preceding each Analysis Technique number. All of the Analysis Techniques can be found in ⚡*SWL Electronic*.

High-Performance Buildings Techniques provide tools to set targets for energy use and building emissions and to evaluate net-zero energy and carbon-neutral building performance. They are designated in the chart and in the table of contents by a capital letter *P* preceding each High-Performance Building Technique number. All of these techniques can be found in Part VII, "High Performance Building," and are also supported by the *SWL Tools* spreadsheet found in ⚡*SWL Electronic*.

The **Design Decision Chart Overview Diagram** provides a summary of the structure and logic of the Design Decision Chart found on the following pages. The chart is horizontally divided into two main parts that correspond to the Opportunities and Responses, or Unbuilt and Built, pairs described previously in the "Integrated Design" section of "Buildings and Energy Use." In the Opportunities part of the decision chart, question sets 1 and 2 deal with



Design Decision Chart Overview Diagram

environmental and occupant variables, which fall into the Climate and Use categories, respectively, while question sets 3 through 7 pertain to Design and Systems, the built Responses.

A negative answer to any question leads to an explanation of the relative design importance of each answer both in terms of achieving net-zero or peak-zero, net-positive buildings and in terms of the constraints it may place on design freedom. Affirmative answers lead to the Synergy that applies to each question set and to the associated Bundles and Strategies on the right-hand side of the chart. Each Synergy diagram highlights its focus of with black shading, while the remaining parts of the icon appear white.

The questions can be addressed nonsequentially, and questions that are not applicable to a particular project can be skipped.

Conceptual breakdown of questions and synergies

Net-zero and peak-zero, net-positive buildings can be achieved at different scales and in multiple ways. The greater the number of possible solutions, the more freedom the designer has to make a high-performance building that also accomplishes other architectural goals. Some of the questions listed in the chart have greater potential impact on design freedom than others.

Question 1 **[Resources]** and the related CLIMATE AS A RESOURCE synergy are intended to help the designer think about the climate resources available on the site and their relationship to the potential building loads. In climates characterized by extreme heat, cold or lack of sunlight it becomes critical to trim building loads to a minimum. However, some aspects of even the most extreme climates can be viewed as opportunities; for example, in hot desert climates the plentiful sunlight can be converted to power and used for supplemental cooling. The Strategies listed on the right-hand side of the chart can help determine important climate variables and load profiles.

Question 2 **[Use]** points out occupancy patterns and behaviors as elements that can be influenced by design and that have a large impact on building energy use. The associated ENERGY-CONSCIOUS OCCUPANT BEHAVIORS synergy suggests ways to design buildings that encourage energy-saving occupant behaviors or that take advantage of physiological traits, such as adaptation to thermal or lighting levels, to reduce loads. The four related Strategies show specific examples of how to harness occupant behaviors to minimize energy use.

Question 3 **[Neighborhood Access and Site Microclimate],** which has two parts, addresses outdoor spaces and access to climate resources at the neighborhood or urban scale. Both parts of the question emphasize the importance of access to sun, wind and light over the possible utility of blocking access to the resources at this scale, so that in most climates and sites the choice of admitting or blocking resources is preserved at the scale of the building or its parts. Outdoor comfort; access to site resources of sun, wind and light; and power generation are the priorities of this question set and its synergy, RESOURCE-RICH ENVIRONMENTS. A number of neighborhood scale strategy bundles, NEIGHBORHOOD OF LIGHT, COOLING NEIGHBORHOOD, SOLAR NEIGHBORHOOD, INTEGRATED URBAN PATTERN, along with associated strategies are suggested to help users optimize the arrangement of building groups and landscape elements, primarily for purposes of insuring access to on-site energy resources for passive design and renewable energy production. The OUTDOOR MICROCLIMATES bundle and several design strategies help configure space to improve outdoor conditions and improve the climate around and between buildings.

Question 4 **[Morphology, Zoning and Pathways]**, which has three parts, focuses on design decisions dealing with the morphology of the building and its interior organization. This question and the SPATIAL ZONING synergy highlight the need to think about climate and use considerations together when seeking to optimize zoning and spatial relationships for energy use reductions and occupant comfort. The bundles at the whole building scale, DAYLIGHT BUILDING, PASSIVELY COOLED BUILDING and PASSIVE SOLAR BUILDING, along with strategies they help organize, identify building scale methods for ensuring access to resources for all spaces. *[continued on p. 86]*

RESOURCES?

1 Are site resources sufficient to meet heating, cooling, lighting, ventilation and power needs?

YES →

NO ↓

Net-zero or peak-zero, net-positive buildings cannot be achieved unless loads can be met with site resources. It may be possible to substitute one resource for another, or to stockpile resources from one time to another.

S1 VIEW CLIMATE AS A RESOURCE for load reduction and power generation.

OPPORTUNITIES

USE?

2 Can schedules, comfort criteria or occupant behavior be changed to avoid or reduce peak loads?

YES →

NO ↓

Design freedom, or the range of strategies available to reduce loads, is highly constrained and therefore achieving a net-zero or net-positive building becomes much more difficult. Breaking the building into parts based on the malleability of schedules or comfort criteria may allow some of the parts to be net-zero or peak-zero, net-positive.

S2 ENERGY-CONSCIOUS OCCUPANT BEHAVIORS reduce peak heating, cooling, ventilation and lighting loads.

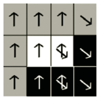
CLIMATE


A1 Sundial


A2 Sun Path Diagram


A3 Solar Radiation


A4 Wind Rose

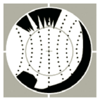

A5 Wind Square


A6 AirMovement Principles


A7 Site Microclimates


A8 Sky Cover


A9 Daylight Availability


A10 Daylight Obstructions

USE


A16 Occupancy Heat Gain


A17 Electric Light Gain


A18 Equipment Heat Gain


A19 Electric Loads


A20 Hot Water Loads


A21 Skin Heat Flow

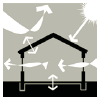

A22 Window Solar Gain


A23 Vent./Infilt. Gain/Loss


A24 Bioclimatic Chart

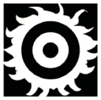

A25 Earth Contact

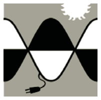

A26 Shading Calendar


A27 Total Heat Gains/Losses

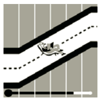

A28 Balance Point Temp.


A29 Balance Point Profiles

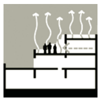

P1 Energy Targets


P3 Net-Zero Energy Balance


A11 Design Daylight Factor


A13 Adaptive Comfort


A15 Load-Response Schedules


24 Migration

NEIGHBORHOOD ACCESS?

3a If the project includes multiple buildings, can they be arranged to allow access to fresh air and sunlight throughout the site?

YES →

NO ↓

This decision will greatly affect the ability of the individual buildings to achieve net-zero or peak-zero, net-positive. One solution is to zone the site into areas that have different degrees of access to resources and then match buildings with fewer resource requirements to areas that have less access to resources and buildings with higher requirements to areas with greater access to resources.

RESPONSES

SITE MICROCLIMATE?

3b Can the site design enhance access to desirable resources while mitigating unwanted resources for part or all of the year?

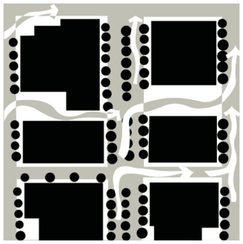
YES →

NO ↓

Design freedom will be constrained on sites that lack access to sun, wind and light; creating a net-zero or peak-zero, net-positive building becomes very difficult. If the site has limited access to necessary resources, one option is to seek a different site where resources better match the building's needs.

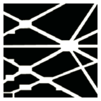
S3 Form and organize buildings and open spaces to create RESOURCE-RICH ENVIRONMENTS that provide livable outdoor space and access to site resources.


B1 Neighborhood of Light


B2 Cooling Neighborhood


B3 Solar Neighborhood


B4. Integrated Urban Pattern


1 Converging Vent Corridors


2 Shared Shade


3 Topographic Microclimates

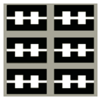

4 Daylight Density


5 Climatic Envelopes

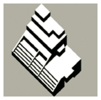

6 Glazed Streets

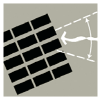

7 Loose/Dense Urban Patterns


8 Gradual Ht Transitions


13 Daylight Blocks


14 Daylight Envelopes


15 Solar Envelopes


17 Breezy or Calm Streets

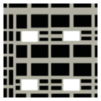

18 Tall Bldg. Currents


19 Dispersed Buildings

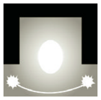

20 East/West Bldg Groups


58 Breezy/ Calm Courtyards


B6 Outdoor Microclimates


9 Interwoven Bldgs & Plants


10 Interwoven Bldgs & Water


11 Winter Courts

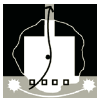

12 Neighborhood Sunshine


16 Shadow Umbrella


21 Wind-breaks

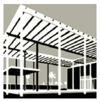

22 Green Edges


23 Overhead Shades


32 Locating Outdoor Rms


59 Shady Courtyards


61 Water Edges


63 Layer of Shades

MORPHOLOGY?

4a Can the building form and orientation allow access to sun, wind and light for most internal and external spaces?

YES →

NO ↓

Achieving net-zero or peak-zero, net-positive is moderately to highly difficult if buildings have an unfavorable form or orientation, especially in demanding climates or when internal loads are high. The design may be driven towards a "thermos" approach, in which the building is isolated from the climate.

ZONING?

4b Can spaces with similar heating, cooling, ventilation and lighting requirements be grouped together?

YES →

NO ↓

Design freedom is slightly to moderately constrained. It may still be possible to achieve net-zero or peak-zero, net-positive if similar spaces are grouped together and the remainder are served by mechanical systems suited to their individual needs.

PATHWAYS?

4c Can the design accommodate unobstructed pathways, allowing sun, wind and light to be distributed throughout the entire building?

YES →

NO ↓

Achieving net-zero or peak-zero, net-positive becomes very difficult, and whole building solutions are nearly impossible. A "NO" answer here pushes the design towards a mechanical distribution method, which in turn increases the importance of sizing the mechanical systems accurately.

54 Integrating climate and use variables yields opportunities for SPATIAL ZONING according to "best-fit" passive design strategies.

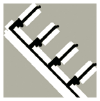
RESPONSES


B5 Daylight Building


B7 Passively Cooled Building


B8 Passive Solar Building


33 Passive Solar Building


35 Thin Plan


36 East-West Plan

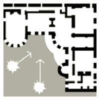

38 Skylight Building


43 Rooms Facing Sun & Wind


45 Wind Catchers

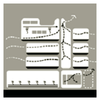

46 Evaporative Cooling Towers

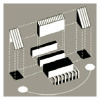

64 Reflected Sunlight


70 Well-Placed Windows

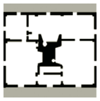

81 Solar Reflectors


A14 Energy Programming


26 Cooling Zones


28 Heating Zones


29 Buffer Zones


34 Clustered Rooms


40 Stratifcation Zones

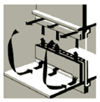

41 Daylight Zones


30 Permeable Buildings

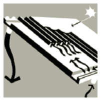

31 Borrowed Daylight


37 Deep Sun

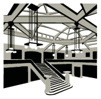

39 Moving Heat to Cold Rms

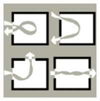

42 Convective Loops


44 Cross-Ventilation Rms


51 Thermal Collectors


57 Sidelight Room Depth


65 Open Roof Structure


69 Vent Opening Arrangement


83 Skylight Wells

BUILDING & SITE DESIGN

RESPONSES

THERMAL STORAGE?

5a Can the design include thermal mass, and do daily temperature swings and radiation levels promote storage strategies?

YES →

NO ↓

Depending on climate and internal loads, design freedom becomes moderately to severely constrained. When resource availability and resource need do not coincide (for example, a need for solar gain at night) and the resource cannot be stored, a non-passive source must be used. The design will likely be driven towards a highly insulated envelope with minimal glazing and an efficient mechanical system.

ENVELOPE?

5b Can the envelope be designed to resist or allow convective, conductive and radiative heat transfer when desirable?

YES →

NO ↓

The likelihood of achieving net-zero or peak-zero, net-positive will be highly dependent on climate and use factors. In climates with large diurnal and seasonal variation or high internal loads, a net-zero or peak-zero, net-positive building will be extremely difficult to achieve.

S5 A building designed for THERMAL SAILING uses thermal storage and a responsive envelope to regulate comfort and energy use by exploiting changing patterns of sun, wind & light.

APERTURES?

6 Can apertures be designed to admit resources without adverse effects such as overheating or glare?

YES →

NO ↓

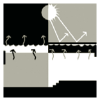
Design freedom will be constrained by the necessity to either block the desired resource (e.g., allow fewer and smaller apertures, if any) or mitigate the associated problems through strategies that do not involve the aperture design (e.g., provide more cooling if solar gain cannot be excluded in the window design).

S6 MULTIVALENT DESIGN combines two or more functions within a single building element.


48 Direct Gain Rooms


49 Sunspaces


50 Thermal Storage Walls


52 Roof Ponds


54 Night-Cooled Mass


60 Mass Arangement

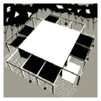

75 Thermal Mass


76 Earth Edges


94 Rock Beds


102 Mass Surf Absorptance


B9 Responsive Envelope


25 Periodic Transformations


62 Insulation Outside


74 Skin Thickness


80 Breathing Walls


87 Air Flow Windows


89 Movable Insulation


91 External Shading


103 Daylight Reflect Surf


104 Exterior Surface Color


105 Double Skin Materials

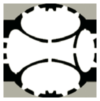

47 Toplight Room


53 Stack-Ventilation Rms


55 Daylight Rm. Geometry


67 Sep./Comb. Openings


68 Window Placement


82 Low Contrast


84 Solar Apertures


85 Daylight Apertures


86 Ventilation Apertures


88 Light Shelves


90 Daylight Enhance Shade


92 Internal/In-btw Shade


106 Window & Glass Types

BUILDING & SITE DESIGN

SYSTEMS?

7a If needed, are mechanical and/or electrical systems selected and sized appropriately to supplement passive strategies?

YES →

NO ↓

A net-zero or peak-zero, net-positive building is more difficult to achieve if mechanical systems are not tailored to the building load characteristics. If performance uncertainty has resulted in too large a safety margin and systems that are too extensive or large, consider making the building or parts of it HVAC-ready.

CONTROLS?

7b Can manual controls be used reliably given the program and climate context?

YES →

NO ↓

Automatic controls are expensive and decrease people's understanding of building operation. Consider training the occupants in the proper use of manual controls, or add building operation as a job requirement.

GENERATION?

7c Are power generation systems sized appropriately to provide power when needed?

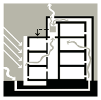
YES →

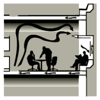
NO ↓

Without adequate on-site power production, net-zero or peak-zero, net-positive cannot be achieved. It may still be possible to design a very energy-efficient building, and environmentally benign off-site power can be purchased.

S7 When all available load reduction strategies and their controls have been exploited, meet the remaining load with an ACTIVE TAILORED SYSTEM that fits the load characteristics.

RESPONSES


72 Mech Heat Distribution


95 Mech Mass Ventilation


96 Mech Space Ventilation

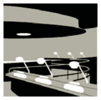

97 Ducts & Plenums


98 Earth-Air Heat Exchanger


99 Air-Air Heat Exchanger


27 Mixed Mode Cooling

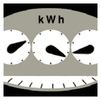

73 Electric Light Zones


93 Task Lighting

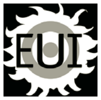
101 Manual/ Auto. Controls


78 PV Roofs & Walls


79 Solar Hot Water



P2 Annual Energy Use

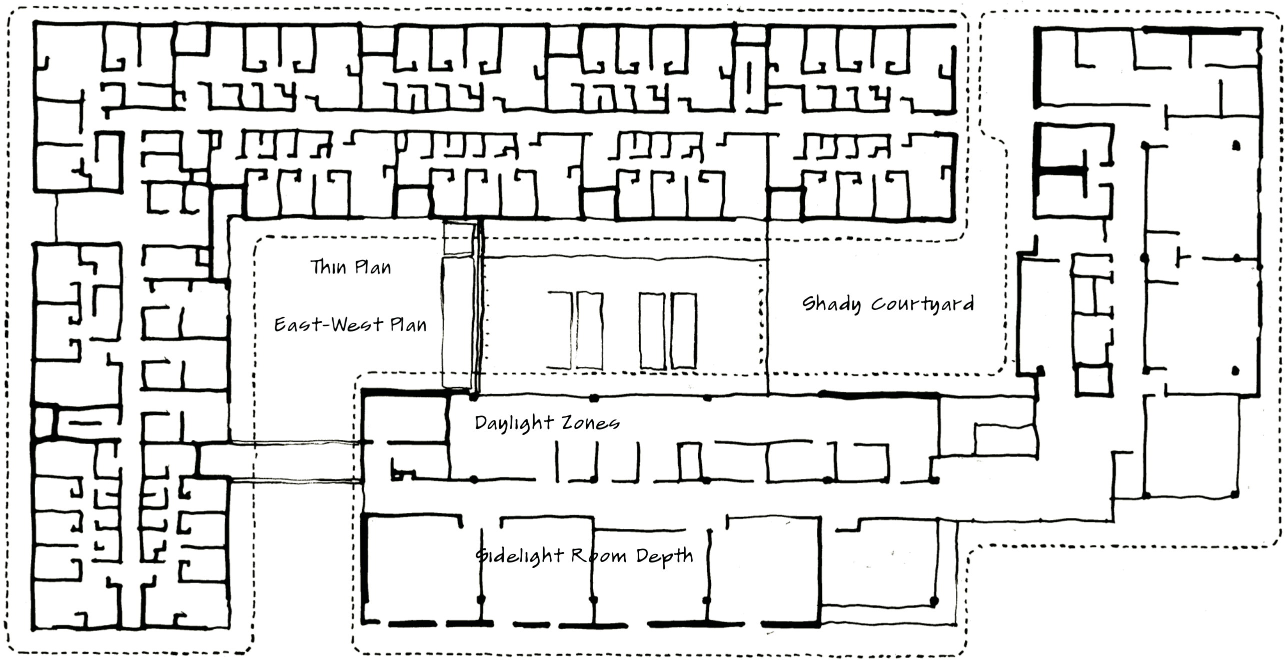


93 Task Lighting


P5 Emissions Targets

P6 Carbon-Neutral Building

SYSTEMS

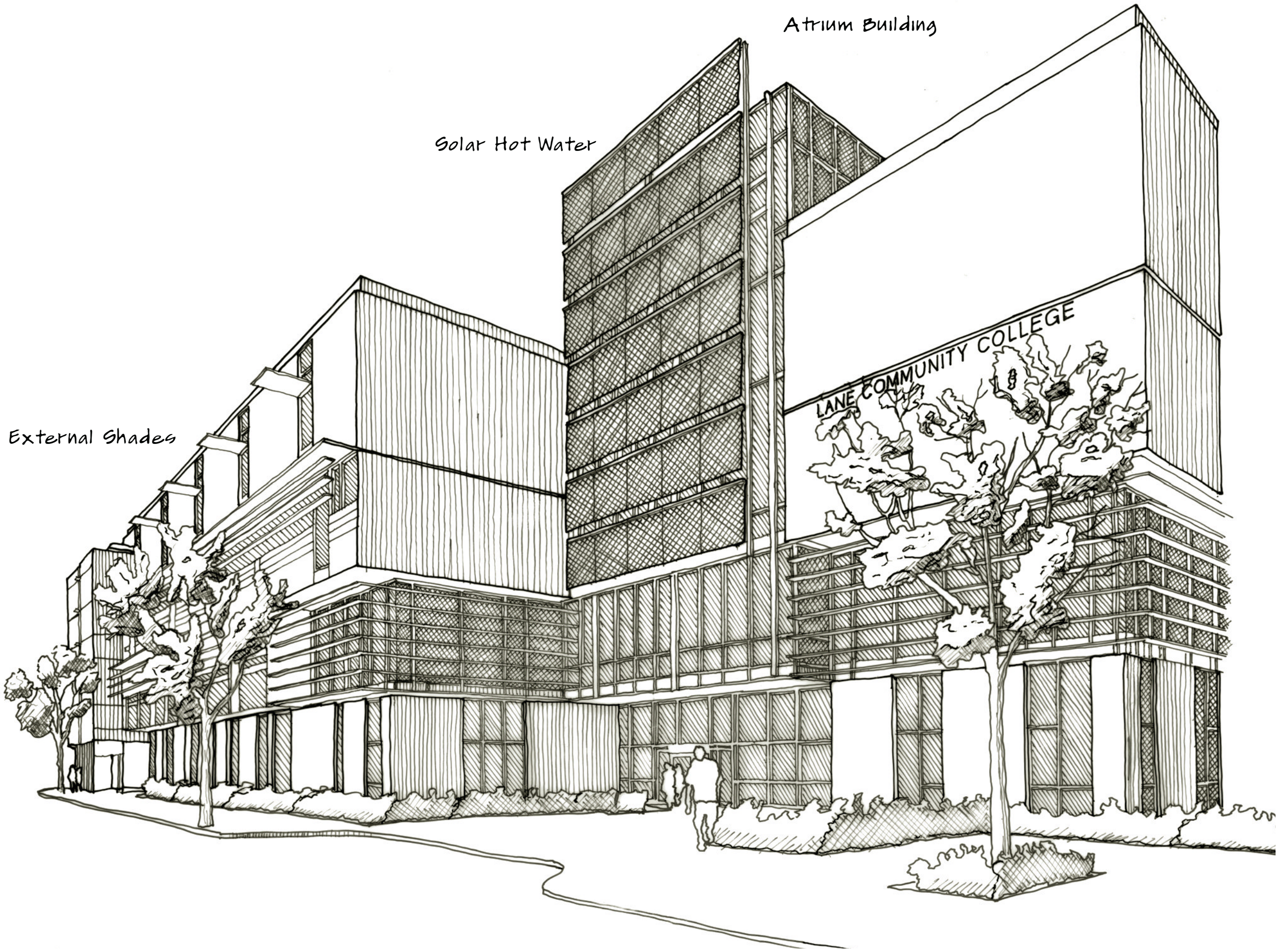


Lane Community College Downtown Campus, Eugene, Oregon, 2012
Robertson Sherwood and SRG Partnership, architects

Question 5 **[Thermal Storage and Envelope],** which has two parts, addresses the integration of thermal storage and responsive envelopes in buildings to create a system that interacts positively with temporal variations in sun, wind and light resources. The associated THERMAL SAILING synergy suggests a dynamic building that incorporates the bundle RESPONSIVE ENVELOPE, which has three climatic variations, as well as design Strategies that support designing for thermal mass.

Question 6 **[Apertures]** and its associated MULTIVALENT DESIGN synergy concentrate on some of the complex considerations involved in designing apertures and other multi-use elements. Sizing methods and other pertinent information are given by the design Strategies on the right side of the chart.

Question 7 **[Systems, Controls and Generation]**, which has three parts, constitutes the stage of design decision-making when mechanical systems, controls and on-site power generation systems are selected. The primary message of this question set and its corresponding

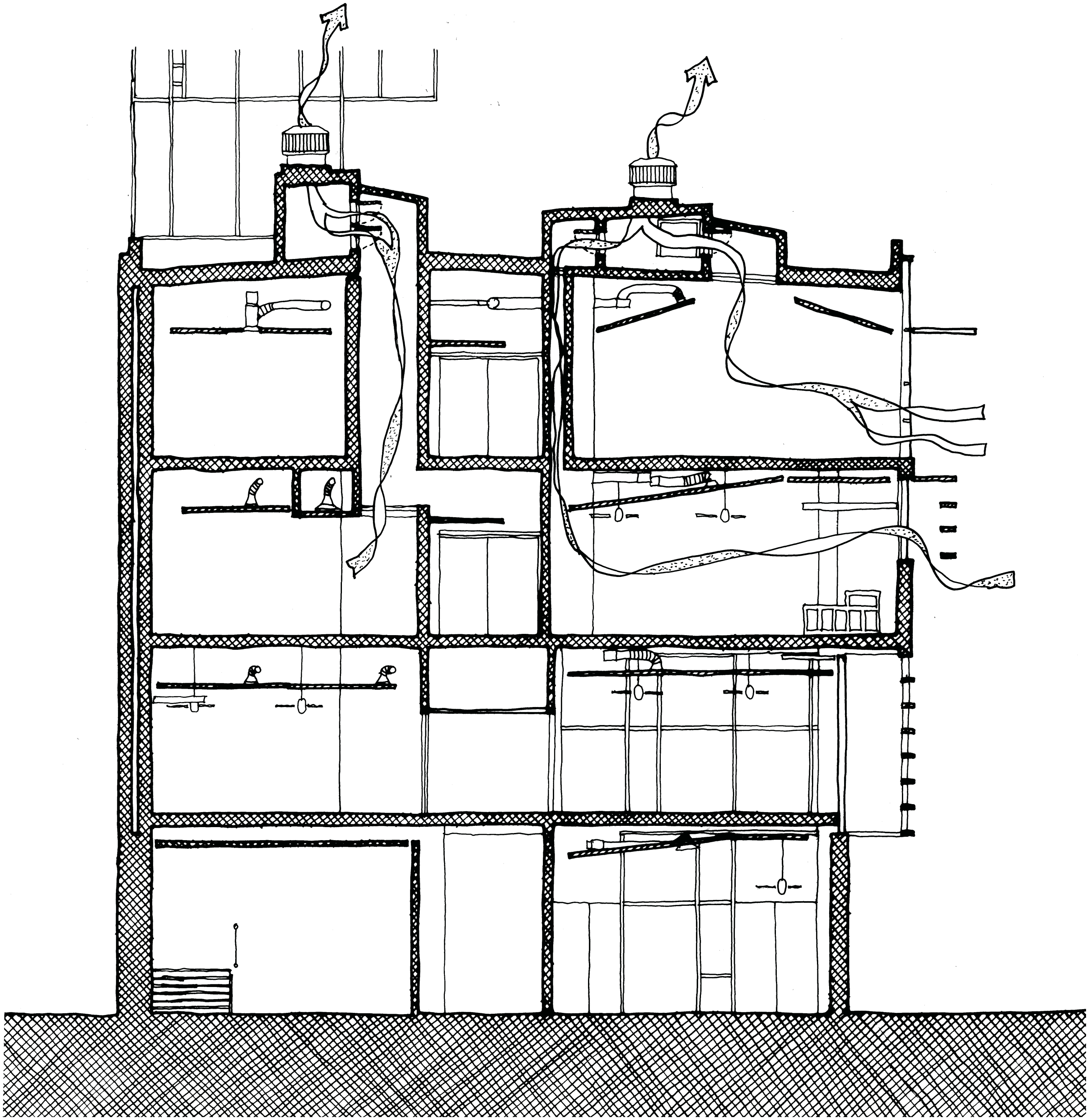


Lane Community College Downtown Campus

ACTIVE TAILORED SYSTEMS synergy is to tailor the systems as precisely as possible to the size and timing of the peak heating, cooling, ventilation and lighting loads. Several design Strategies are suggested to help identify appropriate energy use targets and select efficient mechanical and lighting systems, if needed.

Example of Design Decision Chart use

The **Lane Community College Downtown Campus** in Eugene, Oregon, was chosen as an example of using the Design Decision Chart for several reasons: One of the authors of *SWL3* had intimate knowledge and involvement during the design phase of the project; the use of the Integrated Design Process was a vehicle for early communication between design team members; and all project stakeholders were committed to achieving a "net-zero-ready" building. For this project, the use of the term "net-zero-ready" indicated a desire to reduce building loads to the point that they could be met entirely by passive strategies and on-site power generation when funding



Lane Community College Downtown Campus

for sufficient photovoltaic panels became available.

Although Eugene has a heating-dominated climate, cooling was the condition that required the most problem solving and design manipulation, since the requirements for a PASSIVELY COOLED BUILDING bundle using NIGHT-COOLED MASS span the entire gamut of architectural considerations, including structural, mechanical, electrical, lighting and acoustical systems; occupant scheduling, comfort criteria and security; climate patterns; and existing site or code constraints. In addition, while the mass was sized for cooling, it also functions as storage for the high internal gain and solar gain during the heating season. Daylighting was also considered an imperative objective, as it is recommended in most climate and program combinations, due to the high level of electricity used for electric lighting, the productivity and health improvements that have been observed in well-daylighted buildings and the high visual quality of natural lighting.

A step-by-step review of the design decision-making process, numbered according to the Design Decision Chart, follows below.

Question 1—YES.

The design team used WIND ROSE, SOLAR RADIATION, DAYLIGHT AVAILABILITY, DAYLIGHT OBSTRUCTIONS, SKY COVER and temperature and relative humidity information from TMY3 weather data from the National Solar Radiation Data Base (NREL, 2005). Based on potential load profiles determined from BIOCLIMATIC CHART, TOTAL HEAT GAINS AND LOSSES, HOT WATER LOADS and ELECTRIC LOADS, the team concluded that a net-zero or peak-zero, net-positive building was possible, given the climate and program.

Question 2—YES.

Using a combination of ADAPTIVE COMFORT CRITERIA, LOAD-RESPONSIVE SCHEDULING and close scrutiny of DESIGN DAYLIGHT FACTORS, the designers seized an opportunity to reduce occupant-associated loads.

Questions 3a and 3b—N/A and YES.

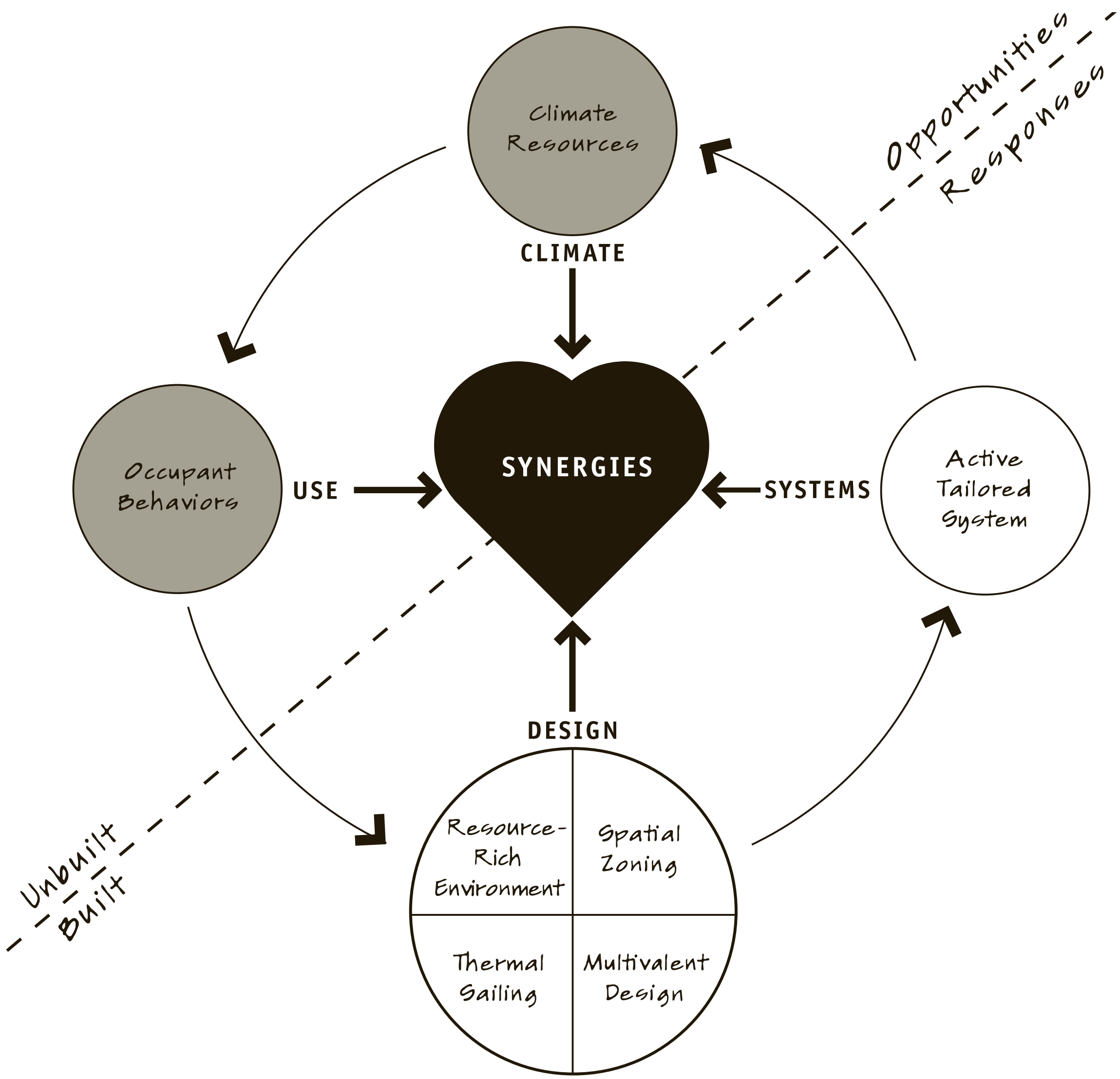
While the urban infill site was constrained by lot size and surrounding context, GREEN EDGES along the stepped-back south side of the site and SHADY COURTYARDS were used to create a comfortable OUTDOOR MICROCLIMATE without reducing the desired area for on-site power generation.

Questions 4a, 4b and 4c—YES, SOMEWHAT and MAYBE.

As outlined in the DAYLIGHT BUILDING bundle, this solution is a combination of thin and thick building strategies. To make a THIN PLAN that allows access to sun and wind, while still fitting on the site and housing all of the required program elements, the building was split into two L-shaped pieces that wrap a central courtyard. The long legs of the L are oriented to form an EAST–WEST PLAN, and ATRIUM BUILDING was used to both bring light into the central space and to provide ventilation inlets and outlets. Spaces needing higher light levels were strategically placed in the DAYLIGHT ZONES and SIDELIGHT ROOM DEPTH maintained appropriate lighting distribution throughout the classrooms. PERMEABLE BUILDINGS and STACK-VENTILATION ROOMS were used to ensure adequate openings and unobstructed pathways for cooling and ventilation of all spaces.

Questions 5a and 5b—YES and YES.

THERMAL MASS was incorporated into the design of the building from the inception of the project, used primarily for NIGHT-COOLED MASS but also for DIRECT GAIN ROOMS. MASS ARRANGEMENT called for exposed concrete floors that also provide the ceiling of the space below and concrete masonry walls to accommodate the mass surface area that was required. The RESPONSIVE ENVELOPE bundle, which includes EXTERNAL SHADES, SKIN THICKNESS and EXTERIOR SURFACE COLOR, is illustrated by the façade design and exterior wall section. Innovative design strategies such as MOVABLE INSULATION and PERIODIC TRANSFORMATIONS were also considered but were not implemented.



Synergies and the Elements of Integrated Design

Question 6—YES.

External glazing design used SEPARATED OR COMBINED OPENINGS to accommodate the multiple functions of windows, lightwells and skylights. Proper sizing was achieved with VENTILATION APERTURES and DAYLIGHT APERTURES. The large windows allow for INTERNAL/IN-BETWEEN SHADES and LIGHT SHELVES to control glare and heat gain and distribute light without falling below minimum daylight levels.

Questions 7a, 7b and 7c—YES, SOMEWHAT and SOMEWHAT.

The mechanical systems were selected and sized appropriately. Both AIR–AIR HEAT EXCHANGERS and EARTH-AIR HEAT EXCHANGERS were used, along with MECHANICAL HEAT DISTRIBUTION and DUCTS AND PLENUMS. ELECTRIC LIGHT ZONES and TASK LIGHTING were used in concert with MANUAL OR AUTOMATIC CONTROLS to provide combinations of controls that would work reliably in different program scenarios. Overall, the site area constraints do not allow for sufficient PHOTOVOLTAIC ROOFS AND WALLS to achieve net-zero energy use at its current projected ENERGY USE INTENSITY. However, the SOLAR HOT WATER system does provide a significant energy contribution by supplying most of the academic hot water needs.

Remembering the Synergies

Design is a complex task. The process of designing net-zero and peak-zero, net-positive buildings has been simplified into seven sets of questions for your consideration. The diagram **Synergies and the Elements of Integrated Design,** is offered as an aid to help remember the synergies that correspond to these question sets.

The diagram shows the four primary elements (Climate, Use, Design and Systems) of integrated design, each of which has one associated synergy, except for the Design component, which has four synergies that apply to different scales (Building Groups, Buildings and Building Parts).

Part III
SYNERGIES

This Part describes seven Synergies, or key design concepts, that if implemented properly, can help designers create net-zero and peak-zero, net-positive buildings. As explained in Part IV, each of the synergies primarily addresses one of the four aspects of integrated design: one synergy each for the Climate, Use and Systems components and four synergies for the Design component that covers the range of scales from building groups to buildings to building parts.

The primary integrated design component is listed in bold above each synergy title, along with any secondary components. As an additional cue, the relevant question(s) from the Design Decision Chart are reiterated at the beginning of each synergy description.

S1 *VIEW CLIMATE AS A RESOURCE* for load reduction and power generation.

This synergy addresses Question 1 in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

> **1** Are site resources sufficient to meet heating, cooling, lighting, ventilation and power needs?

The physical location of a given building site defines a set of climatic conditions that will influence the energy use of the building. Key climate variables include temperature and relative humidity, the position and intensity of the sun, the speed and direction of the wind and the dominant sky conditions, or cloudiness, which influences the quality and quantity of light. More important than simply analyzing the climate resources is an ability to recognize the architectural implications of certain climatic conditions.

Net-zero and peak-zero, net-positive buildings strike a balance between resource supply and demand. A climate with optimal sun, wind and light resources coupled with a building program that introduces relatively few additional loads allows the designer latitude in implementing passive strategies. At the opposite end of the spectrum, an extreme climate coupled with high internal loads requires more careful consideration of each design decision. Designers are advised to address early in the design process the potential conflicts between building loads and climatic resource availability over time, since the size and timing of the various loads determine whether they can be met with on-site climatic resources.

First analyze the climatic conditions of the site, including temperature, relative humidity, wind, daylight and solar radiation using design strategies such as BIOCLIMATIC CHART, WIND ROSE, DAYLIGHT AVAILABILITY and SOLAR RADIATION.

Then assess the anticipated building loads with TOTAL HEAT GAINS AND LOSSES, ELECTRIC LOADS and HOT WATER LOADS and compare them to the previously determined climatic resources. Based on this information, ***identify opportunities for creating synergies*** with the building design and program to reduce loads.

After implementing load reducing strategies, use the climate resources to generate on-site power.

The graph of **Photovoltaic Area Required for Net-Zero** can be used to estimate the area of PHOTOVOLTAIC WALLS AND ROOFS needed to satisfy the target building Energy Use Intensity (EUI) for several example climates.

To use the nomograph, enter on the right-hand side at the target EUI value. Move vertically to intersect the desired Energy Balance Index (EBI) performance, and then move horizontally to intersect an appropriate climate line and drop to the lower left axis to read the ratio of PV area to floor area.

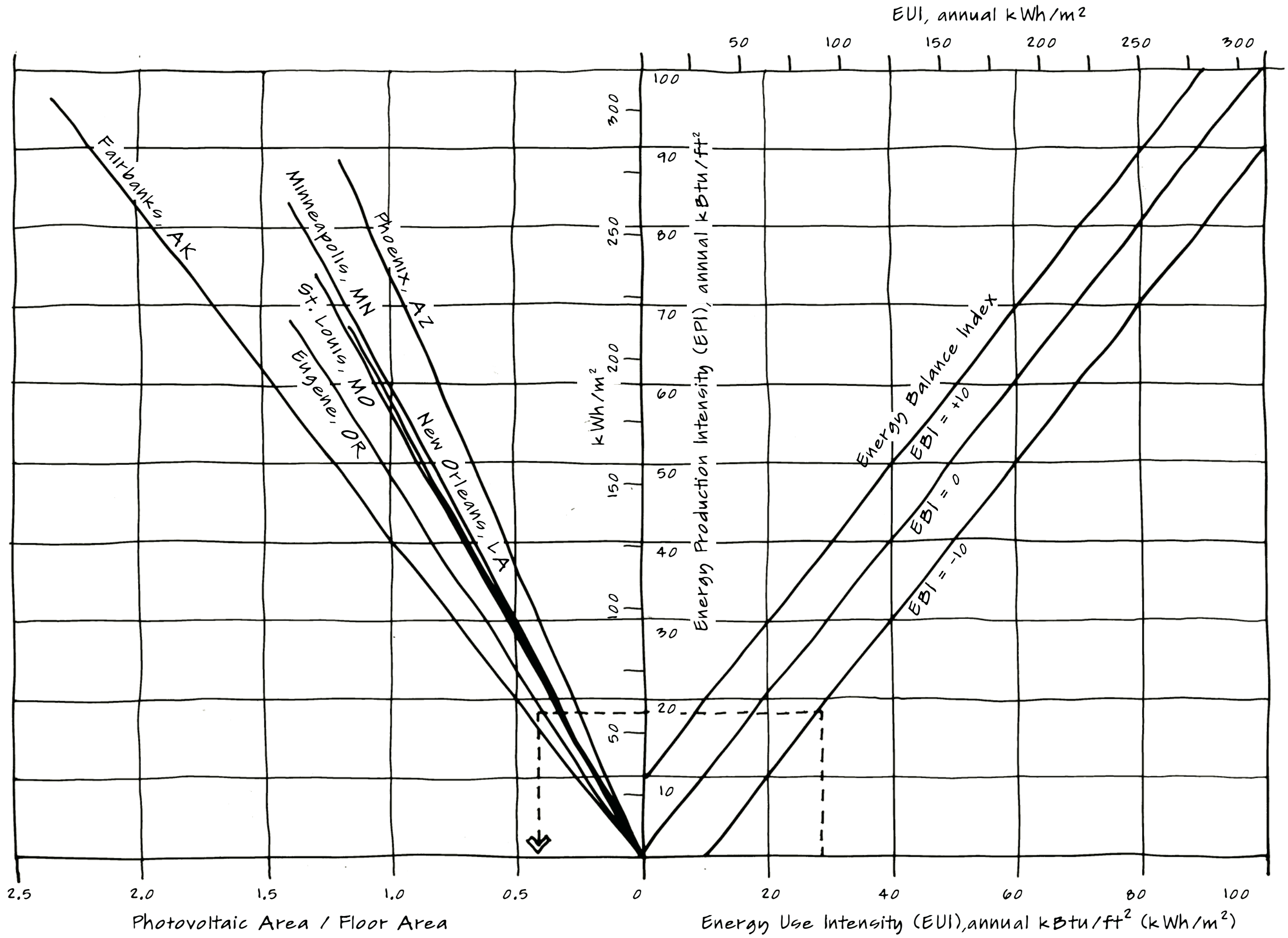
EBI = 0 is a *net-zero* building. EBI > 0 is a *net-positive* building. EBI < 0 is an energy consuming building. It is also possible to begin from the PV area/floor area ratio or from the vertical Energy Production Intensity (EPI) axis, depending on which values are known or prioritized. The following assumptions were used for PV panel area calculations: weather based on TMY2 data, fixed axis panels facing south, tilt equal to latitude and an overall DC to AC derate factor of 0.77.

For a more detailed look at loads versus on-site production, see NET-ZERO ENERGY BALANCE. PV sizing is covered in PHOTOVOLTAIC WALLS AND ROOFS. EUI targets can be evaluated in ENERGY USE INTENSITY.

EUI is an annual energy use rate that doesn't address the amount of energy used on a daily or hourly basis, which may vary significantly. A building may have a low

EUI but still have a high peak load or have most of its energy use in one season or another. Two questions arise: 1) Does the generating capacity equal the annual EUI or the peak demand? 2) Does the highest generation coincide with the peak demand? The nomograph does not answer either question, but rather allows the designer to estimate the area needed to accommodate sufficient PV panels (which can be sizable) to satisfy the energy demand in the absence of peaks.

Assuming that the building loads have been reduced as much as possible, peaks can occur when climate and occupancy factors align. The cooling peak occurs when the outdoor temperature is highest and often the greatest number of occupants are present. By contrast, the heating peak occurs when it is coldest, generally at night, and when, in nonresidential buildings, fewer people tend to be present. A low peak is desirable since equipment is often sized based on peak loads, and higher capacity equipment is both more expensive to purchase and less efficient to run during low demand. When resource availability does not coincide with the need for heating, cooling and lighting, the energy must be stored for later use, for example, in batteries or pumped water. The efficiency of the storage system will affect the amount of power generation required.



Photovoltaic Area Required for Net-Zero

S2 *ENERGY-CONSCIOUS OCCUPANT BEHAVIORS* reduce peak heating, cooling, ventilation and lighting loads.

This synergy addresses Question 2 in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

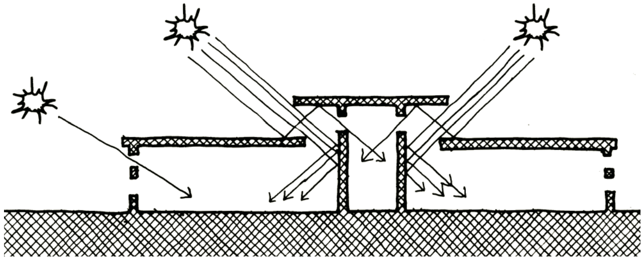
2 Can schedules, comfort criteria or occupant behavior be changed to avoid or reduce peak loads?

The primary purpose of the built environment is to provide places for humans to work, play and live. According to the *2011 Buildings Energy Data Book* (DOE, 2012, Table 3.1.4), a large percentage of the energy used in buildings is expended to keep thermal and visual conditions within fixed ranges. For example, in 2010 almost 60% of the primary energy used in commercial buildings was spent on lighting, thermal conditioning and ventilation. Because building loads tend to follow users, significant progress towards net-zero or peak-zero, net-positive buildings can be made by coupling occupant habits to climatic conditions and minimizing the periods when those habits exacerbate climate peaks.

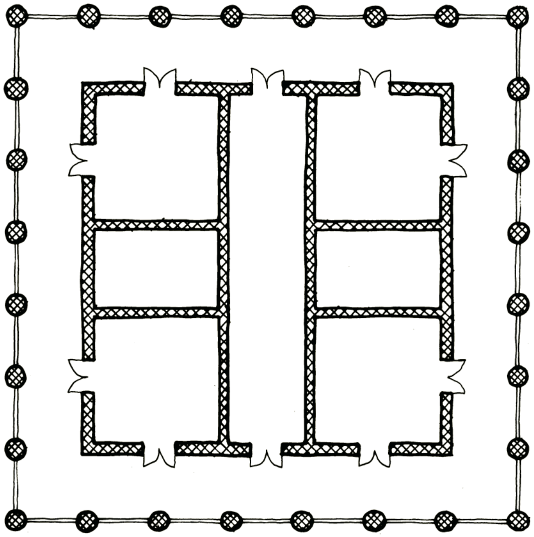
It is important to recognize the different roles played by people and by climate in driving peak building loads. While climate conditions can contribute to either a heating or cooling peak, human occupants are always heat sources (and often turn on additional heat sources) and thus may increase the climate-driven cooling peak or may decrease the climate-driven heating peak.

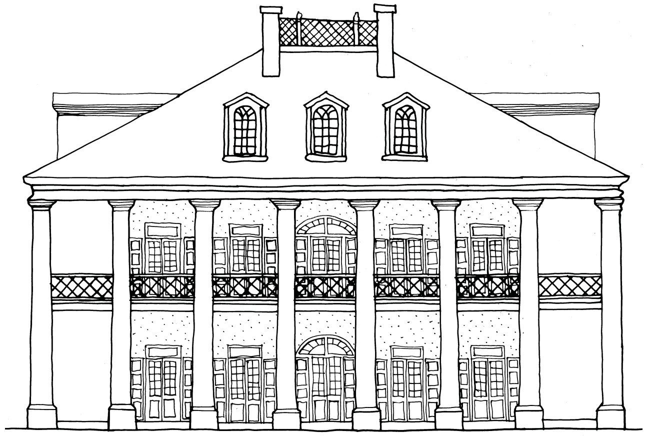
When occupants are allowed the flexibility to adapt to environmental conditions (either spatially, temporally or behaviorally), their ability to be comfortable indoors is increased. Occupants are spatially flexible if they can migrate to areas that they find most comfortable at different times of the day and year, for example, to sunny east-facing spaces on cold winter mornings [see MIGRATION]. Temporal flexibility means that occupants can shift their schedules, either as a group or individually, according to seasonal conditions [see LOAD-RESPONSIVE SCHEDULING]. Behavioral flexibility describes the physical and psychological adjustments that occupants can make in order to adapt to their surroundings. These behavioral adaptations include changing the amount and type of clothing, drinking warm or cold beverages and doing light exercise [see ADAPTIVE COMFORT CRITERIA]. How flexible occupants can be is partly determined by the building's type and use.

Spaces that encourage climate-responsive use patterns can influence operational energy use. For example, people turn on lights in rooms if they perceive the room to be dark relative to other rooms. The diagram **Designing Well-Lighted Primary Spaces** shows a daylighting strategy for ensuring that a double-loaded corridor has lower illuminance than the classrooms it serves. The apertures into the corridor are smaller than those for the classrooms, allowing less daylight into the corridor while the majority is reflected into the classroom. Since the perceived brightness of any space is influenced by the light level of the most recently occupied space, people entering a classroom from the hallway will perceive it to be brightly lighted



Designing Well-Lighted Primary Spaces





Oak Alley Plantation, Vacherie, Louisiana, 1830's, architect unknown

because their eyes have adapted to the lower light level of the hallway. They will then be less inclined to turn on the lights in the classroom. To set lighting criteria see DESIGN DAYLIGHT FACTOR.

Design internal building spaces that allow occupants opportunities to adjust their comfort criteria, schedules, or behavior patterns in a way that minimizes energy use.

Conscious behavioral patterns can also be harnessed to reduce loads and energy use. **Oak Alley Plantation** in Vacherie, Louisiana, is a traditional-style plantation house that employs a responsive envelope to modulate indoor conditions throughout the year and relies on the building users to operate the building effectively. The variety of thermal and luminous conditions characterizing the house allows occupants to consciously seek out more pleasurable spaces [MIGRATION]. The house is divided into two distinct zones: an outdoor gallery shaded by the parasol roof and an indoor thermal enclave operating by PERIODIC TRANSFORMATIONS that can be closed or open depending on season and occupant preferences. During the summer, people tend to occupy the outer gallery under the LAYER OF SHADES, while during the winter they are more likely to use the thermal enclave. In the spring and fall, the envelope of the interior thermal enclave can be opened up to make the space behave more like the outdoor gallery or kept closed to exterior conditions. Occupants can also alter their behaviors within a diurnal time frame: they can choose to stay outside under the shelter of the parasol all day and night, moving furniture out to the gallery when it is more comfortable, or they can choose to inhabit the thermal enclave at night, while opening the windows to make it more like the outdoor conditions.

S3 Form and organize buildings and open spaces to create *RESOURCE-RICH ENVIRONMENTS* that provide livable outdoor space and access to site resources.

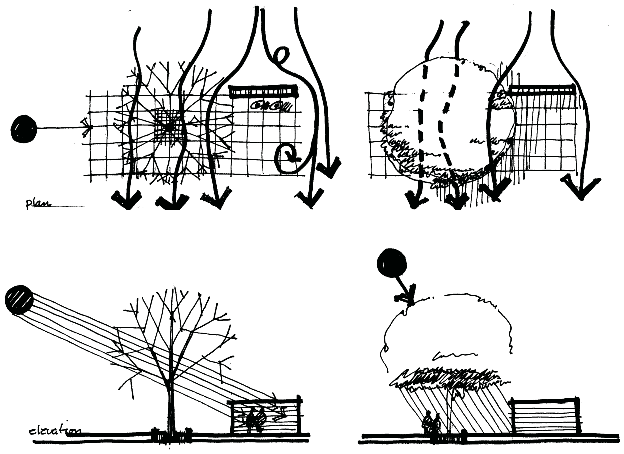
This synergy addresses Questions 3a and 3b in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

3a If the project includes multiple buildings, can they be arranged to allow access to fresh air and sunlight throughout the site?

3b Can the site design enhance access to desirable resources while mitigating unwanted resources for part or all of the year?

Urban outdoor spaces, including plazas, sidewalks, streets and parks, constitute the majority of a city's land use. Together they form important meeting and resting places, and their character largely determines the image of the city. Using site energy to produce thermally comfortable conditions extends the occupancy period of these spaces. Habitable outdoor rooms can result in less conditioned indoor area and therefore reduce energy consumption. An energy-conscious city provides human habitat with less energy, cost and environmental impact.

Microclimate conditions change throughout both the day and the year. Design strategies that manifest concurrently or that involve a time lag can promote outdoor comfort during different seasons or periods of the day. Microclimates also have qualities that can be characterized as either static or dynamic depending on whether they alter their state over time. In the diagram **Static Versus Dynamic Strategies,** the tree represents both concurrent and dynamic strategies in that it does not store heat or coolth over time, but it does drop its leaves to admit the sun during the winter and leafs out to provide shade during the summer. The masonry wall stores heat that it collects from the sun during the day and releases it gradually after the sun goes down, and thus is static with a temporal lag.

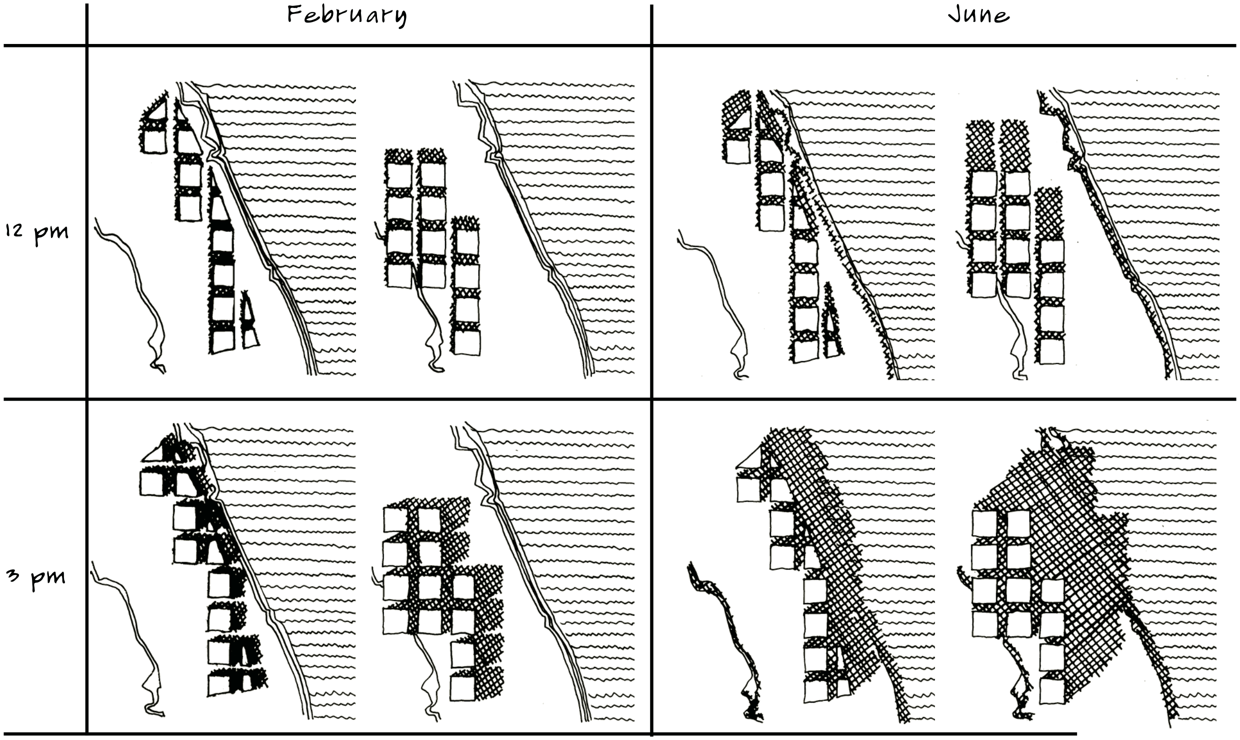


Static Versus Dynamic Strategies

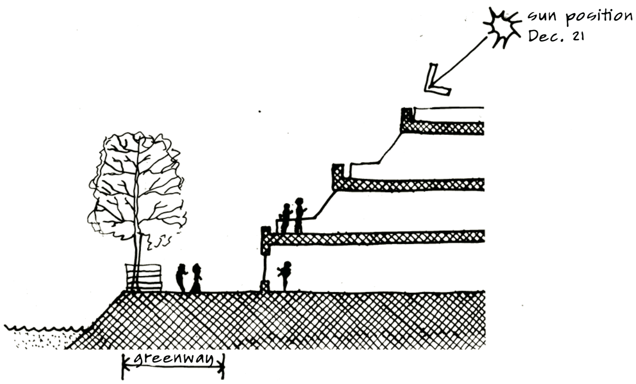
When designing outdoor microclimates, ensure that outdoor spaces and neighboring buildings have adequate access to climatic resources, because sun and wind can be blocked at smaller scales, but cannot be created if they are not present [see bundles NEIGHBORHOOD OF LIGHT, COOLING NEIGHBORHOOD and SOLAR NEIGHBORHOOD].

Once resource access is established, site organization and elements can be used to create localized conditions of variation in sun, shade, wind and lee [see bundles INTEGRATED URBAN PATTERN and OUTDOOR MICROCLIMATES].

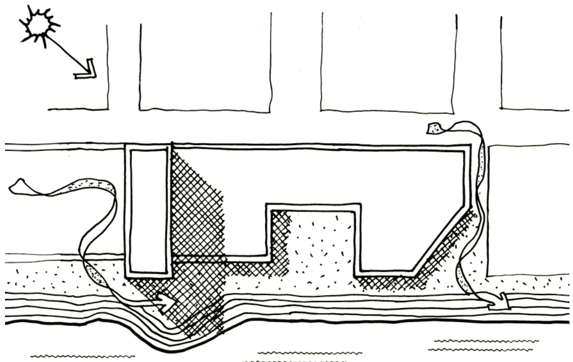
In the **North Macadam Greenway Microclimate Study for Portland, Oregon,** the patterns of sun, shade, wind and lee are determined by the configuration of the buildings and vary by season and time of day. The diagram illustrates the shading impact of buildings built to the maximum zoned heights of 125' (38 m) at a 25' (7.6 m) setback and 250' (76 m) at a 50' (15.2 m) setback during the months of February and June at noon and 3:00 PM. In February, the greenway adjacent to the river is



North Macadam Greenway Microclimate Study, Portland, Oregon, 2000, ESBL



Full Sun and Wind: massing provides full access for passive design and green power, while achieving microclimates using vegetation or small-scale forms.


Climate Smorgasbord: a variety of shade and wind conditions, using building form, so some space is always comfortable

Microclimate-Shaping Scenarios

significantly shaded by buildings in both height zones at 3 PM, although shading is undesirable at this time of year. In June, shade is desirable at noon and at 3 PM, but the greenway is not significantly shaded by the buildings at any time. Other options are shown by the **Microclimate-Shaping Scenarios**.

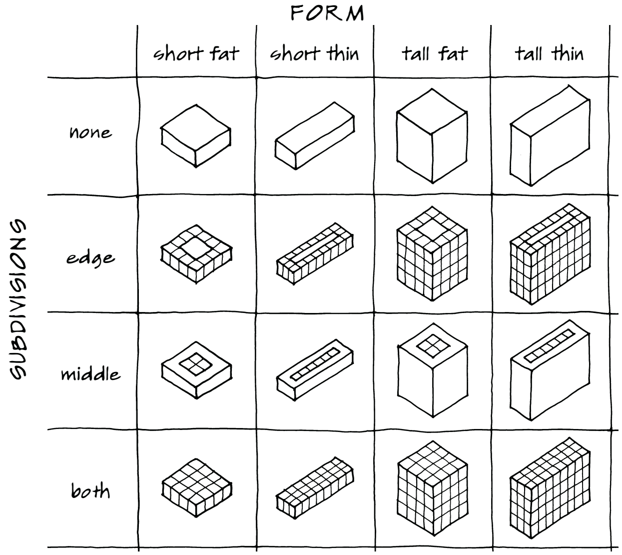
S4 Integrating climate and use variables yields opportunities for *SPATIAL ZONING* according to "best-fit" passive design strategies.

This synergy addresses Questions 4a, 4b and 4c in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

4a Can the building form and orientation allow access to sun, wind and light resources for most internal and external spaces?

4b Can spaces with similar heating, cooling, ventilation and lighting requirements be grouped together?

4c Can the design accommodate unobstructed pathways that allow sun, wind and light to be distributed throughout the entire building?



Building Form and Subdivisions Matrix

Initial decisions about building form, orientation and organization set the stage for patterns of sun, wind and light interaction that vary with changing climatic conditions over the course of days and seasons. The building design modulates sunlight and wind resources by controlling their access and distribution throughout the building.

Building form determines which internal spaces have direct access to sun, wind and light [DEEP SUN, SKYLIGHT BUILDING]; one of the primary drivers of building form is the desirability of spaces along the skin of the building [THIN PLAN; EAST–WEST PLAN].

Orientation influences the quantity and quality of the resources that enter the building, as well as the degree to which admission can be controlled, as observed in south-facing glazing, which permits the best access to solar radiation during winter months while also being the easiest to shade during summer months [ROOMS FACING THE SUN AND WIND, LOCATING OUTDOOR ROOMS].

Internal organization groups together spaces with similar needs [HEATING ZONES, COOLING ZONES, DAYLIGHTING ZONES, ELECTRIC LIGHT ZONES, STRATIFICATION ZONES].

The **Building Form and Subdivisions Matrix** shows the four primary building form categories—short and fat, short and thin, tall and fat, or tall and thin—and four possibilities for subdivisions of internal spaces. Of the four form types, the tall and fat building has the least amount of surface area relative to floor area, and thus its internal spaces have the least access to sun, wind and light resources. The short and thin building has the greatest amount of surface area relative to floor area and the best access to resources.

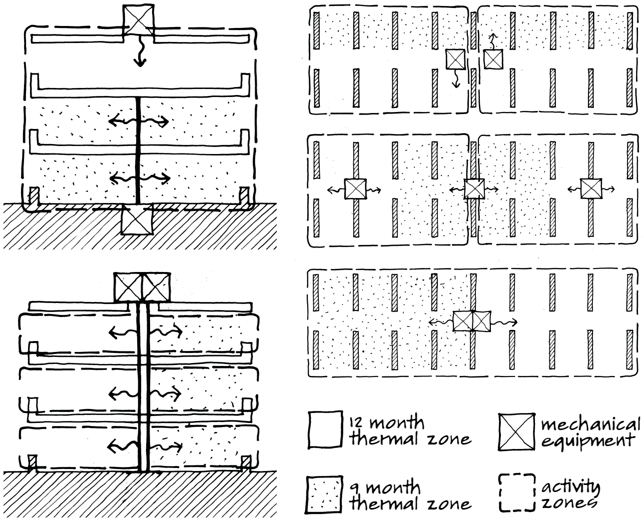
Internal spaces can be organized in a number of ways. In plan, for example, a double-loaded corridor might be divided into different zones lengthwise, transversely, or from the middle core out, as illustrated by the **Spatial**

Zoning in Section and in Plan diagram. Additionally, it shows how the building can also be divided into zones sectionally, by floor or by orientation. The subdivision of internal spaces affects distribution pathways through the building. Air flow and daylight are particularly sensitive to internal partitioning [PERMEABLE BUILDINGS] and in thick buildings may require MOVING HEAT TO COLD ROOMS or methods for getting daylight deep into the building, such as DEEP SUN, ATRIUM BUILDING, BORROWED LIGHT or SKYLIGHT WELLS, to achieve the desired distribution to interior rooms.

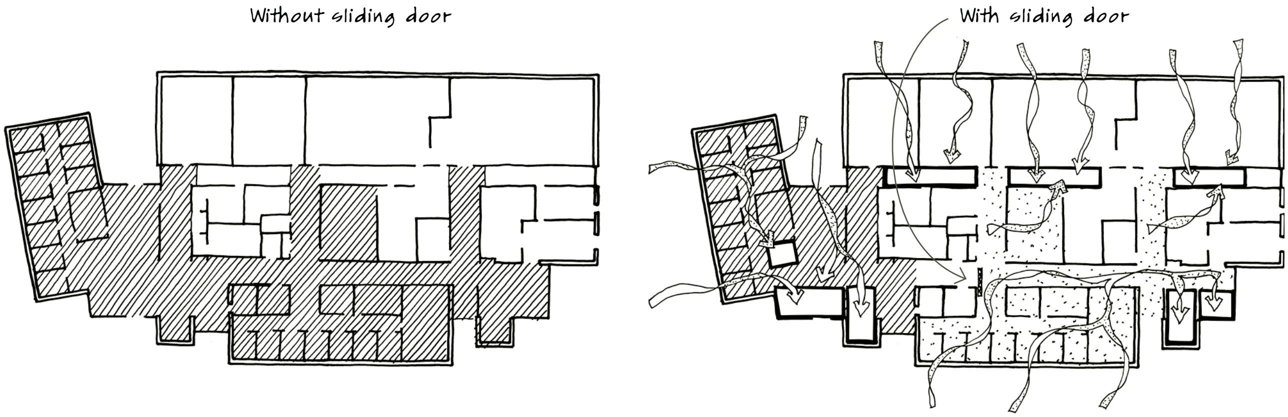
Design buildings to provide access to sun, wind and light for as many of the interior spaces as possible [see DAYLIGHT BUILDING, PASSIVELY COOLED BUILDING and PASSIVE SOLAR BUILDING]. Often this means that buildings will be thin (either literally or functionally, e.g., courtyard buildings)

Use* ENERGY PROGRAMMING *to identify the degree to which different types of spaces require different levels of heating, cooling, lighting and ventilation. Use the many zoning strategies in* SWL *to organize, locate and orient groups of spaces with similar needs.

The **Lane Community College Health and Wellness Building** in Eugene, Oregon, by SRG Partnership is an example of using zoning principles and distribution pathways to achieve a primarily daylit and naturally ventilated building. The building is divided into two parts for the purpose of night cooling the thermal mass. A sliding door located in the central hallway is closed at night to ensure that ventilation air travels the planned route through each separate zone of the building so that the thermal mass in each zone receives adequate night ventilation to remove heat collected during daytime use.



Spatial Zoning in Section and in Plan



Lane Community College Health and Wellness Building, Eugene, Oregon, 2010, SRG Partnership

S5 A building designed for *THERMAL SAILING* integrates thermal storage and a responsive envelope that exploit changing patterns of sun, wind and light to regulate comfort and energy use.

This Synergy addresses Questions 5a and 5b in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

5a Can the design include thermal mass, and do daily temperature swings and radiation levels promote storage strategies?

5b Can the envelope be designed to resist or allow convective, conductive and radiative heat transfer when desirable?

Designers of net-zero or peak-zero, net-positive buildings are attuned to the pulse of climatic patterns. Similarly, building operators can adjust building controls to harvest, reject or modulate climatic forces. Examples of building elements (both active and passive) that can be combined to form a RESPONSIVE ENVELOPE bundle include: INTERNAL AND IN-BETWEEN SHADES, EXTERNAL SHADES, operable VENTILATION APERTURES and MOVABLE INSULATION panels.

Integrating THERMAL MASS into the building design helps modulate temperature swings, resulting in greater thermal comfort and less energy use. To realize these potential benefits, designers can consider not only the gross area and thickness but also other details that affect mass performance, such as the provision of INSULATION OUTSIDE the THERMAL MASS and the different pathways and sources for heat loss and gain. Many other factors play a role in the effectiveness of thermal storage strategies. MASS ARRANGEMENT, for example, affects its access to either warm or cool air and its ability for radiant exchange. The surface reflectivity and MASS SURFACE ABSORPTANCE also influences how much heat is gained or lost through radiation.

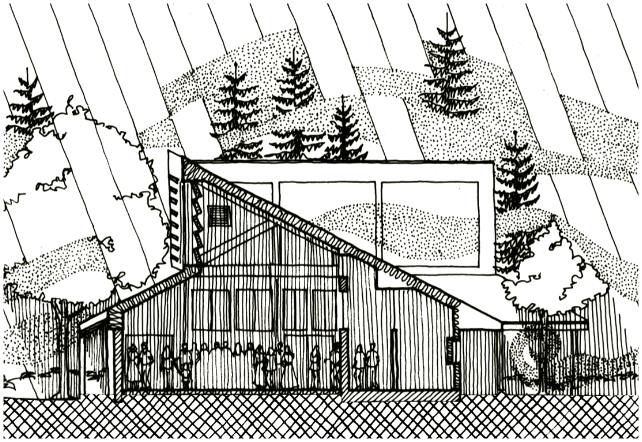
During the cooling season when it is desirable to reject heat gain while promoting heat loss in a masonry storage system, exterior or interior shades can be used to prevent direct radiation from entering the space and VENTILATION OPENINGS ARRANGEMENT provides a pathway for cool night air to flow across the mass. In the heating season, an opposite strategy applies: solar gain is encouraged during the daytime, and MOVABLE INSULATION is used to prevent heat loss at night. It is worth noting that selectively applying insulation to some high-loss areas of external walls, such as window apertures, has more impact on the overall wall *R*-value than increasing the level of insulation in the wall area itself. For example, a wall insulated to R-30 with a 30% glazing fraction has an overall wall *R*-value of 7.79 using windows with 0.35 U-factor, but the same wall has an overall wall *R*-value of 18.75 when R-10 shutters are used.

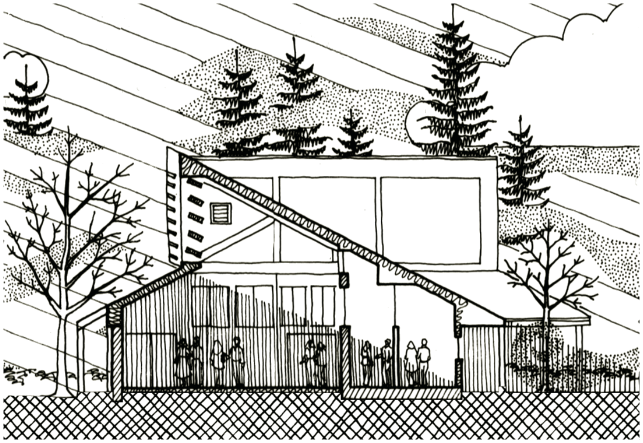
To design a building for* THERMAL SAILING*, first determine whether the exterior envelope elements are to act as a connector, barrier, filter or switch, or combinations of these (Norberg-Schulz, 1965) based on prevailing climatic conditions and indoor comfort criteria.

A fixed window acts as a barrier to air movement, and as a connector for sunlight and daylight. An operable window acts as a switch in terms of air flow, while an electrochromic window and operable shades act as switches for sunlight. Switches and filters are more adaptable to varying conditions than barriers or connectors alone.

Consider the following general principles for a mixed climate with heating and cooling needs:

- During overheated periods, when the indoor temperature is above the outdoor temperature, VENTILATION APERTURES may be opened to allow





SUMMER

Midnight: Vents and night insulation are open. Cool night air circulates through the meeting hall, cooling the trombe wall, masonry interior walls and floor.

Sunrise: Vents and night insulation are open, allowing breezes. Shades and exterior louvers prevent direct sun from heating the cool mass.

Noon: As it gets too hot out, vents and windows are closed and can be covered with the insulation to keep the meeting hall cool. Shading is used to exclude direct sun, and the night-cooled mass keeps interior temperatures down.

Sunset: Vents, windows and night insulation are opened as the outside air cools off. Interior walls, floor and trombe wall remain well-shaded.

WINTER

Midnight: Vents, windows and night insulation are closed to keep warmth inside. The masonry walls and floors warmed by yesterday's sun radiate heat throughout the building.

Noon: Vents and windows are kept shut. Night insulation is opened to admit direct sun which heats the trombe wall and masonry floors and walls, as well as the people.

Sunset: Night insulation is closed after sunset. The thermal mass radiates heat collected during the day.

Deadwood Creek Community Center, Deadwood, Oregon, 1980, Equinox Design, Inc.

natural ventilation for cooling.

- If the outdoor temperature is warmer than the upper limit of the comfort range, close apertures to retard excess heat gain.
- If NIGHT-COOLED MASS is employed, open apertures at night once the outdoor temperature has dropped below the indoor temperature.
- Organizing occupancy patterns in LOAD-RESPONSIVE SCHEDULES so that occupant-associated heat gains do not exceed the rate at which the THERMAL MASS can absorb heat will increase the ability of the mass to provide cooling throughout the day.
- During the cooling season, shade all glazing from direct radiation. Employ MOVABLE INSULATION as a barrier against heat gain during the daytime, so long as sufficient glazing area for daylight is maintained, or in the case of unoccupied rooms.
- During underheated periods, open INTERNAL SHADES and operable EXTERNAL SHADES to admit sun.
- Organize occupancy patterns using MIGRATION so that the parts of the building that warm up first, such as those with east-facing glazing and those on upper levels, are occupied early in the day. As spaces become unoccupied and lose access to direct solar radiation, employ MOVABLE INSULATION over the glazing to reduce heat loss.
- All glazing can use MOVABLE INSULATION at night when windows are the main source of heat loss.

In the **Deadwood Creek Community Center**, in Deadwood, Oregon, by Equinox Design, night insulation and THERMAL MASS in a trombe wall [THERMAL STORAGE WALL], as well as in masonry walls and floor, passively condition the space throughout the year. Users proactively operate the MOVABLE INSULATION, ventilation openings and operable shading devices to keep the building comfortable while using a minimum of off-site energy.

S6 ***MULTIVALENT DESIGN*** **combines two or more functions within a single building element.**

This synergy addresses Question 6 in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

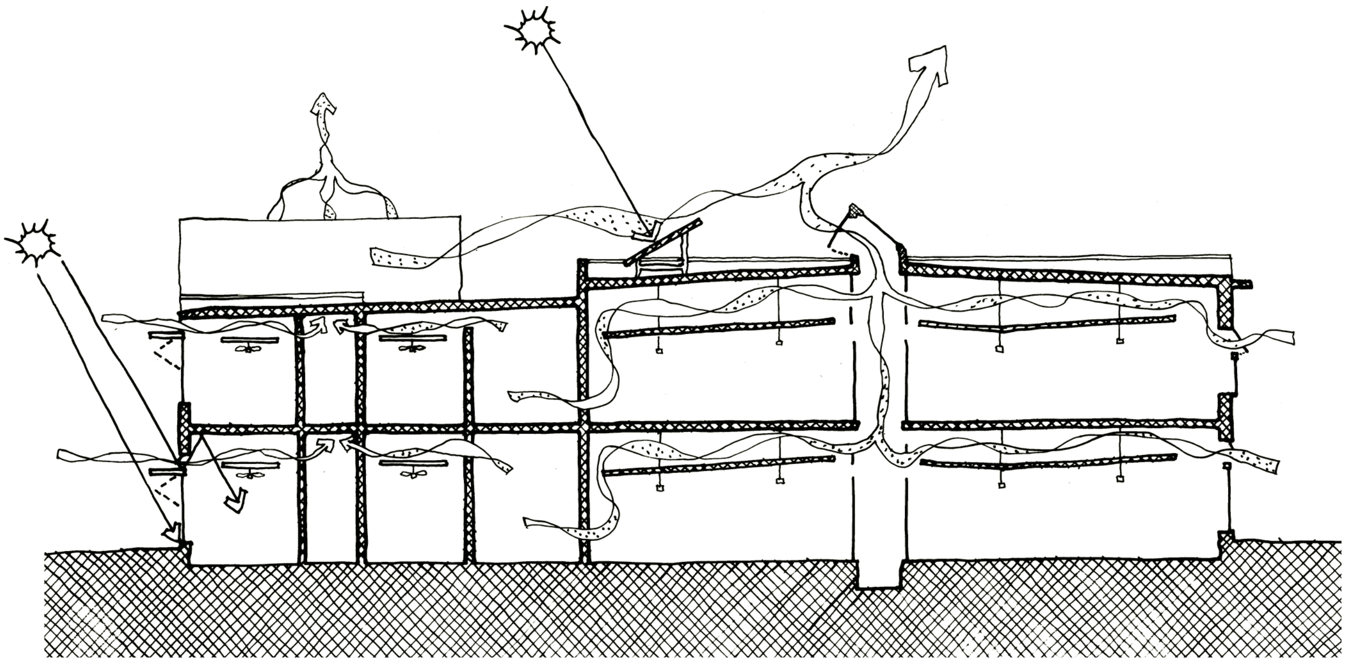
> **6** Can apertures be designed to admit resources without adverse effects, such as overheating and glare?

Some building elements, such as windows, can be designed to perform multiple functions, often simultaneously. These elements are important loci for synergies among heating, cooling, lighting and ventilation strategies, but can introduce problems when designed poorly. For example, a well-designed window can provide views in and/or out, sitting places and visual modulation of the wall, all possible sources of sensory pleasure. It can also contribute to a high-performance building. However, windows can also present problems: they can reduce privacy, increase heating and cooling loads, create potential for glare, demand sizing for different needs, introduce security issues, or require appropriate operation.

When designing multivalent elements, create a table like the example for vertical windows given in the **Multivalent Elements Table*****, which lists the functions of each element and the potential conflicts or problems. Fill in possible design strategy solutions for each problem and then look for strategies that fulfill multiple functions.***

When aperture sizing conflicts arise between two or more of the needs for heating, cooling, daylighting and ventilation, consult SEPARATED OR COMBINED OPENINGS for alternatives. If SOLAR APERTURES present glare issues or seem too large, collection openings for DIRECT GAIN ROOMS can be combined with other solar heating systems, such as THERMAL STORAGE WALLS, SUNSPACES, or THERMAL COLLECTOR WALLS AND ROOFS to provide heat with less daylight and glare, as outlined in the RESPONSIVE ENVELOPE bundle.

For the **Lane Community College Health and Wellness Building,** in Salem, Oregon, the SRG Partnership designed window apertures and lightwells to fulfil multiple functions. Apertures in the exterior wall are sectioned into distinct parts that permit views, daylighting and ventilation. The VENTILATION APERTURES provide inlets for CROSS VENTILATION ROOMS and STACK-VENTILATION ROOMS, used both to supply outside air requirements and for cooling. The DAYLIGHT APERTURES are equipped with EXTERNAL SHADING louvers which allow a high percentage of reflected light to enter while minimizing unwanted solar gain when the sun is at a high angle, thus serving as DAYLIGHT ENHANCING SHADES. Central SKYLIGHT WELLS are used to provide daylight and become STACK-VENTILATION ROOMS with exhaust outlets for ventilation air. Automatically actuated glazing in the vertical south-facing side of the lightwells opens at night to allow sufficient nighttime air to flow through the building for NIGHT-COOLED MASS. Translucent panels separate the classrooms from the lightwells, allowing additional BORROWED DAYLIGHT to enter the rooms.



Lane Community College Health and Wellness Building, Eugene, Oregon, 2010, SRG Partnership

Element	Function & Prime Strategy	Potential Problems	Possible Solutions
Vertical Windows	**Daylight:** DAYLIGHT APERTURES	• Glare and uneven light distribution • Heat gain and loss from radiation and conduction • Inadequate privacy, appropriate operation	• LIGHT SHELVES; DAYLIGHT ENHANCING SHADES; LOW CONTRAST; WINDOW PLACEMENT; DAYLIGHT REFLECTING SURFACES • EXTERNAL SHADING; INTERNAL AND IN-BETWEEN SHADES; WINDOW AND GLASS TYPES • MANUAL OR AUTOMATIC CONTROLS
	Ventilation: VENTILATION APERTURES	• Heat gain/loss from ventilation and infiltration • Security, pollution • Appropriate operation	• AIR FLOW WINDOWS; WINDOW AND GLASS TYPES • SEPARATED OR COMBINED OPENINGS • MANUAL OR AUTOMATIC CONTROLS
	Cooling: VENTILATION APERTURES	• Heat gain from conduction • Security, pollution • Appropriate operation	• WINDOW AND GLASS TYPES; MOVABLE INSULATION • MANUAL OR AUTOMATIC CONTROLS; SEPARATED OR COMBINED OPENINGS
	Heating: SOLAR APERTURES	• Glare • Heat loss from conduction and radiation • Appropriate operation	• WELL-PLACED WINDOWS; SOLAR REFLECTORS • MOVABLE INSULATION; WINDOW AND GLASS TYPES • MANUAL OR AUTOMATIC CONTROLS
	Other Design Considerations (structure, views, etc.)	• Conflicts with structural system • Increased cost • Increased design time and expertise needed	• Integrated design process

Multivalent Elements Table

S7 When all available load reduction strategies and their controls have been exploited, meet the remaining load with an *ACTIVE TAILORED SYSTEM* that fits the load characteristics.

This synergy addresses Questions 7a, 7b and 7c in the Design Decision Chart for Net-Zero and Peak-Zero, Net-Positive Buildings:

7a If needed, are mechanical and electrical systems selected and sized appropriately to supplement load reduction strategies?

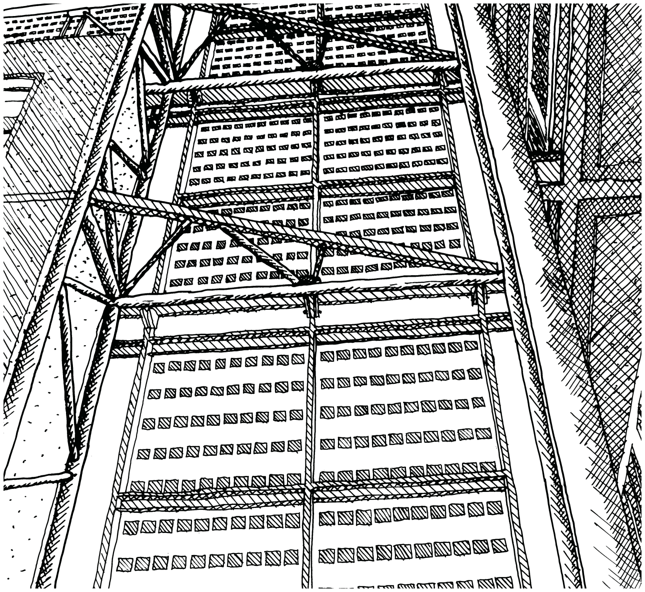
7b Can manual controls be used reliably given the program and climate?

7c Are power generation systems sized appropriately to provide power when needed?

Net-zero and peak-zero, net-positive buildings are most effectively achieved by reducing building loads to a minimum through design and use strategies before determining mechanical system requirements and on-site power generation capacity. Building loads can be evaluated using ANNUAL ENERGY USE and then be compared to the on-site generation potential using NET-ZERO ENERGY BALANCE.

Many buildings have a generally consistent and moderate load with occasional extreme peaks when climatic and occupancy conditions coincide. These peak loads complicate sizing mechanical systems. Should they be sized for the peak, making equipment less efficient during average conditions, or should a variable or two-component system be used that can adapt its output to fit load profiles?

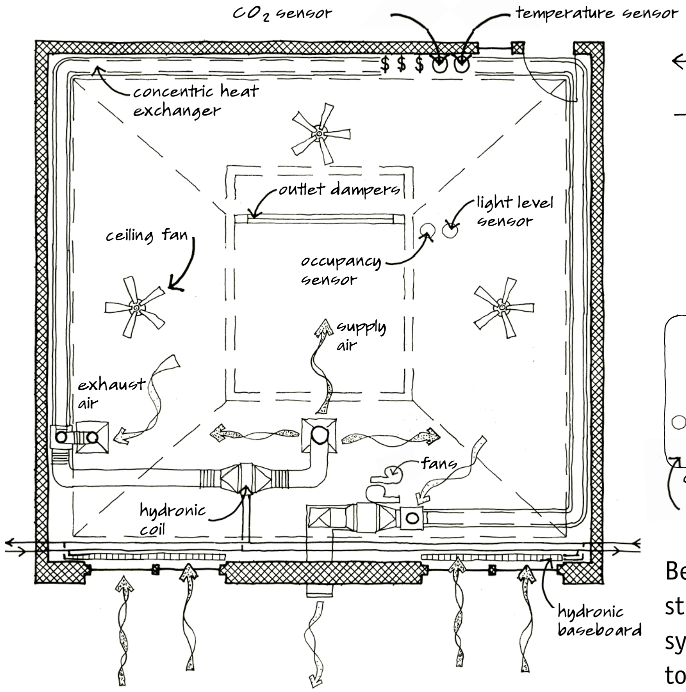
Machinery runs most efficiently at its designed load and continuously, but that is not how systems operate in actual buildings. Building loads change minute to minute as occupants come and go, equipment runs or not, and the climate changes. In an ideal world for building systems, loads would be level, without peaks by the hour, day or season. Designers can use load reduction strategies to make energy demands more level and smaller so that there is less difference between average and peak loads.

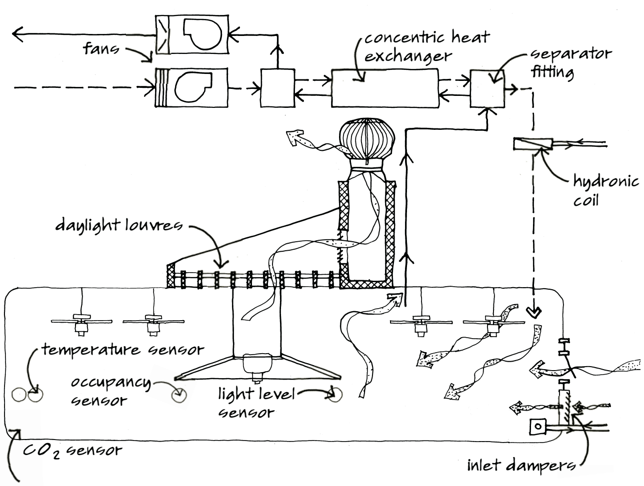


Lillis Business Complex, University of Oregon, Eugene, Oregon, 2003, SRG Partnership

Assuming load reduction strategies have already been applied to the degree possible, consider the following principles for tailoring active systems to building loads:

- See the architectural fabric and the mechanical and electrical systems as an integrated whole.
- Segregate the heating, cooling, ventilation and lighting systems so that each can be sized and efficiently controlled for its own load; systems are efficient at constant operation levels.
- Condition spaces only where and when they are occupied. In other words, use mechanical and electrical systems for the benefit of people rather





Mount Angel Abbey Annunciation Academic Center, SRG Partnership (2006)

than the spaces alone.

- Give people control of their thermal and visual environments; use a combination of MANUAL AND AUTOMATIC CONTROLS to optimize energy use and occupant comfort.
- Use a spectrum of task/ambient heating, cooling and lighting systems matched to occupants' needs. Allow the potential for variety in thermal and luminous conditions [TASK LIGHTING, ADAPTIVE COMFORT].
- Generate renewable energy during peaks, and use it for supplemental heating/cooling or store the energy for later use.

One method that can be used to tailor active systems more precisely to building loads is to design modular spaces that have separate systems sized to meet only the demands of each space. In this way, rooms can be operated independently according to occupancy levels and use, reducing overall building energy consumption. The **Mount Angel Abbey Annunciation Academic Center** in St. Benedict, Oregon, by SRG Partnership, uses load reduction strategies to eliminate the need for mechanical cooling systems and relies on hydronic baseboard radiant heaters to supply heating and AIR–AIR HEAT EXCHANGERS to temper ventilation air, all sized and operated independently for each classroom. Heating, lighting and ventilation systems within the classrooms use a mix of MANUAL OR AUTOMATIC CONTROLS. The baseboard heaters are operated automatically by the building control system; the electric lighting systems are controlled by photosensors, but can be manually overridden; outside air vents use automatic controls for night ventilation and manual controls for increased ventilation.

In the **Lillis Business Complex** at the University of Oregon, in Eugene, Oregon, by SRG, photovoltaics are integrated into the building envelope [PHOTOVOLTAIC ROOFS AND WALLS]. The building employs key load reduction strategies, including THERMAL MASS used to store both heat and coolth; solar gain allowed in the winter when needed and excluded in the summer; ceiling fans used to expand the comfort zone; lights automatically turned on or off depending on ambient lighting conditions and temperature; and windows opened for natural ventilation when outdoor temperature is 2–3 °F (1–1.7 °C) below indoor temperature [MIXED MODE COOLING]. Overall the building uses 41% less energy than Oregon code requires.

Part IV
BUNDLES

The first section of this part, **"Bundles Explained,"** introduces strategy Bundles in more detail as sets of related design strategies that work together synergistically to solve common problems encountered when designing high-performance buildings. It explains the principles that define a bundle and their graphic representation in the bundle diagrams used throughout the bundle spreads in the last section, "Some Fundamental Bundles."

The second section of Part IV is **"Making Your Own Bundles,"** which offers the reader a step-by-step process for creating customized bundles for a particular building project or for adding new bundles to the repertoire beyond those fundamental bundles presented in *SWL*. Bundles offer a flexible and creative conceptual framework that is only begun in this edition. The number of potential bundles and their variations equals that of the recurring problems and situations encountered in high-performance building design.

The final section, **"Some Fundamental Bundles,"** presents nine bundles: four at the L9 Neighborhoods scale, four at the L6 Whole Buildings scale and one at the L4 Rooms scale.

Bundles Explained

Relationships Among Strategies

Birth of the Bundle

The second edition of *Sun, Wind & Light* included 109 techniques and design strategies across a range of scales. These strategies addressed issues of heating, cooling, lighting and power. The bundle was born in part as a result of finding three challenges that surfaced in over a decade using the second edition:

1. *Difficulty in knowing which strategies to use* for a particular design situation, such as designing the building envelope, especially for novice passive designers.
2. *Identifying how the strategies were related* to each other—or not related—was sometimes implied but often opaque and required substantial practical experience.
3. Also hard to find in the text was *knowing how major variables, like climate type, changed which strategies to employ* or emphasize.

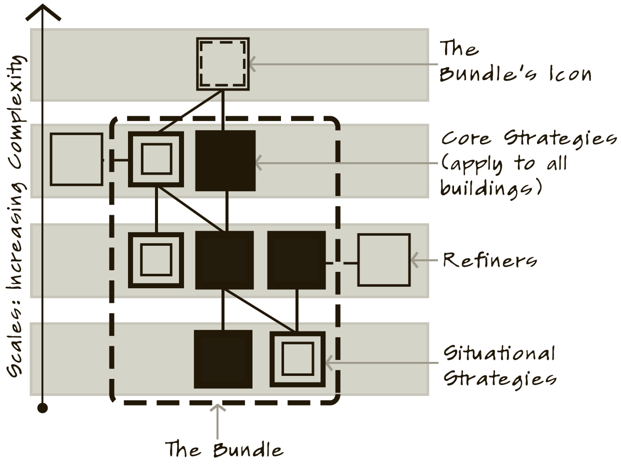
The concept of bundles attempts to address these challenges. Additionally, two other observations are crucial to understanding the purpose of bundles:

Strategies are related to each other across a range of scales, often in nested and hierarchical ways, as described in the section "Navigation by Design Strategy Maps." This new navigation tool is another basis for organizing strategies into bundles.

A strategy that addresses one energy issue, such as heating, often has impacts on other energy issues, such as lighting or cooling. Because designers think about energy issues in more than one way, some bundles address multiple issues and others focus on a single energy issue.

Bundles as generalized solution types to recurring problems

A bundle proposes a set of the almost always required strategies that come together to form solutions to design situations encountered repeatedly in buildings. Some design situations are recurring, such as the problem of how to bring in light through a roof or how to use the building to collect and store heat from the sun in a cold climate. When one is able to generalize about these design situations, one can also generalize about the solutions and the characteristics of these solutions that seem to be workable across a variety of conditions. If a problem is encountered thousands of times in buildings, the building community develops particular solution types from which designers can learn. In many cases, researchers turn their attention to the common and perennial problems of design to verify or improve upon the informally developed solutions of builders and designers. *SWL* attempts to capture



The Structure of a Bundle

this kind of wisdom in the individual design strategies and now, in the bundles, as associations of related strategies.

What is a Bundle?

A ***Bundle*** in *Sun, Wind & Light* is a set of related strategies working together to resolve commonly occurring design problems. A bundle may address a single energy issue or it may address two or more energy topics (heating, cooling, daylighting, ventilation or power. In general, a bundle has the following characteristics, as illustrated in the diagram **The Structure of a Bundle**.

- *A Bundle covers two or more scales* in the hierarchical system for levels of complexity (such as L1 Elements and L2 Building Systems). Most of the fundamental bundles cover three levels (the gray bars). The black lines connecting the squares represent a particular kind of relationship among the strategies of lower and higher complexity. The levels function to make clear how lower complexity strategies help to build higher complexity strategies.
- *A Bundle has 3–5 invariant core strategies* (the solid black squares) that can always be used in the given design situation. Core strategies are recognized as those that apply to all the bundle's variations.
- *A Bundle has two or more situational variations*, each with its own bundle diagram. These adapt the bundle to a major variable commonly present (such as the difference between designing in a cool versus a hot-arid climate) by the addition of situational strategies (hollow squares inside the dashed line) beyond the core strategies. Again, remember that core strategies are common to all of the situational variations. If it is a core strategy, it will be present in all variations as an important strategy.
- *A Bundle may also identify refiner strategies* (squares in the lower grey bars outside the dashed line), which are related to the bundle and are recommended to be considered as the design develops to greater levels of detail.

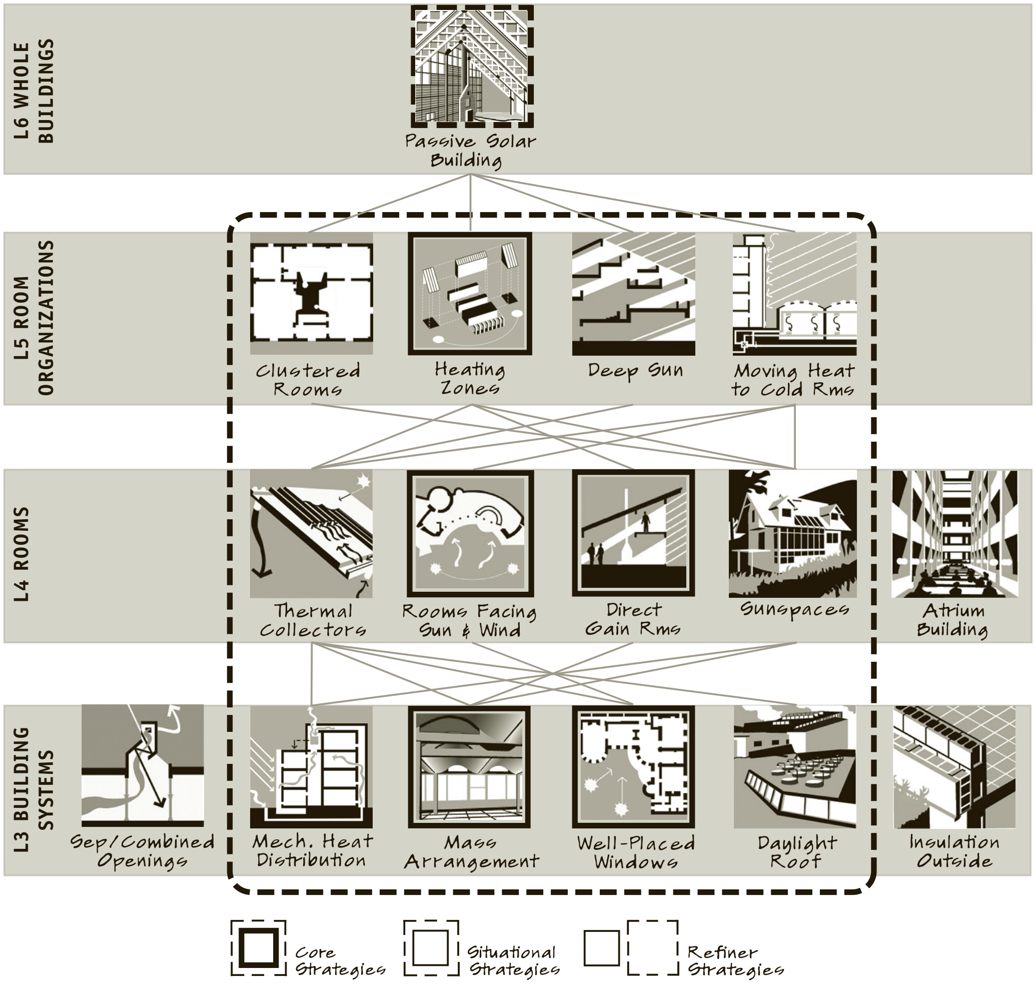
Because each strategy has a range of variables and can be adapted to variations in its context, the particular combination of strategies suggested for a bundle can yield thousands of formal outcomes. Similarly, the relationship of one strategy to another in a bundle will influence the way in which each strategy is applied. The designer fits one strategy to the others in the network of design strategies that forms the bundle.

How to read a bundle diagram

The example bundle diagram for a **Passive Solar Building: Thick Plan Bundle**, one of its two variations, illustrates these four organizational principles of a bundle.

The bundle organizes design strategies at multiple scales, covering three levels of complexity, from lower complexity L3 Building Systems, to L4 Rooms, to higher complexity L5 Room Organizations. This is shown in the range of grey bars on the diagram. Typically, the is also a range from smaller parts to larger wholes. The scale of L6 Whole Buildings is the contextual scale for this bundle and is the level where its particular emergent characteristics are evident.

The gray lines connecting the squares represent a particular kind of relationship between the strategies of lower and higher complexity. For example, the less complex strategies of SUNSPACES, ROOMS FACING THE SUN AND WIND and THERMAL COLLECTORS are all strategies for designing at the L4 Rooms scale; they help to build the more complex strategy MOVING HEAT TO COLD ROOMS, which operates



PASSIVE SOLAR BUILDING: Thick Plan Bundle

at the more complex scale of L5 Room Organizations to orchestrate heat distribution between rooms that collect heat and those that do not. SUNSPACES helps build MOVING HEAT TO COLD ROOMS, while the higher, deeper, larger strategy also depends on the lower, less deep, smaller strategy and its associates.

Note that, for simplicity, the relationship lines for refiner strategies are not shown in the diagrams, but they can be seen on the Design Strategy Maps. Also bear in mind that the bundles represent the most important associations of strategies, and that many additional strategies may be used. For more details of these relationships and their graphic depictions, see the section "Navigation by Design Strategy Maps."

Each graphic icon represents an individual design strategy in Sun, Wind & Light. The *core strategies* are shown with a bold outline: HEATING ZONES, ROOMS FACING THE SUN AND WIND, DIRECT GAIN ROOMS, MASS ARRANGEMENT and WELL-PLACED WINDOWS. These strategies will apply to almost all passive solar buildings of both variations.

The bundle has two situational variations, one for a *thick plan building* (shown in the diagram), in which a

significant portion of rooms do not face the sun, and one for a *thin plan building,* in which access to the sun by each room is easier. The *situational strategies* are located *within* the bundle boundary (bold dashed line); their icons have no border, for example: CLUSTERED ROOMS, SUNSPACES and MECHANICAL HEAT DISTRIBUTION. These design strategies will typically apply to one of the bundle variations, but not to all of the variations. The situational strategies are appropriate almost all of the time, yet not every strategy will be used on every project. For example, most thick plan buildings will need MECHANICAL HEAT DISTRIBUTION to move heat from rooms or surfaces that collect solar heat to remote rooms without direct access to solar heat, but a thin plan building can usually use passive radiation or local passive CONVECTIVE LOOPS to distribute heat.

Refiner strategies are less critical to the bundle's success or have less impact on architectural form than core or situational strategies. However, they may still have a large impact on performance, depending on the situation. The refiner strategies are located *outside* the bundle boundary (*bold dashed line*) and their icons have no borders: ATRIUM BUILDING, INSULATION OUTSIDE and SEPARATED OR COMBINED OPENINGS. For example, in a thick plan PASSIVE SOLAR BUILDING, a light court may be used in an ATRIUM BUILDING arrangement; the atrium may also double as a SUNSPACE to collect heat if its roof or one wall has SOLAR APERTURES oriented to the sun. This refiner strategy will not apply to all buildings, but if used, could improve the performance of the bundle.

Two broad types of Bundles

Bundles can be thought of in two main ways:

Topically focused Bundles are composed of strategies that are primarily related by their association with a particular climatic design issue, such as the way a daylighted building needs strategies that cross a range of scales. Bundles of this type include:

NEIGHBORHOOD OF LIGHT
SOLAR NEIGHBORHOOD
COOLING NEIGHBORHOOD
DAYLIGHT BUILDING
PASSIVELY COOLED BUILDING
PASSIVE SOLAR BUILDING

Topically integrated Bundles are related across multiple topics, such as the way the building envelope can address heating, ventilation, cooling and daylighting. Bundles of this type include:

OUTDOOR MICROCLIMATES
RESPONSIVE ENVELOPE

Situational variations

In theory, a bundle can have situational variations based on any variable that significantly changes the designer's response because of a relatively large change in the design situation. These could relate to the following situational factors, among others:

- *Different climates* (cold/hot, humid/arid, low/high altitude or continental/marine)
- *Rates of internal gains* (high lighting, people and equipment density vs. low density)
- *Occupancy schedules* (no summer use vs. buildings used all year, no weekends vs. seven days a week)
- *Morphological alternatives* (short/tall and thick/thin buildings, etc.)
- *Energy goals* (such as site net-zero energy buildings/net-positive energy buildings, etc.)

Bundle variations could also be based on combinations of these and other variables. The point is that when the situation changes significantly, the strategy family that is appropriate may also change.

It is also important for the user to remember that many of the *SWL* strategies already have built-in recommendations for differences in design response based some of the variables mentioned above. Therefore, in some cases, one strategy will apply to *all* situations. This is the root of the core strategies found in the bundle variations based on climate. As covered in greater depth in "Navigation by Climate" in Part II, one fundamental context for design used in *SWL* is the building's climatic region. Some bundles use climate as a situational differentiator. When using these bundles, refer to the basic climate types and guidance on their selection and/or combination found in "Navigation by Climate."

Bundles in the design process

When Bundles are used in a design process, they are a way of touching the bases to make sure that critical strategies in the network of the design have not been left out. This usually takes two forms:

1 The designer checks for the presence of the *family of strategies* needed for the success of one system, such as a solar-heated building, and that, at a minimum, nothing critical has been left out.

2 The designer checks that the major common *implications* of that system are accounted for, such as the extra attention to shading and glare needed when using large, sun-facing windows for collecting solar heat.

The *fundamental bundles* included in this edition are simply examples and not intended to represent an exhaustive list. However, they are based on decades of experience with designing and thinking about the best way to design climate-responsive buildings that use very little energy. Two things are certain in this regard: First, additional important bundles can and will be defined in the future, whether by the *SWL* authors or others. Hopefully, you will create your own bundles that work in your practice, climate and projects. Second, the details of each bundle could be written or defined in different ways. *SWL* takes a particular perspective and defines the design situation in a broad and generalized way so that the bundle might be widely applicable in a variety of building design situations. If you have a specific situation that calls for adaptation, by all means, adapt away!

Making Your Own Bundles

There are several ways to select bundles in *SWL*. First, the **Design Decision Chart** in Part II suggests a set of broad, topically integrated synergies that apply to almost all buildings almost all the time. The seven sets of questions there identify the bundles that help the designer explore design schemes based on the questions' themes.

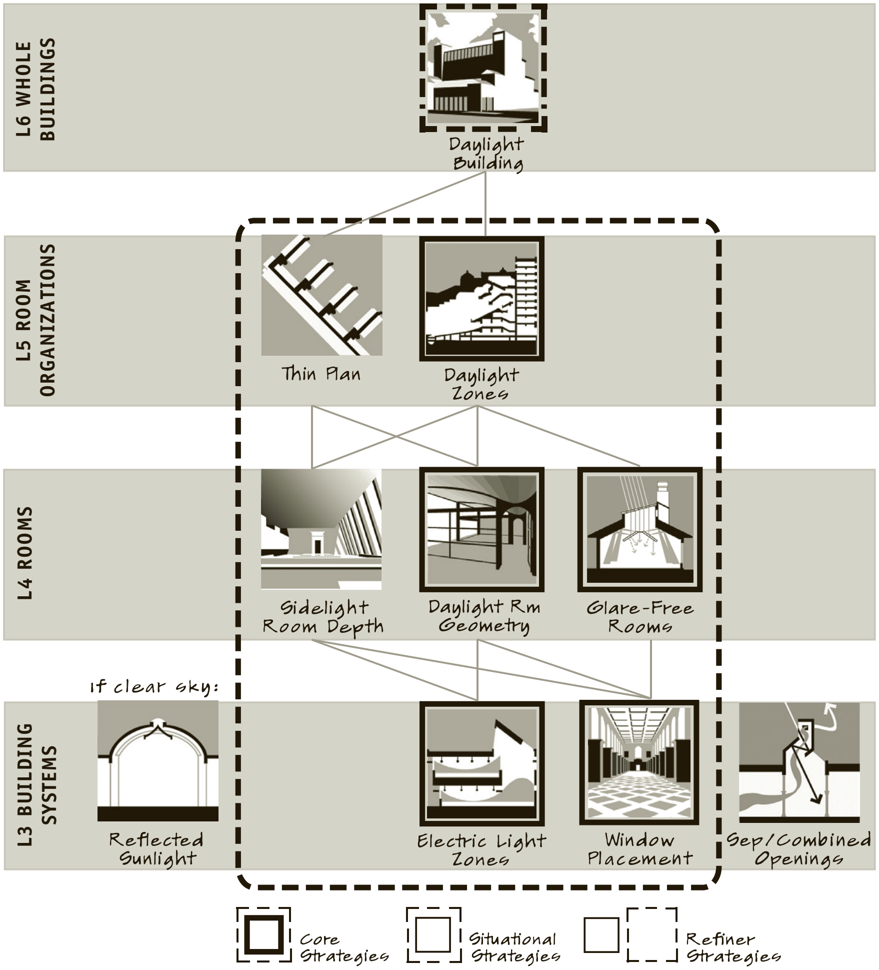
Second, each bundle is listed in the other navigation methods in Part 1, "Navigation"; so if the designer is working at a particular scale or is investigating a particular issue, such as cooling or daylighting, then the bundles most related to these concerns can be easily identified.

Third, designers oriented toward what works in a certain climate will find the "Navigation by Climate" section helpful in identifying bundles and their climatic variants that are most appropriate. Sometimes the fundamental bundles defined in this edition may not work for a particular project and the designer will want to construct a custom bundle or a set of custom bundles. A common example would be the custom bundle constructed for a mixed climate having both heating and cooling needs. The call for custom, make-your-own bundles is especially apparent in these mixed climates for two reasons: First, the hot climate strategies are further differentiated by arid vs. humid summers. And second, the weighting between heating and cooling concerns in mixed climates varies between about 5:2 and about 1:6; that is, from a heavy weighting toward cooling, with minor concern for heating, such as in Atlanta, Georgia, Zone 2A, to a heavy weighting towards heating with minor concern for cooling, such as in Minneapolis, Minnesota, Zone 6A. In such cases, first determine the weighted mix for the building in "Navigation by Climate."

Other combinations or hybrids of the bundle variations are possible and often appropriate. An example is the variations of SOLAR NEIGHBORHOOD, which are "Low Density Urban Fabric" and "High Density Urban Fabric." Clearly there can also be a "medium density urban fabric" between the two ends of the spectrum, calling for a custom bundle variation. In other cases, the designer may wish to invent new bundles or to add strategies not currently defined in *SWL*. On one hand, constructing custom bundles is an advanced art requiring substantial experience; on the other hand, it is a process done informally in every building design.

To construct your own custom design strategy bundle:

1) Define the design situation that the bundle addresses, usually a recurring problem in architectural design. This will be related to the "Forces" section of the fundamental bundles. For example in DAYLIGHT BUILDING, the situation



DAYLIGHT BUILDING: Thin Plan Bundle

is to design a building that maintains the geometric relationships between building and sky.

2) Name the bundle and write an action statement. Use the bold header statements in the *SWL* bundles as a guide. The action statement also captures the intention of the bundle. A bundle that cannot be named will not be memorable and may suggest that the design idea is not clear enough or powerful enough to have a significant influence on design. An example of an action statement is, “A DAYLIGHT BUILDING is organized to light itself with the sky using a family of strategies fit to place and purpose.”

3) Define the situational variations. One bundle will rarely if ever address all situations with a fixed set of strategies. Explore the range of variables that influence the context of the design problem and the strategies that one might use. From your own experience and viewpoint, select the *one* situational variable that has the greatest architectural form impact. Alternatively, choose the situational variable that is likely to have the greatest impact on energy or emissions performance—or on an issue defined by the designer. For example, the DAYLIGHT BUILDING bundle focuses on strategies that work best with *thin*

buildings, which can use primarily sidelight, and *thick buildings,* which most often require toplight.

4) Beginning with the blank* Bundle Diagram Form*, determine the scales at play in the bundle. The form is found on the following page. Any three scales in the nine-level system may be chosen. Write in the three scales that make up your bundle and the scale of the bundle itself (top band). For example, the DAYLIGHT BUILDING bundle organizes strategies at L3 Buildings Systems, L4 Rooms and L5 Room Organizations. The bundle itself is located at L6 Whole Buildings.

5) Fill in the square on the top level with the name of your bundle(s).

6) Make a copy of the **Bundle Diagram Form** for the other variation(s) you have identified. For example, the DAYLIGHT BUILDING bundle has a bundle diagram for each of two situational variations: "Thin Plan" bundle (shown on previous page) and "Thick Plan" bundle (see the B5 bundle spread). Fill in the blank on each form with the situation name.

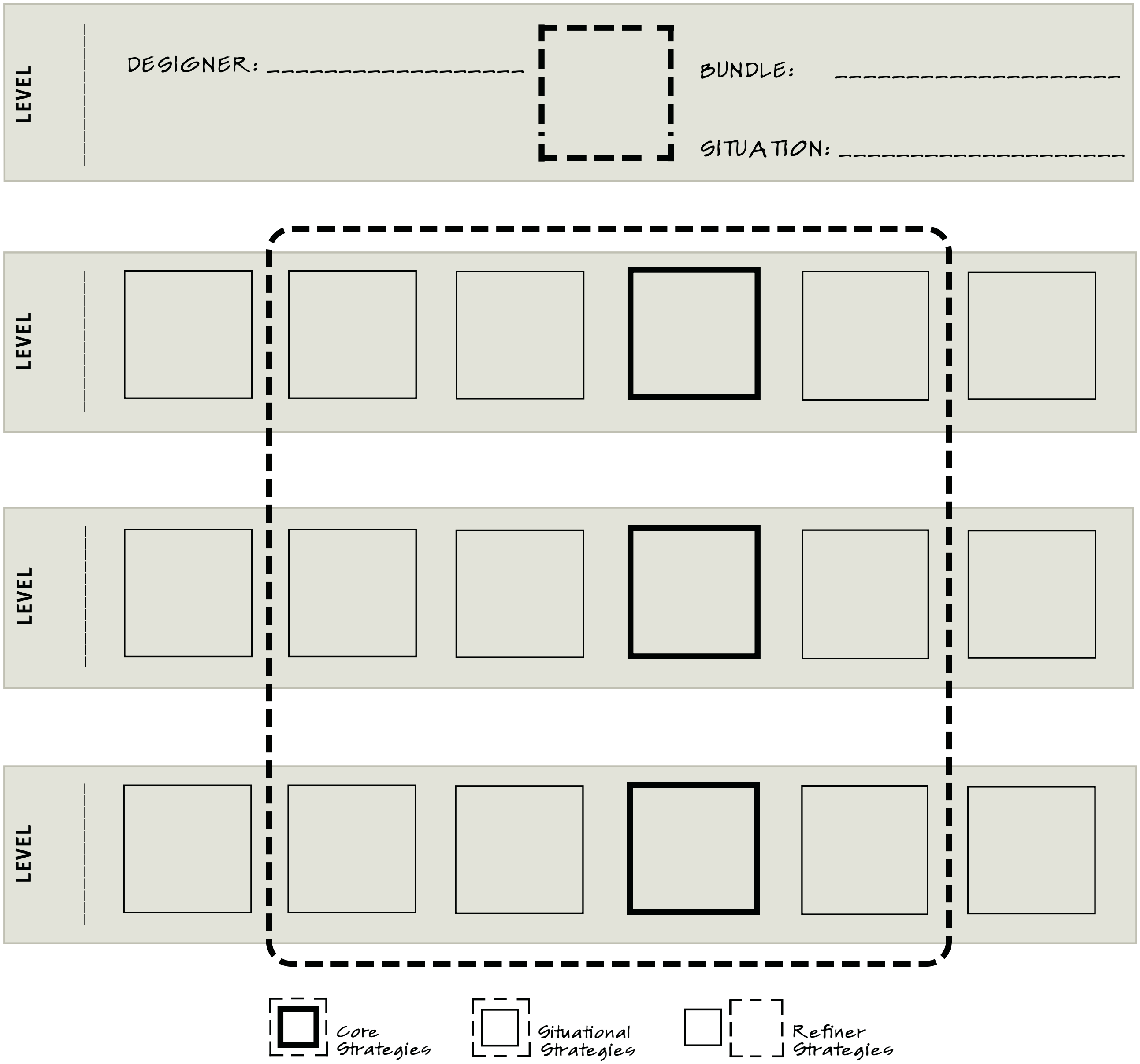
7) Complete the bundle in one of several ways. Depending on the designer, the route to bundle definition could be more or less linear. Some designers begin with the strategies that are already known and will most likely be used in the design. For example, in the Thin Plan variation on DAYLIGHT BUILDING, the THIN PLAN strategy is a given, see **Daylight Building: Thin Plan Bundle**. So this is a good place to start. Some strategies may be preselected; for example, the engineer may wish to use ELECTRIC LIGHT ZONES along with daylight as a way to save energy. Another designer may begin with a strategy that to her seems most essential to the success of the bundle. In any case, it is easiest to begin somewhere where the strategy is more known.

8) Now ask three kinds of questions:

- *What other strategies are essential to this bundle?*
  For example, from experience, it was known that DAYLIGHT ZONES applies to most buildings and would likely be helpful in the Thin Plan variation.
- *What smaller strategies does this strategy help to organize, or what lower level strategies does it help to organize, configure or relate?*
  For example, the THIN PLAN strategy depends on an appropriate SIDELIGHT ROOM DEPTH and a good DAYLIGHT ROOM GEOMETRY to establish room size and shapes that are organized into a plan.
- *What other strategies does this strategy help to build? Or what higher level strategies depend on it?*
  For example, proper WINDOW PLACEMENT, ideally on multiple orientations, helps build a GLARE-FREE ROOM.

9) Work on two or three variations of the bundle diagram simultaneously. As you add strategies related to one another, look for those strategies that occur in *each and every* situational bundle. These are candidates for *core strategies*. As these Core Strategies become clear, move them to the center of the diagram into the bold squares. For example, in the DAYLIGHT BUILDING bundle, five strategies will work in both the "Thin Plan" and the "Thick Plan" variations. Signified by the bold borders in the diagram, they are: DAYLIGHT ZONES, DAYLIGHT ROOM GEOMETRY, GLARE-FREE ROOMS, ELECTRIC LIGHT ZONES and WINDOW PLACEMENT. The **Bundle Diagram Form** provides space for these Core Strategies with at least one at each scale. Look for about 3–5 Core Strategies. If you find more than three—and this is common—add a bold border to the squares that contain them in a position adjacent to the printed central core square on that level.

10) Fill in the links between strategies. Consult the **Design Strategy Maps** in Part I for possible important linkages. Linkage lines in the *SWL* bundle diagrams define their nested relationships as outlined in "Navigation by Design Strategy Maps" in Part I, "Navigation." Many other kinds of relatedness are possible, including horizontal relationships within a level. Feel free to improvise on top of the structure provided and identify other kinds of relationships or associations and to represent these graphically. For example, conditional or impact relationships might be represented with directional arrows. In the largest sense, since bundles are simply configurations



Bundle Diagram Form

of relationships among strategies, the designer is free to define both the set of strategies and their significant relationships.

11) Look for ways to simplify the bundle. Can some strategies that are less important be moved to the *refiner strategy* squares or eliminated entirely? Do your Core Strategies work in all the bundle's variations? For example, when writing the DAYLIGHT BUILDING bundle, there were initially variations for "Clear Skies" and "Overcast Skies." It became apparent that very few of the daylighting strategies applied to only one sky condition and that many strategies applied to both or were a matter of degree. One strategy, REFLECTED SUNLIGHT, was primarily applicable to clear skies, it was moved to a Refiner Strategy status.

12) Share your draft custom bundles with your knowledgeable colleagues for feedback on what may be missing. Determine whether they agree with the core strategies you have chosen. Inquire into how they would propose to solve the problem that the bundle addresses. The fundamental bundles included in this edition were significantly improved and refined by peer input. Have fun improvising and inventing!

Bundles may combine strategies for *multiple integrated topical issues* (heating, cooling, lighting, ventilation or power) into associations that help the designer resolve the relationships among the issues. Often the relationships take the form of a context of conflicting forces. Such conflicting forces generate recurring questions for designers, some of which rise to what can be called "perennial questions," or concerns that are present over and over again in buildings.

In addition, bundles may combine strategies organized around a *single topical issue* (heating, cooling, lighting, ventilation or power) that are *linked across multiple scales* into associations that help the designer resolve the relationships among the issues.

Bundles answer the primary design questions:

- How do smaller and less complex strategies help to build larger and more complex strategies?
- How do larger, more complex strategies help or organize groups of smaller, less complex strategies?
- What strategies are critical at each scale for the building or neighborhood to work as a system with regard to the particular energy topic?

Traced for each of these bundles is the "flow" of the forces from where it arrives at the urban scale, down through a series of smaller scales to where it is used for heating, cooling, lighting or ventilation.

Some Fundamental Bundles

Each scale of design has a role to play in employing the forces of climate for human use. For example, in considering the neighborhood bundles it becomes clear that when the form of buildings blocks access to the sun, wind or light resources at any point before it reaches the photovoltaic array, the solar hot water collector, passive solar aperture, daylight aperture or ventilation aperture, the passive strategy at the building will fail. In this way, the levels of complexity are like the links in a chain.

Included on the pages that follow are these fundamental bundles, a few of the many possible:

NEIGHBORHOODS → URBAN FABRICS → URBAN ELEMENTS

B1 A *NEIGHBORHOOD OF LIGHT* configures the urban fabric in response to climate to provide daylight access for all buildings and the spaces between. [daylighting]

KEY POINTS

- Urban pattern can insure that daylight reaches each building.
- Open space proportions are the key daylight access variable.
- Daylight is closely connected to solar access and shading; thus, variations are driven by climate type.

CONTEXT

Each bundle helps build one or more larger strategies at the next scale of complexity. In our system of complexity, the scales above the neighborhood are truly urban and beyond the scope of the current book; these are the scales of Urban Quarter (a configuration of neighborhoods), City, Metro and Region. The design strategies for light at these more complex scales are yet to be defined. Speculatively, they might include strategies such as those to support clean air and reduce urban clouds or fog.

FORCES

In the USA, buildings are responsible for 70% of electricity use and an even greater proportion of peak energy use. The single most cost-effective way to reduce energy use in nonresidential buildings is the replacement of electric light, which constitutes about one-third of commercial building energy use, with daylight.

For any building to use daylight, it first needs access to daylight. This means that windows must be able to "see" enough of the sky, a simple idea that has enormous implications for neighborhood design.

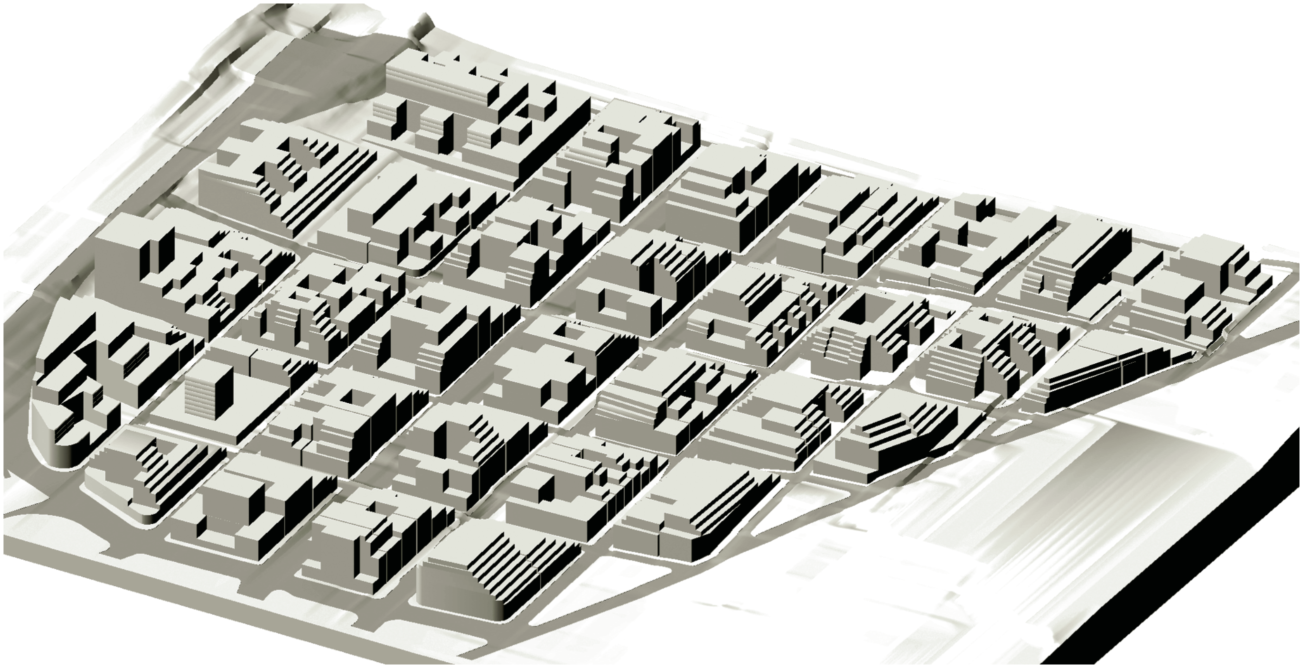
What would the form of our neighborhoods and urban districts be like if we were to take seriously the provision of free daylight to all buildings? Light has a behavior and a geometry; it has a logic and a rhythm. Built form has all these, too; the intersection of these logics—of light and form—creates a NEIGHBORHOOD OF LIGHT.

Light arrives to buildings from both the sun and the sky and from light reflected in the spaces between and around buildings. This geometry of window and sky in dense settings is driven by the proportions of the spaces between buildings. The design criterion, which varies with climate and the project's goals for indoor daylight, is to keep an appropriate sector of the sky dome visible to apertures. This can be done prescriptively, like the DAYLIGHT ENVELOPE, or performative ways, such as Boston's BRADA tool.

Sky exposure planes and daylight envelopes are the basis of almost all urban daylight planning regulations and zoning rules (DeKay, 1992). They limit heights of buildings along streets and, when based on rational criteria, tend to drive buildings to cover more of the site, so there is distance from building to the street. Buildings in a NEIGHBORHOOD OF LIGHT will tend to have strong relationships to the street and create pleasant, climate-moderated and active streets and public spaces. Regulating development for daylight access produces buildings of finer grain than does conventional development regulations, a pattern more prevalent in inner historic city districts prior to fluorescent lighting.

RECOMMENDATIONS

- ***Lay out neighborhoods by proportioning blocks, streets alleys and buildings to preserve the sky view from the building facade.***
- ***In colder climates, combine daylight access with solar access.***
- ***In hotter climates, combine daylight access with daylight-enhancing shading and reflection strategies.***



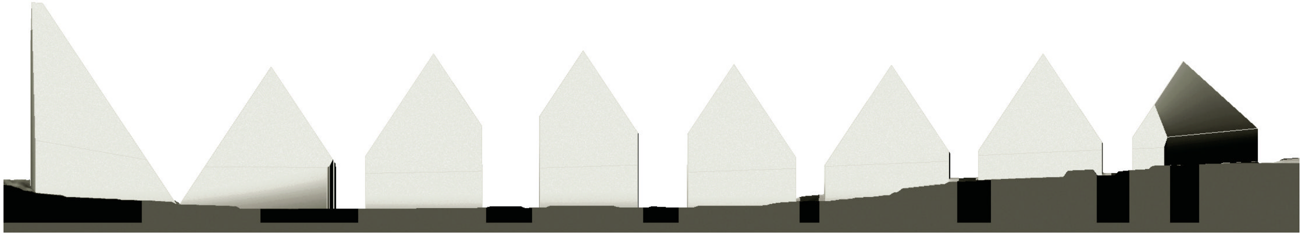
Hypothetical Daylight Development in Chattanooga, Tennessee, GreenVision Studio, 2006
View from southeast (looking towards northwest)

EXAMPLE

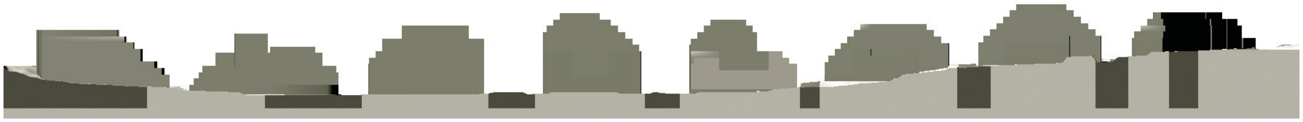
The **Climatic Neighborhoods Study of Chattanooga Tennessee's Downtown Plan** by GreenVision Studio (DeKay and Moir-McClean, 2003) shows that substantial increase in density is possible while protecting each street facade's access to daylight. The drawings in **Hypothetical Daylight Development in Chattanooga** show possible DAYLIGHT BUILDING massing configurations, generated by students, that satisfy composite CLIMATIC ENVELOPES (for both solar and daylight) and follow several daylighting design strategies, allowing good natural lighting for most rooms, while attempting to maximize development potential (DeKay, 2010).

Within the DAYLIGHT ENVELOPE, buildings can be taller on the wider streets. Relatively tall buildings, up to 14 stories, are possible along Broad St., while cross streets allow for 6 stories. The large parcels and the wide right-of-way along the highway (left side) create tall peaks on the district's western edge, so this is a good place for tall buildings. Buildings follow one of two patterns: buildings with THIN PLANS of 50–70 ft thick or ATRIUM BUILDINGS where the size of DAYLIGHT BLOCKS allow. The envelope peaks have been cut off where the size of the floor under the envelope was too small to be practically occupied. Light courts are shown without roofs, but in many cases, could be a TOPLIGHT ROOM covered in a glazed or partially glazed OPEN ROOF STRUCTURE. Often, though not always, we have located light courts with an open side to the south. This allows an occupied roof garden to be a sunny and wind-protected WINTER COURT. If the southern side of an atrium is lower than the north side it also works better as a solar heated SUNSPACE. Finally, students were instructed to add a certain amount of randomness, based in part on the underlying parcel sizes and configurations and on the patterns of existing development. Some blocks were treated as a single large building, others as two large sites, and some as composed of several smaller parcels.

In creating this speculative downtown NEIGHBORHOOD



Daylight Envelopes, East-West Section Looking North



Hypothetical Buildings Under Envelopes, East-West Section Looking North

Hypothetical Daylight Development in Chattanooga, Tennessee, GreenVision Studio, 2006

OF LIGHT, students attempted to maximize floor area ratio (FAR) within the development envelopes. Density analysis of the project is discussed in DAYLIGHT DENSITY.

CORE STRATEGIES

The core strategies apply to almost all neighborhoods and groups of buildings where the designer or planner has control over more than a single building. The daylighting-specific strategies are written to cover a wide range of variables for different climates; however, because heating or cooling strategies can affect lighting, there are two variations based on "Cold Climate" and "Hot Climate."

CLIMATIC ENVELOPE combines DAYLIGHT ENVELOPE with SOLAR ENVELOPE (cold climate) or SHADOW UMBRELLA (hot climate) or with both (temperate climate) to propose development envelopes that balance site resources.

DAYLIGHT DENSITY helps the designer configure streets, blocks and buildings to support light to each building. It demonstrates that while daylighting design may generate urban forms different from those generated by rules that ignore daylight, high density development is indeed possible. It combines DAYLIGHT BLOCKS and DAYLIGHT ENVELOPES into a composite pattern.

DAYLIGHT BLOCKS helps the designer determine block sizes based on daylighted building form or, conversely, to fit appropriate daylight massing of buildings to existing block dimensions.

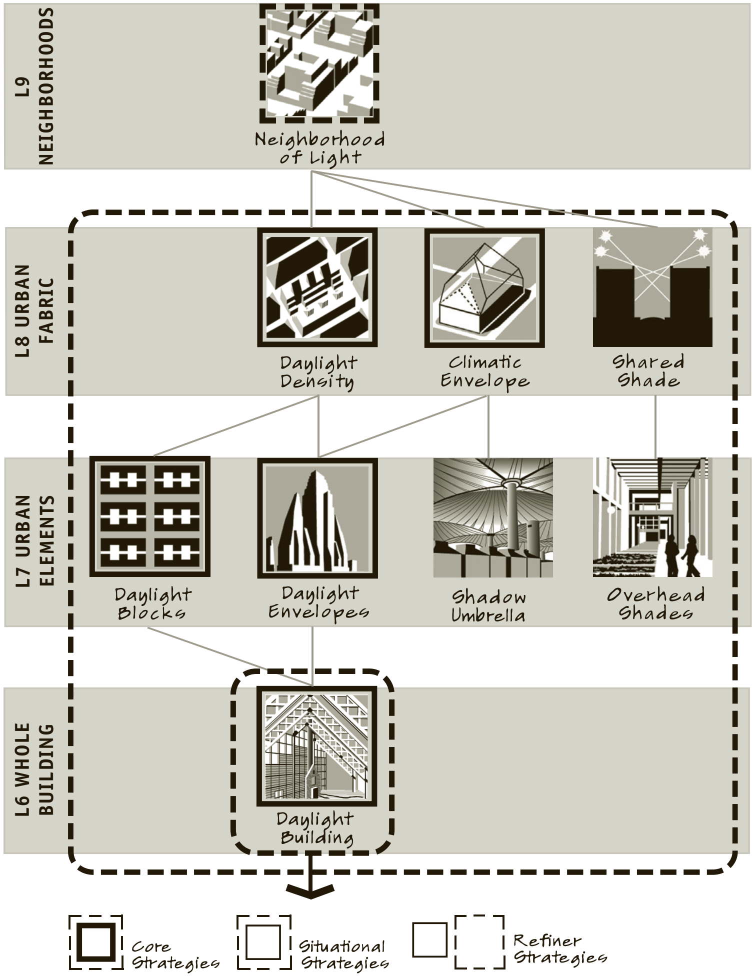
DAYLIGHT ENVELOPES is perhaps the *most* critical strategy in this bundle. It creates a three-dimensional development envelope that, if building massing is kept within it, insures that all surrounding buildings will get adequate access to daylight. It can be applied at the building or block scale, depending on which adjacent facades are being protected.

DAYLIGHT BUILDING is itself a bundle of numerous strategies in the sequence from sky to interior surfaces. Each scale along the way is critical to effective daylighting. It offers combinations of strategies for THIN PLAN and thick plan buildings [ATRIUM BUILDING and TOPLIGHT BUILDING].

SITUATIONAL STRATEGIES

Variations Based on Hot and Cold Climates

Depending on the climate, access to daylight has to be balanced against access to sun, which on some orientations may be more restrictive, and against needs for shade, which for some geometries can reduce the available daylight. For this reason, and perhaps counterintuitively, we have selected hot and cold climates for the variations, rather than clear and overcast skies.



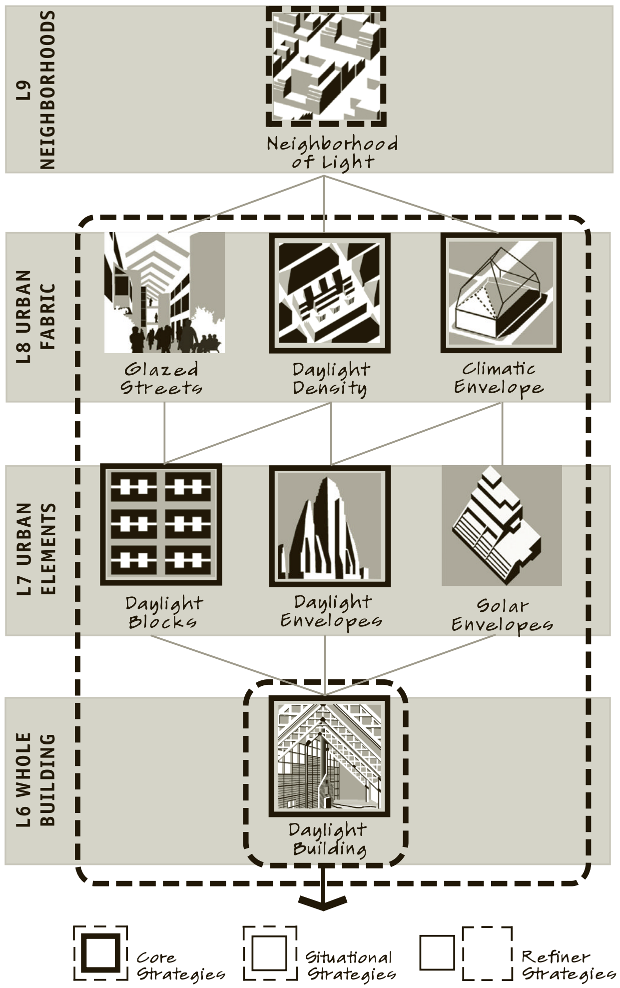
NEIGHBORHOOD OF LIGHT: Hot Climate Bundle

Urban scale research on daylighting design is not well developed. Most studies use overcast conditions. Clear sky cities are still able to use the strategies given here because, "without the sun," illuminance from the clear sky is similar to that of overcast skies at the same latitude; however, the distribution of that light over the sky dome is different [see DAYLIGHT AVAILABILITY and SKY COVER]. The clear sky makes for uneven and changing light, a pattern to which the building envelope scale can respond.

In terms of design, a clear sky climate often has very bright, glare-inducing outdoor light, so many of the shading strategies in COOL NEIGHBORHOOD are appropriate, as they also reduce daylight levels. In warm clear sky climates, consider OVERHEAD SHADES and SHARED SHADE. However, take care not to reduce the light to the daylight apertures too much by shading strategies at any scale [DAYLIGHT ENHANCING SHADES].

1. Hot Climate NEIGHBORHOOD OF LIGHT Bundle

Designing for access to light in a hot climate tends to limit building height along the street edges. This



NEIGHBORHOOD OF LIGHT: Cold Climate Bundle

is good if winter solar access is desired, but care must be taken not to be overprotective of daylight at the expense of shade.

Hot Climate Situational Strategies

SHARED SHADE helps designers size height to width (H/W) ratios for shading streets and adjacent buildings in hot climates. Compare the H/W needed for DAYLIGHT ENVELOPES with the H/W needed for shading criteria. DAYLIGHT APERTURES facing shaded streets can be enlarged to account for less daylight availability.

SHADOW UMBRELLA provides building massing strategies for shading open spaces. Open spaces, such as courtyards help bring light to rooms on the interior of a site. Remember that the same principles of daylight access can be applied to open spaces as those applied to streets.

OVERHEAD SHADES are elements in the horizontal plane for shading high sun in the middle of the day. When H/W is small and space between buildings large, ample light is provided, but overhead shade is often required. Consider this strategy along south facades and for pedestrian circulation along the north side of streets.

Northern City Center: newer coarse grain buildings with leisure and educational uses

SVF Equiv. H/W Ratio
0.8 = open space or roof
0.7 = 1.2
0.6 = 1:1.75
0.5 = 1:1.15

SVF Equiv. H/W Ratio
0.4 = 1:1.125
0.3 = 1:1
0.2 = 1:0.75
0.1 = 1:0.5

Passive zones (light gray) < 6 m from facade

Nottingham City Center Analyses: Sky View Factor Mapping (left) and Passive Zones (right)

2. Cold Climate NEIGHBORHOOD OF LIGHT Bundle

Cold climate neighborhoods have to provide access to both daylight and direct-beam sunlight. This situational bundle adds three strategies.

Cold Climate Situational Strategies

GLAZED STREETS in cold climates provide wind protected BUFFER ZONES for buildings and function like a linear atrium [ATRIUM BUILDING] that will be hotter than outside. They are generally not appropriate for hot climates as they perform these same functions in summer.

SOLAR ENVELOPES regulate building massing to protect the neighboring buildings' access to winter sun and in some cases, year-round for PV and solar hot water. Since DAYLIGHT ENVELOPES are orientation neutral and SOLAR ENVELOPES are solar orientation specific, this relationship is resolved by CLIMATIC ENVELOPES.

Cold Climate Example

The Martin Center at Cambridge University conducted morphology studies for the ***Nottingham City Center Urban Design Guide*** (Urbanism, Environment and Design, 2009). They analyzed the existing urban fabric for *sky view factor* (SVF) and for *passive zones*.

The images in **Nottingham City Center Analyses** shows sky view factor mapping and passive zones based on analyses from 3D digital models using image analysis techniques. The *sky view factor* indicates how much sky is visible from each street. According to the Martin Center “A low SVF creates a feeling of density and enclosure and a sheltered microclimate, but reduces natural daylighting and solar gain so increasing energy usage.” Higher sky view factors allow more light and sun to buildings and streets and reduce the need for electric lighting and mechanical heating. Higher SVFs can also increase both summer and winter winds and reduce urban shade, a benefit in winter, but a liability in summer. For more on SVF,

Historic Core: fine grain buildings with retail/food areas

SVF	Equiv. H/W Ratio	SVF	Equiv. H/W Ratio
0.8 =	open space or roof	0.4	= 1:1.125
0.7 =	1.2	0.3	= 1:1
0.6 =	1:1.75	0.2	= 1:0.75
0.5 =	1:1.15	0.1	= 1:0.5

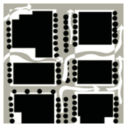
Passive zones (light gray) < 6 m from facade

Nottingham City Center Analyses: Sky View Factor Mapping (left) and Passive Zones (right)

see the COOLING NEIGHBORHOOD bundle, and the DAYLIGHT ENVELOPES and DAYLIGHT APERTURES strategies.

Passive zones are defined in Nottingham as "the proportion of a building's floor area that can be naturally daylit, heated or ventilated," identified as floor areas within 6 m (20 ft) from the facades. Deep plan buildings with low ceilings require more electric lighting [DAYLIGHT ROOM DEPTH] and typically, more mechanical heating [unless designed for DEEP SUN] and more mechanical cooling [unless designed as PERMEABLE BUILDINGS], significantly increasing their energy use. The passive zone analysis shows how the historic core works far better for passive strategies than the large buildings in the northern part of the city center.

In response to this analysis, Nottingham's urban design guide addresses both passive design and traditional urban design issues. Building heights are limited to 5–8 stories for residential and 4–6 stories for commercial buildings. Their desired sense of street enclosure further limits buildings heights along streets in proportion to their width (H/W ratio). These range from 1:0.5 (H/W = 2) on alleyways to 1:2 (H/W = 0.5) on multilane arterials. High (commercial) streets are limited to 1:1 (H/W = 1). This has the effect of preserving better SVF. Design rules call for commercial buildings limited to 12 m (39 ft) deep for single story spaces with windows on both sides and 8 m (26 ft) deep if lighted from one side or on narrower streets. Single exposure residential occupancies are limited to 6 m (20 ft) depth and are prohibited on northerly facing streets. Minimum glazing ratios for daylight are set at 30–50% of the elevation, depending on orientation.



B2 A *COOLING NEIGHBORHOOD* configures the urban fabric in response to climate to promote passive cooling for all buildings and the spaces between. [cooling]

KEY POINTS

- Both minimizing solar gains and maximizing night sky exposure are important to urban cooling.
- Arid climates can benefit from urban water strategies while humid climates may not.
- Trees and colonnades can improve cooling in most urban fabrics.

CONTEXT

Each bundle helps to build one or more larger strategies at the next scale of complexity. In our system of complexity, the scales above the neighborhood are truly urban and beyond our scope; these are the scales of Urban Quarter (a configuration of neighborhoods), City, Metro and Region. The design strategies for cooling at these more complex scales are yet to be defined. Speculatively, they might include strategies such as those to support clean air, reduce anthropogenic heat sources, preserve regional tree cover, intersperse neighborhoods with larger parks and locate tall building districts downwind from lower height districts.

FORCES

If buildings are to be passively cooled, they need maximum summer shade and access to cool outside air, whether that is wind for cross-ventilation or clean, cool outdoor air to feed stack-ventilation. At night, outdoor surfaces need a way to be cooled; in the day, pedestrians require cool microclimates.

The design of urban neighborhoods can either make the outdoor climate more intense and uncomfortable or more moderate and comfortable. The effect of urban design on microclimate can make air quality worse and buildings more expensive to operate, or it can help clean the air and help buildings be more energy efficient. In many places, urban development replaces vegetation with asphalt and buildings. Cool, transpiring green surfaces are replaced with heat-absorbing dark surfaces and heat-storing massive surfaces such as concrete. Taller buildings in the inner city block the wind, create more friction and reduce the ability of other buildings to lose heat to the night sky. This causes the urban heat island effect in which central city temperatures are significantly hotter than the surrounding countryside. Higher summer temperatures increase energy costs and health risks.

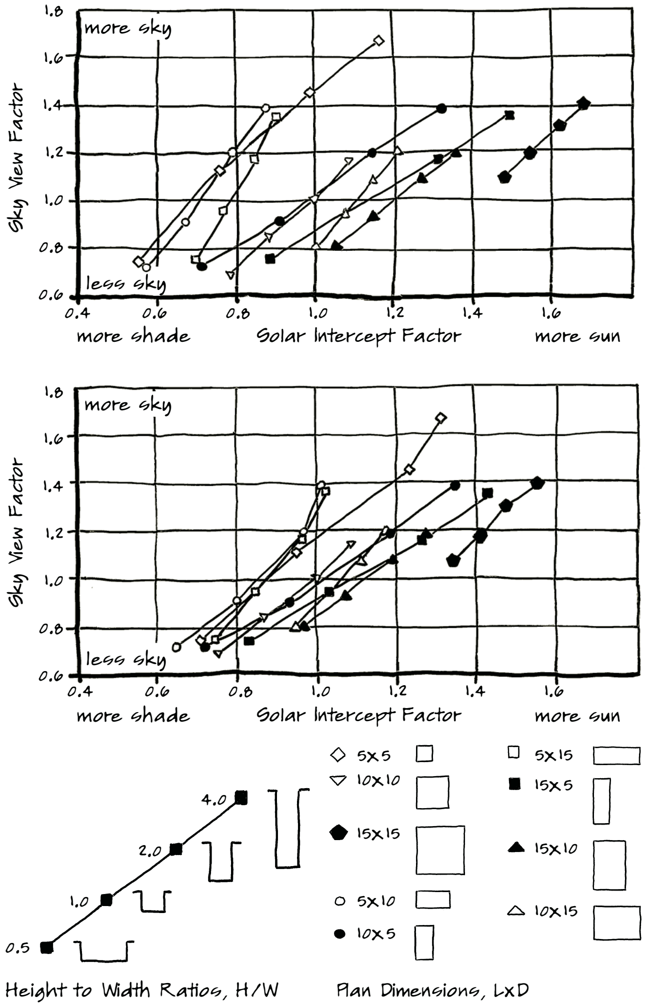
RECOMMENDATIONS

Integrated effects. Building form, particularly the roof area and east and west wall areas exposed to the sun, affect the cooling load in summer.

An urban fabric that uses taller buildings (thus less roof area) organized in* EAST–WEST ELONGATED BUILDING GROUPS *and with buildings having* EAST–WEST PLANS *(less east and west wall area) reduces summer solar gains and increases winter gains. This is particularly important in mixed climates.

On the other hand, if winter heat gain is not a priority, and if the height to width ratio (H/W) is large enough, narrow north–south streets can create* SHARED SHADE *such that longer east and west facades are much less a heat gain liability.

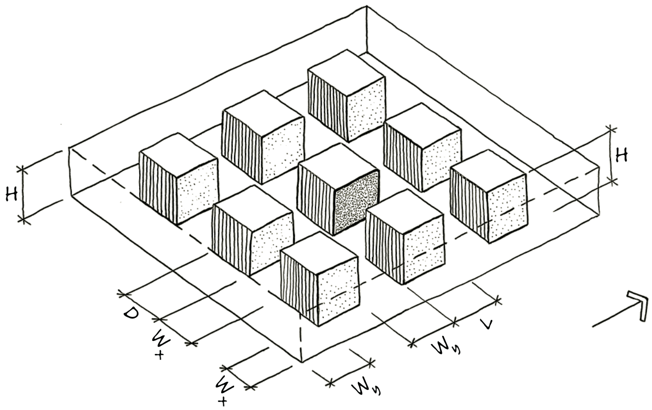
This variation is more appropriate at tropical latitudes or where cooling is needed year round. One of the conflicts in designing COOLING NEIGHBORHOODS in both humid and arid climates is the tension between low building height to width ratios (H/W), which increase the sky view factor and are good for daylighting and radiant cooling, vs. high H/W ratios (taller buildings with narrower spaces



Solar Intercept Factor vs. Sky View Factor for Building Groups

between), which are good for reducing solar gain. In general, larger H/W creates more shade, cooler daytime street temperatures, less solar gain, lower wind speeds, less daylight access, greater increases in the night time urban heat island, and less night sky cooling. A smaller H/W ratio will have the opposite characteristics.

The combination of *efficient building form* that minimizes solar exposure and building-to-building relationships with open *sky view factors* that encourage night cooling and promote wind flows are the fundamental

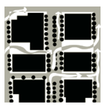


Reference Model for Graphs: 9 structures, evenly spaced, surrounded by wall = H, plan = LxD

urban morphology variables for a COOLING NEIGHBORHOOD. Similar results can be achieved with different combinations of these two factors.

The graphs of **Solar Intercept Factor vs. Sky View Factor for Building Groups** (Mills, 1997) demonstrates the relative cooling potential of a range of different organizations. The study compares different building shapes for the same total volume, combined with a range of building spacings. On the *solar intercept factor (SIF)* scale, lower values mean less sun on the building surfaces and less solar heat for the cooling load. On the *sky view factor (SVF)* scale, lower values mean less view of the sky, thus less daylight and less night sky radiant cooling. Both of these factors are significant indicators for cooling urban neighborhoods.

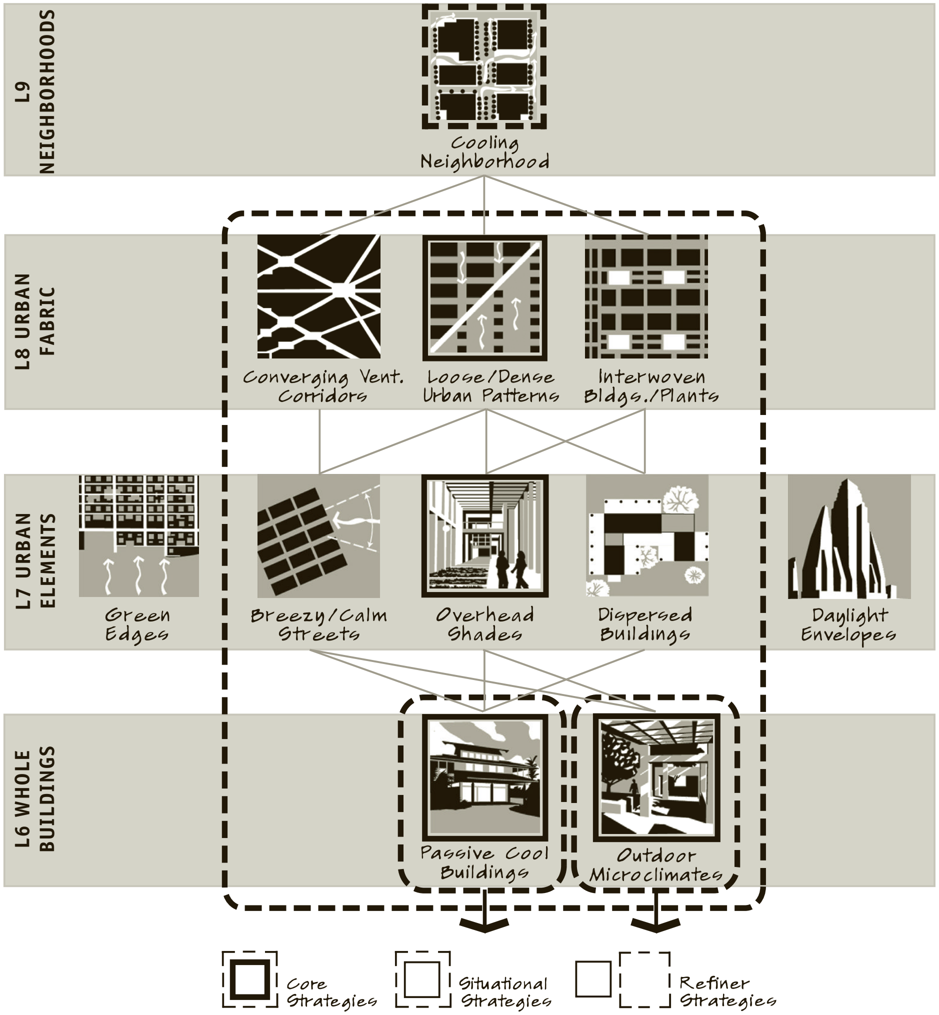
In a hot climate, a building group fabric with a combination of high cooling potential (high SVF) and low solar load (low SIF) is ideal. Configurations on the upper left of the chart perform best.



CORE STRATEGIES

There are four strategies that form the core of both variations on this bundle.

LOOSE OR DENSE URBAN PATTERNS sets the basic wind regime in the fabric for streets parallel to the wind. The blockage ratio is a function of the height of buildings, the area of their faces to the prevailing wind, and the width of

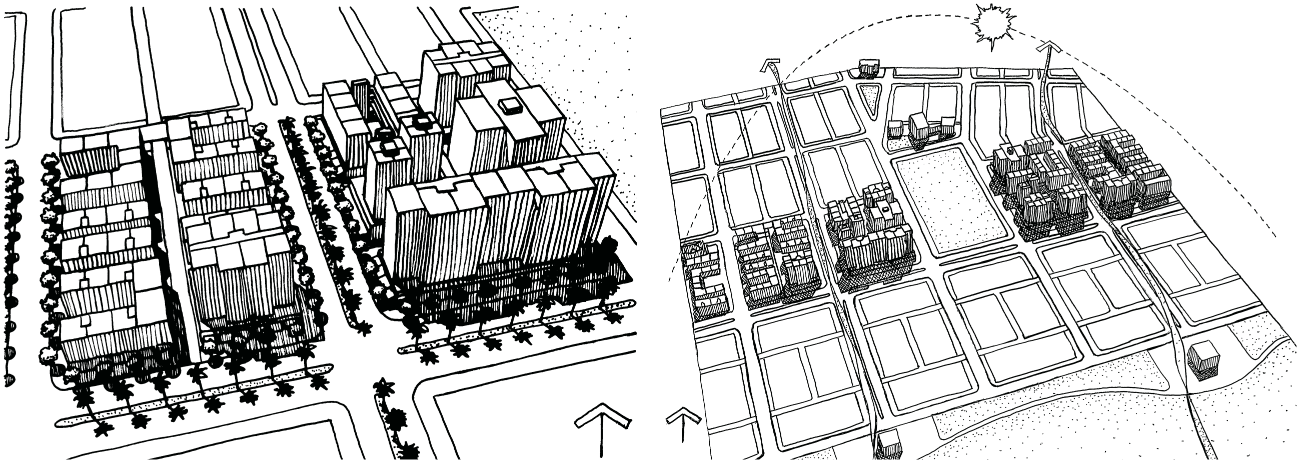


COOLING NEIGHBORHOOD: Hot-Humid Climate Bundle

streets. Wider streets, lower buildings and narrower faces to the wind create more wind in the streets. This is especially significant for the windward edge of building groups, which can be designed to allow winds to pass into the fabric of the neighborhood. This strategy is modified by BREEZY OR CALM STREETS and by the concerns for H/W and building form covered below. Good air movement through streets is important in all hot climates.

OVERHEAD SHADES is a particularly important strategy for shading of pedestrian circulation, of smaller open spaces and of buildings where H/W admits significant sun, such as the south facade (N in SH). Both built shade, such as arcades, and vegetation such as street trees, cool the afternoon air; but as the urban canyon (H/W) increases, the cooling effect diminishes.

PASSIVELY COOLED BUILDINGS are both the benefactors of a cooling neighborhood and help to create its pattern. It is its own bundle of smaller strategies for cooling



Mount Peter Tropical Urbanism, Cairns, Queensland, Australia, DPZ Pacific and Seth Harry Assoc., 2010

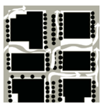
buildings in both humid and arid situations.

OUTDOOR MICROCLIMATES benefit from the larger cooling neighborhood strategies that form its context and block or admit forces of sun, wind and light. It is also a bundle of smaller strategies that shapes outdoor comfort.

SITUATIONAL STRATEGIES

Variations Based on Hot–Arid and Hot–Humid Climates

This bundle may be varied by whether the neighborhood is located in a "Hot–Arid" or a "Hot–Humid" climate. In composite humid–arid climates, such as in west India, which shift seasonally dry to wet with the monsoon, the designer will need to construct a project-specific bundle using both. In mixed heating and cooling climates (the majority of the United States), COOLING NEIGHBORHOODS are balanced by concerns in SOLAR NEIGHBORHOOD. Also see INTEGRATED URBAN NEIGHBORHOOD for advice on multiple urban climatic issues.



1. Hot–Humid COOLING NEIGHBORHOOD Bundle

The hot-humid bundle focuses on reducing solar gain and ventilating.

Hot-Humid Situational Strategies

CONVERGING VENTILATION CORRIDORS is a topographic strategy encouraging cooler air from upslope and outlying areas to drain toward the more built-up areas creating a kind of urban stack effect where polluted hot air rises. Large green source areas draining to green corridors and wide avenues are required.

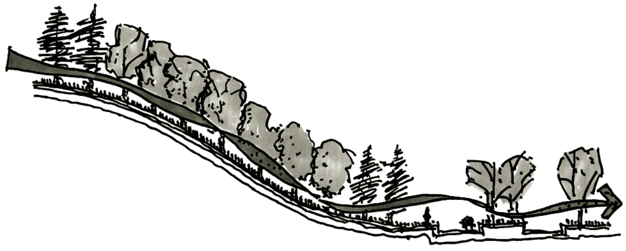
INTERWOVEN BUILDINGS AND PLANTS has two components: green areas *concentrated*, such as in parks, and *distributed*, such as street trees. Plants cool by shading and by evaporation.

BREEZY OR CALM STREETS help designers configure and orient streets to either promote or retard air movement This is important to cool the spaces between buildings and to provide air to buildings for natural ventilation.

DISPERSED BUILDINGS help preserve each building's access to breezes. Combined with breezy streets it makes a composite pattern.

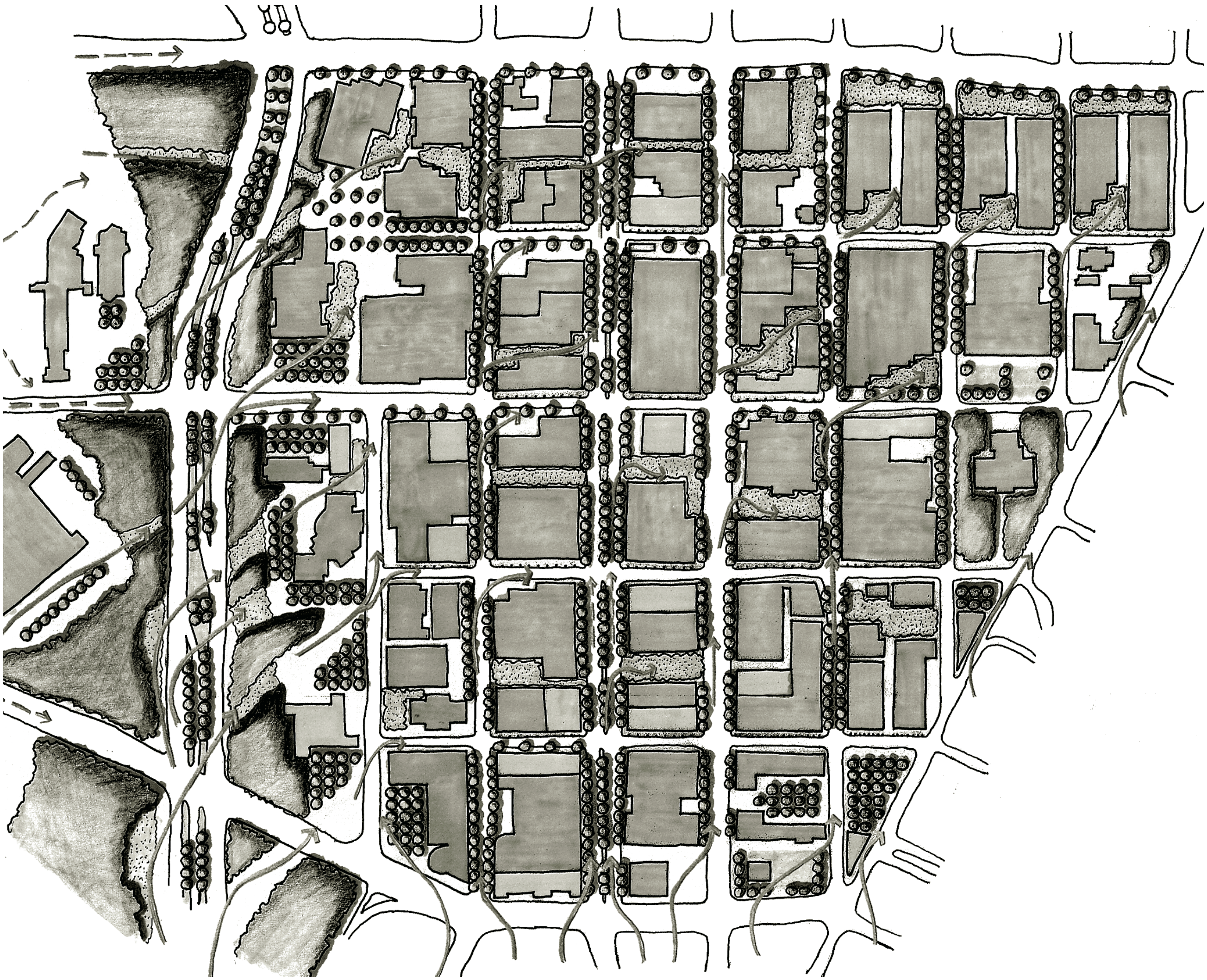
Hot–Humid Example

The **Mount Peter Tropical Urbanism Study** developed design guidelines for urban development in the hot–humid tropics of Cairns, Queensland, in northern Australia (DPZ Pacific and Seth Harry, 2010). The study draws heavily on strategies from *Sun, Wind & Light,* 2nd edition. The example application of the guidelines shown above combines BREEZY STREETS orientation with wide streets for wind flow [LOOSE URBAN PATTERNS] with shady sidewalks [overhead shades]. Wind brings cool air from undeveloped land



Night flow from green slopes cools downtown

down wide avenues, similar to CONVERGING VENTILATION CORRIDORS. Blocks are oriented so that buildings' short sides face east and west [EAST–WEST ELONGATED BUILDING GROUPS] and are interspersed with greens of different sizes [INTERWOVEN BUILDINGS AND PLANTING]. Buildings are staggered on lots so as to direct air flow across the fabric and courts are wide [BREEZY COURTYARDS], while building types are selected to facilitate PERMEABLE BUILDINGS.

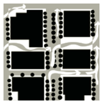


Downtown Cooling Plan for Chattanooga, TN, GreenVision Studio, 2006

Mixed–Humid Example

The **Downtown Cooling Plan for Chattanooga** by Green-Vision Studio (DeKay and Moir-McClean, 2006) shows an integration of numerous urban design strategies to adapt the existing urban fabric to create a cooler summer OUTDOOR MICROCLIMATE and to help distribute winds to more PASSIVELY COOLED BUILDINGS. There are five basic ideas to this approach:

1 Heavily plant the western undeveloped slopes with open understory trees [GREEN EDGES] for night flow from green slopes to CONVERGING VENTILATION CORRIDORS.
2 Cool the downtown district by increasing dispersed vegetation [INTERWOVEN BUILDINGS AND PLANTS], which takes the form of street trees, urban forests and green squares and parks.
3 Disperse wind throughout the urban fabric by creating passages in the middle of blocks and in-between buildings [DISPERSED BUILDINGS] and by encouraging a “densify and withdraw” pattern over time that opens the southwest corners of blocks to help redirect breezes. [LOOSE OR DENSE URBAN PATTERNS]
4 Disperse wind throughout the urban fabric by using landscaping and open space patterns to direct wind to cross streets. [BREEZY AND CALM STREETS]
5 Build on and extend the pattern of cross-block pedestrian mews, providing OVERHEAD SHADES and north–south alleyways that provide SHARED SHADE.

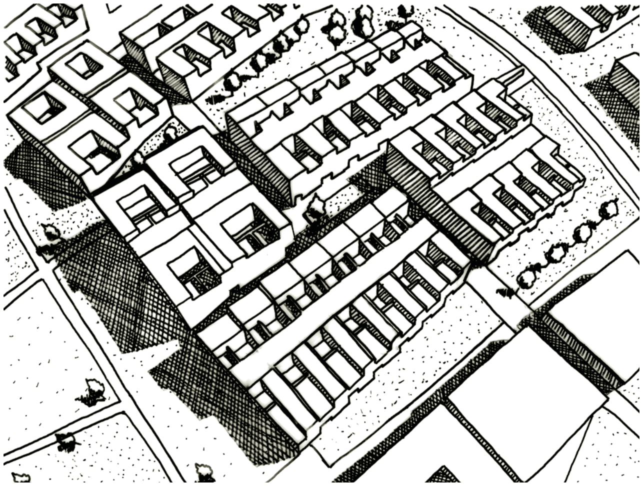


2. Hot–Arid COOLING NEIGHBORHOOD Bundle

As in hot-humid climates, shading is important in hot-arid climates, but the skies are clearer and the sun often more intense. Similarly, wind access is important, but the air can be very hot at times and dust-laden. These factors combine to shift the strategies more toward shade and less toward ventilation. Evaporative cooling strategies also become available in arid climates.

Hot–Arid Example

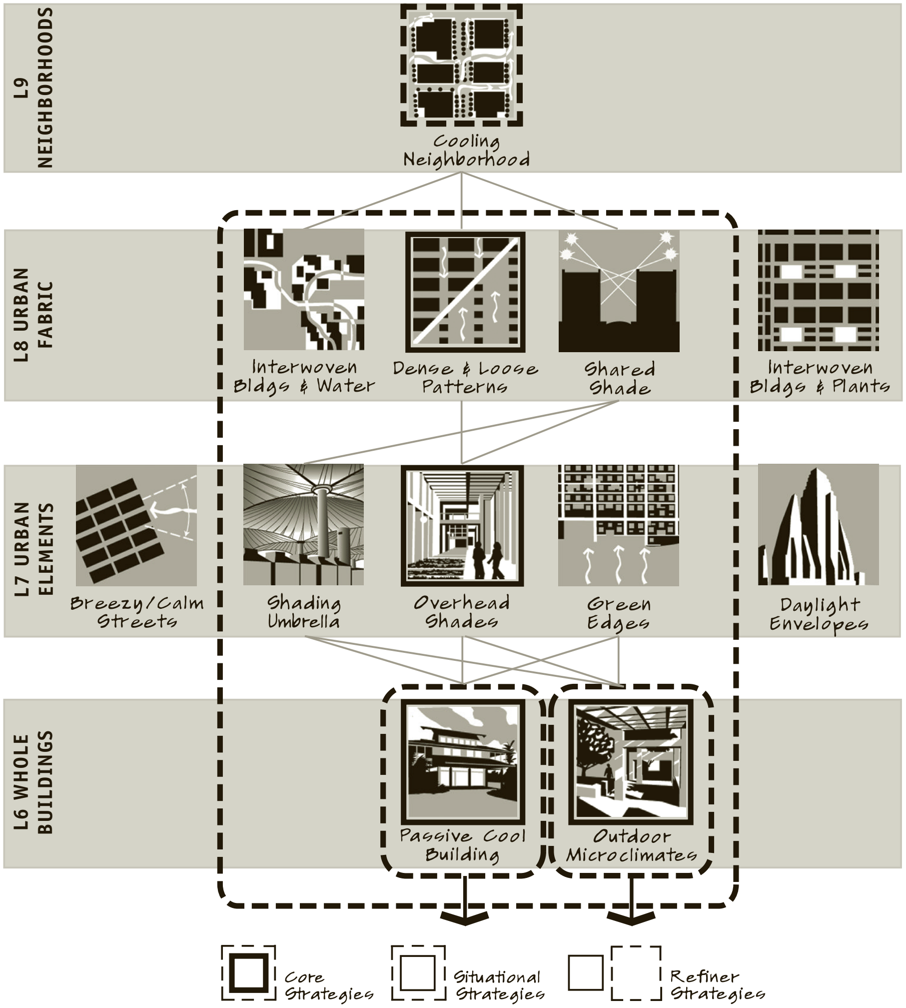
The German-Iranian research project, Young Cities, developed a master plan for a 35 ha (87 ac) area, applying climate-sensitive urban form and culturally adapted building typologies for reduced heating and cooling in the **Hashtgerd New Town** in the Tehran province of Iran (Young Cities, 2011; Seelig, 2011). Like traditional towns in the region, the quarter takes on a compact DENSE URBAN PATTERN, as shown in the **Neighborhood Cluster** drawing, where 29 compact neighborhood clusters are organized along north–south primary roads with each cluster defined by a central SHADY COURTYARD of 15 m x 30 m (49 ft x 98 ft) and surrounded by four building groups. See also the **Site Plan, Hashtgerd New Town** on the next spread. Narrow 6 m (20 ft) wide streets, running N–S connect the courts, giving SHARED SHADE. The arrangement of buildings blocks the prevailing western/northwestern winds and the hot, dusty southeast summer winds while admitting cooler north–south winds from the Alborz Mountains. Solar exposure is minimized by longer south facades [EAST–WEST ELONGATED BUILDING GROUPS], giving each unit winter solar access. INTERWOVEN BUILDINGS AND PLANTING is achieved by a variety of green spaces and tree planting, including constructed wetlands for waste water recycling.



Neighborhood Cluster, Hashtgerd New Town

Hot-Arid Situational Strategies

INTERWOVEN BUILDINGS AND WATER can reduce air temperatures if the water is either very large, such as a large lake



COOLING NEIGHBORHOOD: Hot-Arid Climate Bundle

or ocean with winds blowing over it, or if it is located within semi-enclosed spaces, such as courtyards.

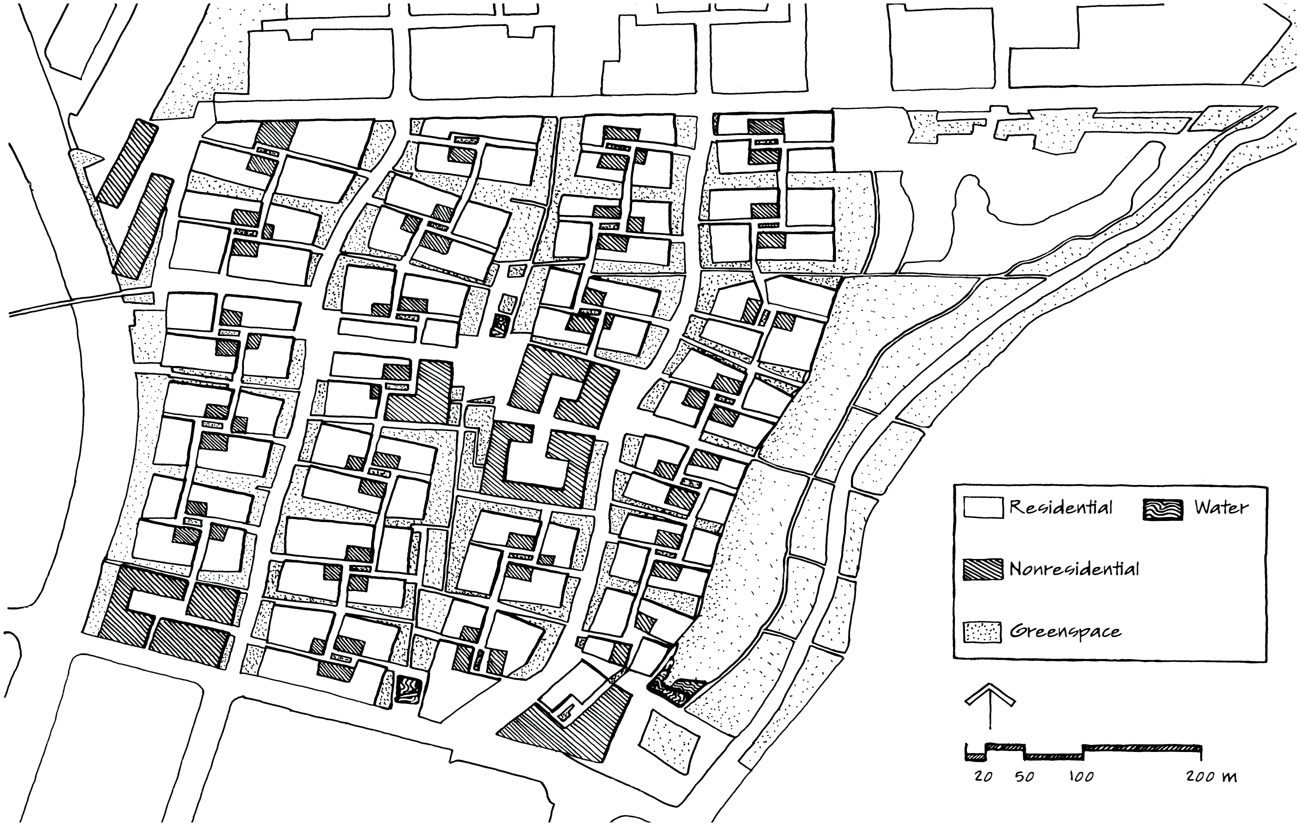
SHARED SHADE helps designers configure buildings to shade each other, particularly on north-south streets.

SHADING UMBRELLA works similarly to shared shade, but on a smaller scale by providing shade to particular open spaces or courts by shaping surrounding buildings and edges to cast shadows.

GREEN EDGES of vegetation can cool incoming breezes if relatively large and especially if irrigated and/or shaded. When located leeward of the built neighborhood, the green edges can also help to remove dust.

RECOMMENDATIONS

Integrated Cooling Effects. A more sophisticated measure than H/W ratio was developed by Shashua-Bar, et al (2006) and is defined as the *envelope ratio*. It is the ratio of the ground area between buildings to the total surface area of the ground and walls, including any articulations



Site Plan, Hashtgerd New Town, Iran, Young Cities Project, 2011

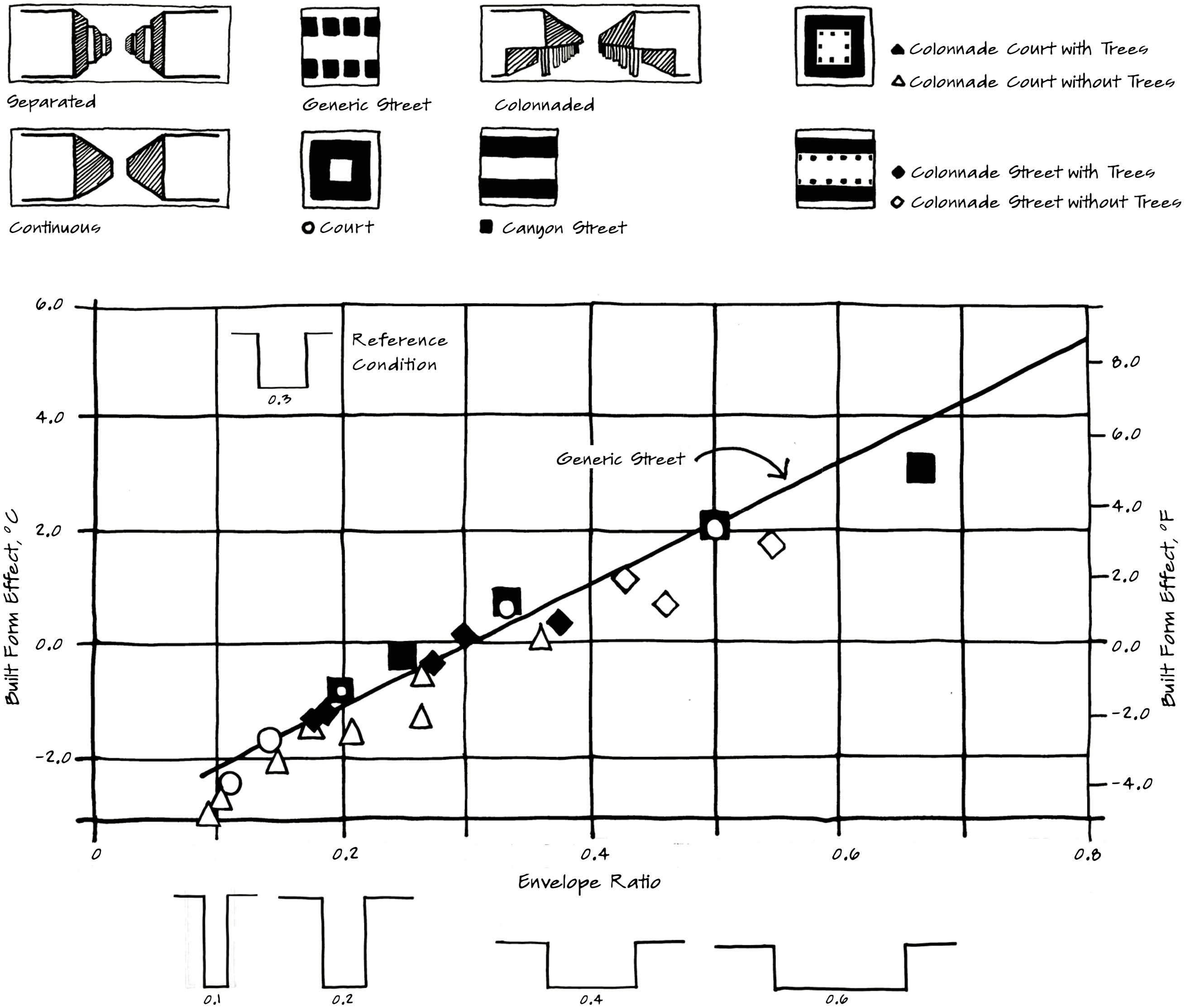
such as with colonnades.

Design for low envelope ratios on N–S streets, but balance with daylight access criteria. On E–W use low envelope ratios (0.1–0.3) in hot climates. In mixed climates, use medium envelope ratios (> 0.3) but remember to limit these ratios to ensure winter solar access. In all cooling climates, use colonnades along street edges and/or trees for shade, especially for built form envelope ratios greater than 0.4.

The graphs of **Cooling Effects from Built Form** and **Cooling Effects from Trees and Colonnades** (next page) illustrate the effectiveness of this morphological characteristic at explaining urban cooling for different configurations. The study is for a hot-humid city at 32° N latitude for the extreme temperature conditions of 3 PM in July, 30.2 °C (86.4 °F)/60% RH under clear skies (adapted from Shashua-Bar et al, 2006).

Built Form Effect is given relative to the temperature for an envelope ratio of 0.3 (set at 0 degrees C temperature difference). From the left graph, note that as envelope ratio gets smaller than the 0.3 reference value, the relative cooling effect increases and the air temperature falls. As envelope ratio increases, the cooling effect is less and the temperature rises relative to the reference condition.

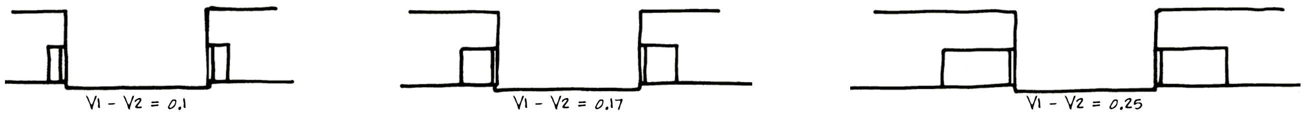
The right graph, **Cooling Effects from Trees and Colonnades**, demonstrates that both trees and colonnades have an additional cooling effect that can be *added to* that of the urban form effect. The largest cooling effect from trees or colonnades comes when the envelope ratio is larger (wider, more open configuration.) As the envelope

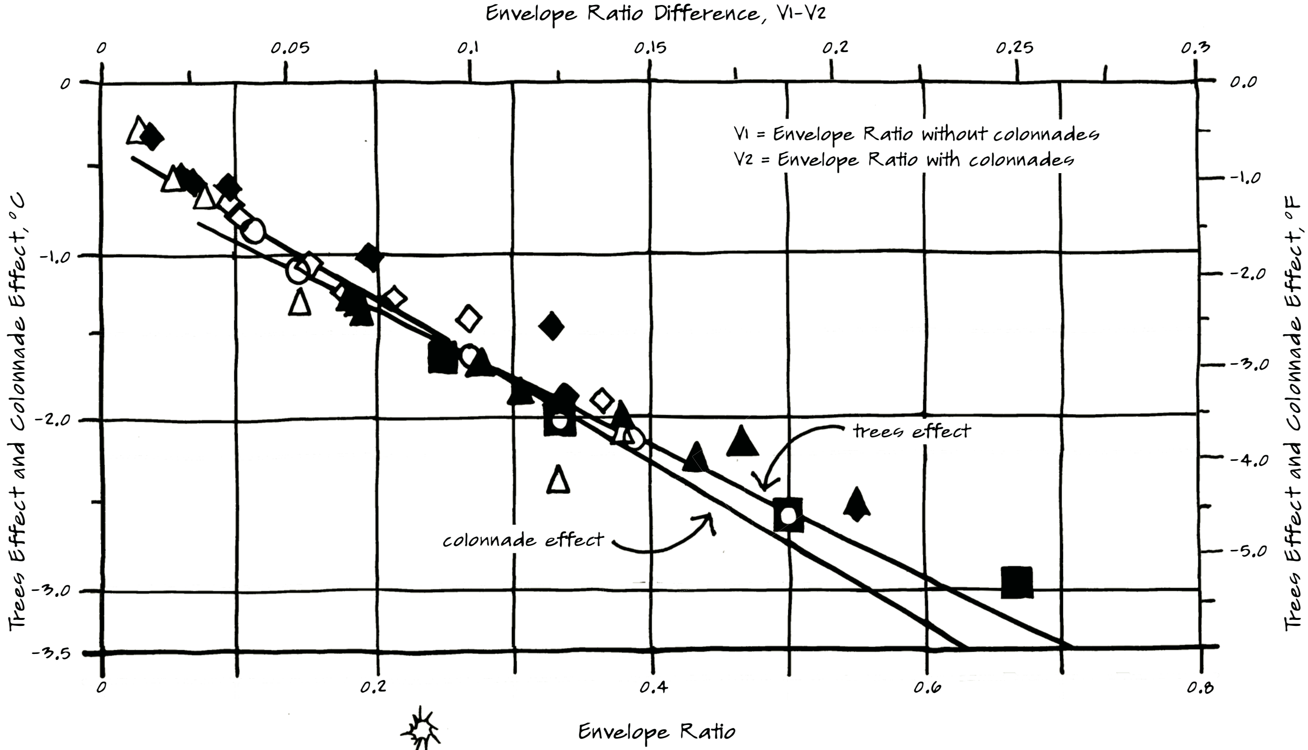


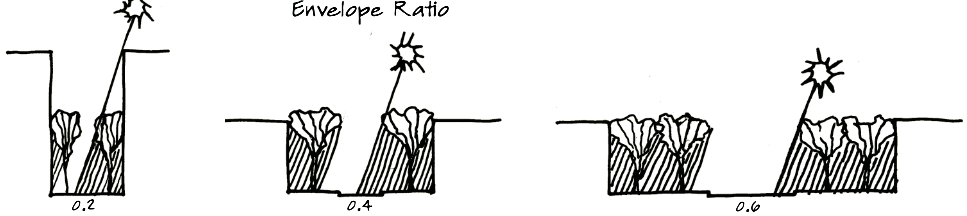
Cooling Effects from Built Form
envelope ratio = ground area / (ground area + wall area)

ratio decreases, so does the effect of these additional strategies. For example, for the 70% tree cover (measured at noon) studied, the maximum cooling effect of 2.8 °C (5 °F) is seen in shallow configurations. The graph's axis "*Trees Effect and Colonnade Effect*" show the differences in air temperature between the same configuration with and without 70% ground cover shaded by trees or with colonnades at the edges.

Canyon Street Forms with Colonnades







Cooling Effects From Trees and Colonnades
envelope ratio = ground area / (ground area + wall area)

NEIGHBORHOODS ➔ URBAN FABRICS ➔ URBAN ELEMENTS

B3 **A *SOLAR NEIGHBORHOOD* configures the urban fabric in response to climate to promote solar power and heating of all buildings and the spaces between. [heating and power]**

KEY POINTS

- Buildings, streets and open spaces work together to bring sun to each building and reduce energy use.
- Urban patterns can make outdoor climates more intense or more moderate.
- Taller building heights increase density but decrease surface area per dwelling for solar collection.

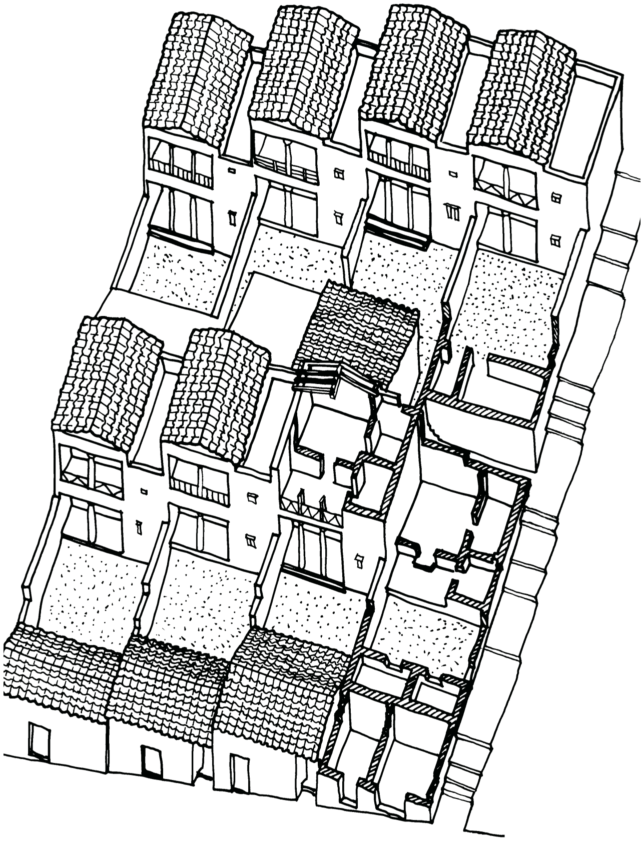
CONTEXT

Each bundle helps build one or more larger strategies at the next scale of complexity. The scales above the Neighborhood—Urban Quarter (a configuration of neighborhoods), City, Metro and Region—are truly urban and beyond our scope. The design strategies for solar heat and power at these more complex scales are yet to be defined. Speculatively, they might include strategies such as those to support clean air; increase solar gain; create urban shelter belts; promote development based on topography and solar aspect; develop 3-D, form-based solar zoning, create sheltered pedestrian networks; and locate tall building districts.

FORCES

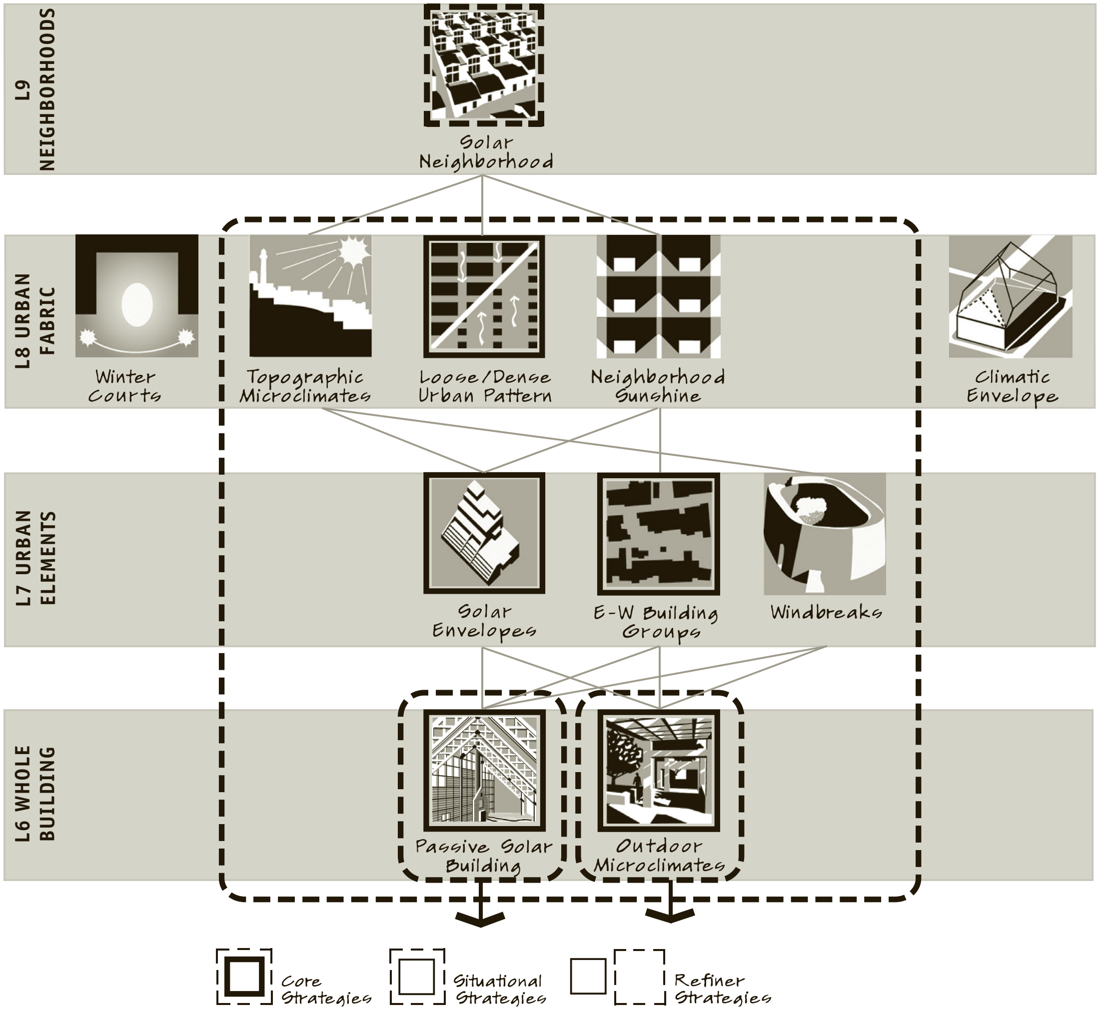
If buildings are to be solar heated, they need access to the winter sun, as do solar collectors for making electricity and hot water. As density increases in urban and even in suburban settings, buildings create shade on each other and on solar collectors. Pedestrians require warm microclimates. Excessive winter winds cool buildings and make outdoor spaces uninhabitable.

Sun and wind are both scalable phenomena; that is they operate at every scale from the region to the building parts. Because the direct sun has to reach the solar apertures or collectors, its access has to be considered and



Reconstruction of a Prostas House, Priene, Turkey, 4th c. BC

maintained at each scale of design. Similarly, wind can be blocked at a number of different design scales. However, because the effect of windbreaks is proportional to their height, the blocking of wind becomes a pattern that needs to be repeated throughout the urban fabric. The combination of these two fundamentals—providing access to sun,



SOLAR NEIGHBORHOOD: Low Density Fabric Bundle

which calls for more space between buildings, and blocking cold winds, which argues for tighter and more dense configurations—is the essential climatic tension to be resolved by the SOLAR NEIGHBORHOOD.

Solar neighborhood planning goes back perhaps three thousand years in Greece. An example of such a solar city is the ancient Greek Town of Priene, Turkey, where east-west residential blocks contained rowhouses, each with a south-facing courtyard and portico, insuring winter sun reaches each house, as shown in the **Reconstruction of a Prostas House** (Whitley, 2001), a house type thought to have developed during a firewood shortage (Butti and Perlin, 1980).

CORE STRATEGIES

There are five strategies common to all well-designed SOLAR NEIGHBORHOODS.

LOOSE OR DENSE URBAN PATTERNS sets the basic wind regime for streets parallel to the wind. The *wind blockage ratio* is a function of the height of buildings, the area

of their faces to the prevailing wind and the width of streets. Wider streets, lower buildings and narrower faces to the wind create more wind in the streets. This is significant especially for the windward edge of building groups, which can be designed to block winds from passing into the fabric of the neighborhood. This strategy is modified by BREEZY OR CALM STREETS. Taken to the extreme by eliminating all spaces between buildings on the leeward edge of a cluster or neighborhood, buildings function as continuous WINDBREAKS and the strategy becomes WINTER COURTS.

EAST—WEST ELONGATED BUILDING GROUPS create long sun-facing winter facades and space buildings in the north–south direction so that these long facades get access to winter sun. This is critical in winter heating climates because the radiation available from the lower winter sun arrives mostly in the midday hours when the sun is in the southern sky (N in SH). The urban implication is for east–west elongated blocks with shorter east and west faces and midblock open spaces. In many neighborhood configurations, some east- and west-facing buildings are inevitable. In that case, building design using DEEP SUN sections and rooftop SOLAR APERTURES can solve the solar access problem.

SOLAR ENVELOPES is a flexible tool that uses solar access criteria to define a maximum development envelope so that one building or group of buildings does not block solar access to the neighboring buildings. It can be applied at the parcel or block level and to provide sun to passive SOLAR APERTURES, PHOTOVOLTAIC WALLS AND ROOFS, BREATHING WALLS and to SOLAR HOT WATER collectors.

PASSIVE SOLAR BUILDING both benefits from a solar neighborhood and helps to create its pattern. It is its own bundle of smaller strategies for heating buildings in both low and high density situations.

OUTDOOR MICROCLIMATES benefits from the larger solar neighborhood strategies that form its context and block or admit forces of sun, wind and light. It is also a bundle of smaller strategies that shapes outdoor comfort.

SITUATIONAL STRATEGIES

Variations Based on Low and High Density Fabric

The basic requirements for this bundle are the same for most situations. Significant variables include latitude, which affects sun angles; severity of the winter climate, which affects the length of the heating season; and sky cover in the climate, which can affect orientation and available radiation. The solar heating strategies in *SWL* typically account for the range of these variables. From a design standpoint, perhaps the greatest impact on this bundle is whether the neighborhood is low or high density. The bundle diagrams show two variations: Low Density Fabric and High Density Fabric.

1. Low Density Fabric SOLAR NEIGHBORHOOD Bundle (see diagram, previous page)

Low density fabrics have shorter buildings that tend to be more detached, with more space between. This gives flexibility for arrangement of individual small buildings on larger sites so that winter overshadowing can mostly be avoided. However, the problem is not always a simple one, especially because the high surface to volume ratio (S/V) of freestanding buildings, and their residential uses with low internal gains, contribute to maximizing the heating loads and season. Additionally, their loose organization is less conducive to blocking winter winds.

Low Density Situational Strategies

In addition to the five core strategies applicable to all neighborhoods, this variation on the bundle adds these strategies that will apply to most lower density neighborhoods.

TOPOGRAPHIC MICROCLIMATES can be used to locate building groups in any climate and at any density; however, new development with a choice of topographic location is much more common at lower density. Locations on south-facing (N in SH) slopes that avoid cool valley pockets and windy ridge tops are best. Steeper sun-facing slopes can promote solar access with increased density.

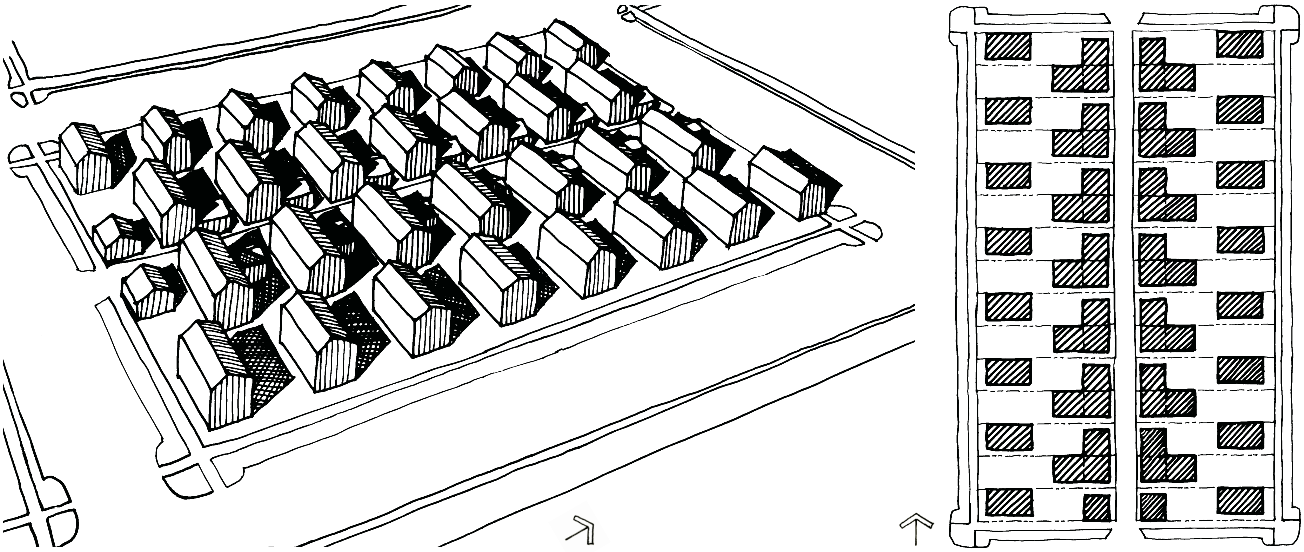
Geos Net-Zero Energy Mixed-Use Neighborhood, Arvada, Colorado, 2006, Michael Tavel Architects and David Kahn Studio

NEIGHBORHOOD SUNSHINE helps the designer find combinations of street orientation, parcel size and configuration and building placement that provide solar access to all buildings. This strategy applies in situations where building location is not fixed, as it can be in dense urban settings where buildings are large relative to their site.

WINDBREAKS at the site scale are more important in low density settings because the fabric as a whole is looser and the more DISPERSED BUILDINGS allow more wind to pass. Therefore, combinations of buildings, walls and vegetation can be employed to both reduce the convective heat loss of buildings caused by winds and to improve the comfort of OUTDOOR MICROCLIMATES.

Low Density Fabric Example

The **Geos Net-Zero Energy Mixed Use Neighborhood** in Arvada, Colorado, by Michael Tavel Architects and David Kahn Studio, a 25 ac (10 ha) development, is a good example of the low density fabric bundle (Kracauer, 2007; McCornick, 2008; Tavel, 2010). The project combines contemporary urbanism approaches, expanded by solar orientation, high-efficiency building design (Passivehaus) and renewable energy power systems. It uses what the designers call a “checkerboard plan” to increase net density up 20 dwelling units per acre while providing NEIGHBORHOOD SUNSHINE to each unit. Alternating PASSIVE SOLAR BUILDINGS are set back from the N–S streets and



Staggered Arrangements for Solar Access in the Geos Neighborhood

accessed by alleys so their longer south faces are in the sun in EAST–WEST ELONGATED BUILDING GROUPS. Half the units have porches on the street with a courtyard behind, and half have porches facing a courtyard that fronts the street. Outdoor spaces around homes are treated like relatively CALM COURTYARDS where the buildings and landscape elements serve as WINDBREAKS to shield from the prevailing north winds in a relatively DENSE URBAN PATTERN. Each unit has a front and back outdoor room that can receive winter sun. Winter sun is also provided to common spaces as the homes open onto common greens [WINTER COURTS] that will receive full midday sun in winter. In summer MIGRATION between different seasonal OUTDOOR MICROCLIMATES is supported by the shady private courts.

The diagrams of **Staggered Arrangements for Solar Access in the Geos Neighborhood** show the final selected study of massing for solar access. The designers used extensive shadow analyses to calibrate building placements on lots such that urban density was optimized for each building type with excellent passive solar access for south walls and active solar access on roofs. Planting is arranged and selected to insure year-round 100% solar access to south-facing roofs, avoiding any shading from trees, for PV and potential solar hot water collectors.

2. High Density Fabric SOLAR NEIGHBORHOOD Bundle

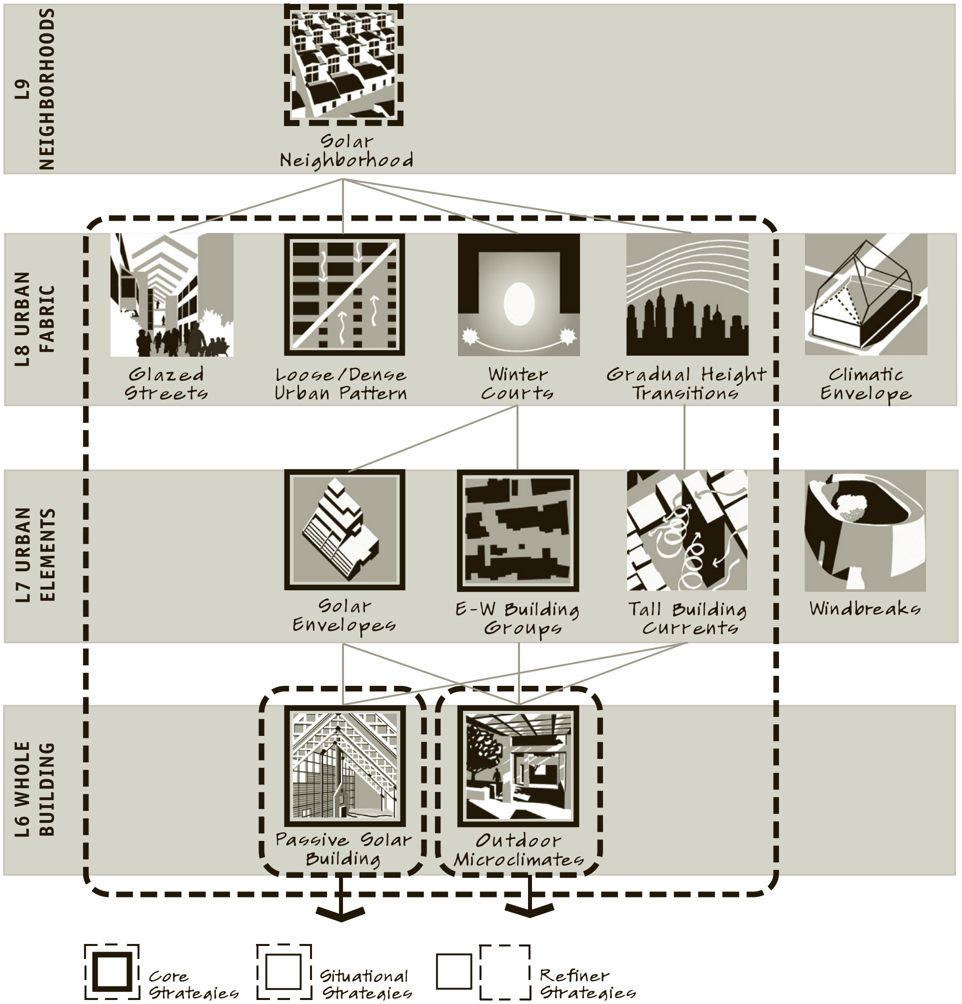
Higher density fabrics are even more challenging for solar access, particularly as latitude increases and winter sun is lower. On the positive side, dense urban patterns and more continuous buildings yield calmer streets and open spaces.

High Density Fabric Situational Strategies

In addition to the five core strategies applicable to all neighborhoods, this variation on the bundle adds strategies that can apply to most higher density neighborhoods.

GRADUAL HEIGHT TRANSITIONS reduce downwash wind effects when there are changes in allowable height between one neighborhood and another. Abrupt height changes between a lower leeward row of buildings and a taller downwind row can significantly increase wind velocity and discomfort in the streets.

TALL BUILDING CURRENTS can be used to positive effect in hot-humid climates, but their effects are better reduced

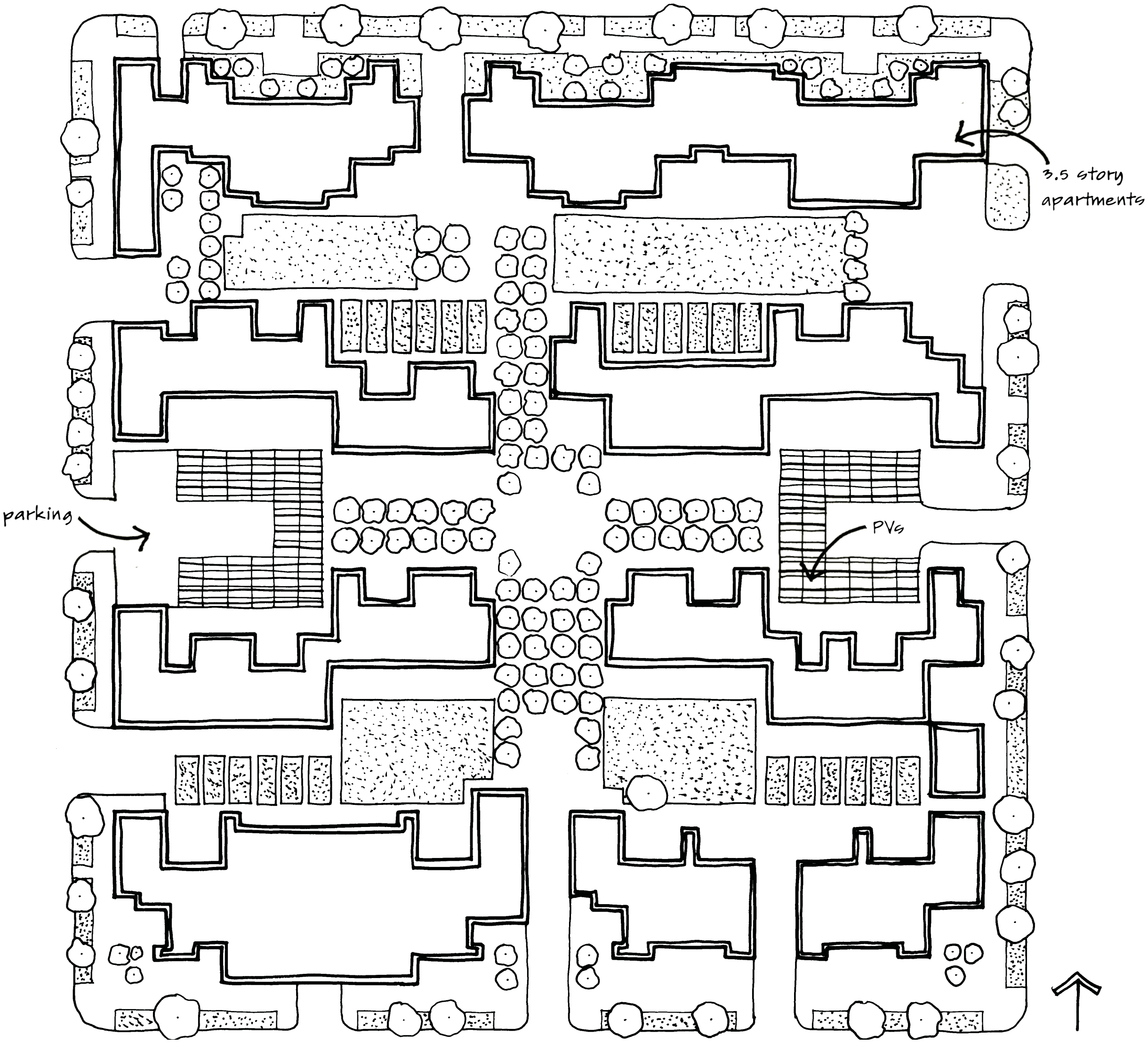


SOLAR NEIGHBORHOOD: High Density Fabric Bundle

in heating climates. As buildings become larger, the effect an individual building can have on the OUTDOOR MICROCLIMATE is more pronounced.

GLAZED STREETS offer a unique option in cold climates to both create a thermal buffer zone outside buildings, thus reducing heat loss from the envelope, and the potential to capture solar gain in an urban scale SUNSPACE. This shared and concentrated solar collection can supply solar heat to buildings that lack winter solar access.

WINTER COURTS are the urban scale version of a sunny CALM COURTYARD and incorporate the strategies for admitting sun and blocking wind. As density increases and private outdoor space decreases, providing comfortable public outdoor space becomes more important.



Somerset Parkside Housing, Sacramento, California, 1984, Van der Ryn, Calthorpe and Matthews

Examples

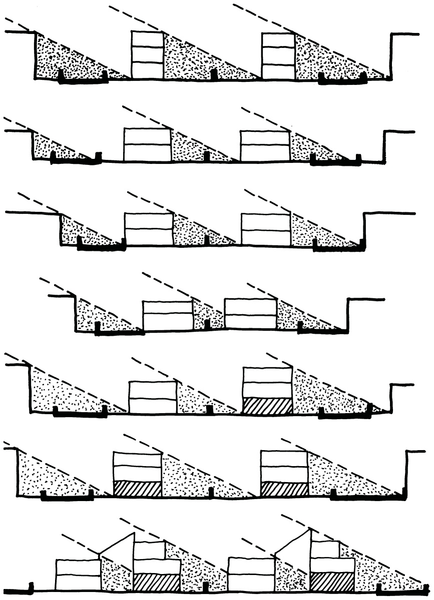
Numerous solar neighborhoods have been designed around the world; examples from *Sun, Wind & Light,* include **Pueblo Acoma,** in New Mexico, and **Solar City Pichling**, in Austria [both in EAST–WEST ELONGATED BUILDING GROUPS]; **Solar Village 3** in Athens [SOLAR HOT WATER]; and **Resolute Bay,** in Canada [WINTER COURTS].

High Density Fabric Example

In the urban core of Sacramento, California, architects Van der Ryn, Calthorpe and Matthews designed 107 units at **Somerset Parkside Housing** covering a full 2.5 ac (1 ha) city block at 43 units/acre (107 units/hectare), which approaches the maximum density possible with full solar access at the 38° latitude (Woodbridge, 1984; Van der Ryn

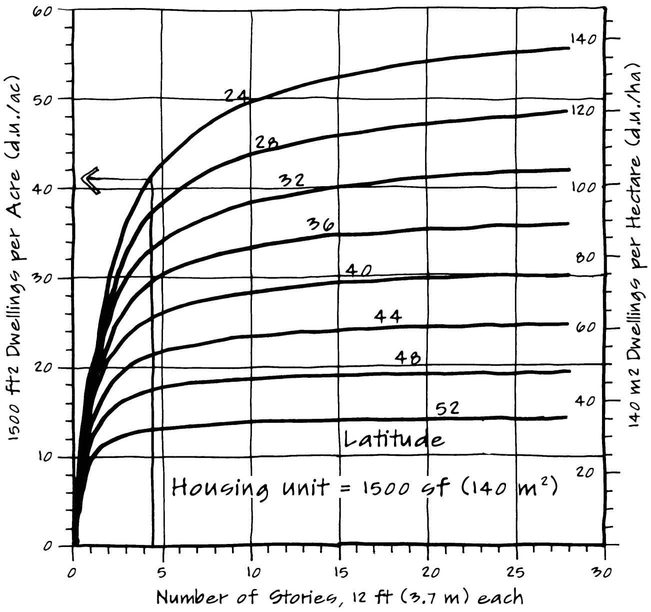
Sumerset Parkside Housing, Sacramento, California, 1984, Van der Ryn, Calthorpe and Matthews

and Calthorpe, 1986). The project is outstanding for its low-rise, high-density, context-sensitive and socially conscious mixed size and income approach to a fabric that supports PASSIVE SOLAR BUILDINGS. Apartment size is modest, ranging from 584 ft^2 (54 m^2) one-bedroom units to 1116 ft^2 (104 m^2) three-bedroom units. The designers created buildings that support and reinforce street activities and spatial definition. At the same time, the project creates a protected interior zone for social life and children and a wide variety of open space and outdoor room types, including both WINTER COURTS and shaded summer retreats. The plan shows an organization of EAST–WEST BUILDING GROUPS; in the N–S section, the scheme creates a fine-grained GRADUAL HEIGHT TRANSITION from taller commercial context on the north, where its 3.5-story mixed-use buildings are placed, to the 2-story detached



Units/Acre	Unit Area ft^2 (m^2)	Yard Area ft^2 (m^2)	Setback ft (m)	Solar Access	Type	Building Spacing ft (m)	Building Width ft (m)
21	1500 (139)	1175 (109)	15 (4.6)	**100%**	Townhouse	62 (19)	20 (6)
22	1500 (139)	875 (81)	15 (4.6)	**100%**	Townhouse	42 (13)	30 (9)
23	1500 (139)	750 (70)	0 (0)	**100%**	Townhouse	42 (13)	30 (9)
28	1500 (139)	437 (41)	0 (0)	**75%**	Townhouse	20 (6)	30 (9)
32	2-1500 (139) 1-750 (70)	600 (56)	15 (4.6)	**100%**	Stacked Townhouse	42 (13)	30 (9)
38	2-1500 (139) 2-750 (70)	562 (52)	15 (4.6)	**100%**	Stacked Townhouse	62 (19)	30 (9)
42	2-1500 (139) 2-1200 (112) 2-750 (70)	250 (23)	15 (4.6)	**100%**	Apartment	30 (9)	80 (24)

Studies of Housing Form and Density for Solar Access



Building Height vs. Density for Solar Access

apartments on the south edge, compatible with the duplexes across the street. Although Sacramento has a relatively mild winter climate, each unit receives full winter sun. It demonstrates that passive solar design is compatible with urban density. The technologies are simple: south-facing DIRECT GAIN ROOMS, balcony overhangs and movable canvas EXTERNAL SHADING, insulating drapery for MOVABLE INSULATION and 1 in (2.5 cm) plaster throughout as THERMAL MASS. Summer and winter winds are both from the south, and Sacramento has warm summers and cool winters, so the project rightly admits winds along a permeable south edge, while providing migration options for winter wind protection. As a low rise complex, TALL BUILDING CURRENTS are not an issue. Somerset Parkside also uses a variety of shading and ventilation techniques to function also as a COOLING NEIGHBORHOOD.

RECOMMENDATIONS

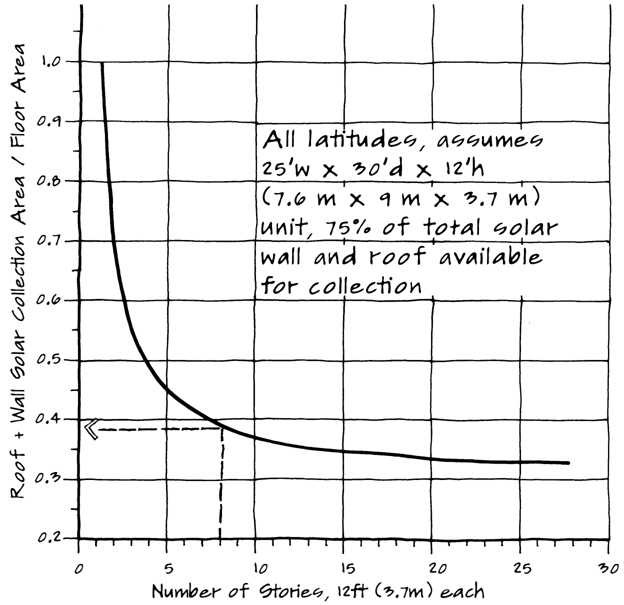
Density that supports solar access has an upper limit at each latitude; Calthorpe's **Studies of Housing Form and Density for Solar Access** (previous page) (Van der Ryn and Calthorpe, 1986) demonstrate that for a given solar access criteria and latitude, many different configurations and building types are possible. The table shows an upper limit at 38° latitude of about 42 du/ac (104 du/ha), for units averaging 1500 ft^2 (140 m^2), a density similar to the old quarters of Savannah, Georgia, which can support a rich urban life.

As building height increases, so does the spacing between buildings, as shown in EAST-WEST BUILDING GROUPS. The graph of **Building Height vs. Density for Solar Access** shows that up to a point, increasing building height while maintaining a profile angle for spacing also increases development density.

Therefore, to maximize density while preserving solar access at midlatitudes, limit building heights to 5–6 stories. At high latitudes, limit building heights to 2–3 stories and at low latitudes, 6–8 stories.

At higher latitudes, the maximum density for solar access decreases. The graph of **Solar Collection Surface Area & Building Height** indicates that, as building heights increase and roof area stays constant, the total surface area of walls and roof available for solar energy collection surface per unit of floor area decreases rapidly. The graph applies to all latitudes.

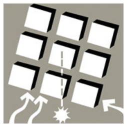
Building heights of 5–6 stories maximum is a good design guideline to keep enough south wall (N in SH) and roof surface area for passive solar heating and active solar conversion. For a more detailed approach,



Solar Collection Surface Area & Building Height

find the area of **SOLAR APERTURE** ***required per unit of floor area and select heights and density from the graphs that preserve this amount of collection surface.***

Perhaps the critical factor to consider is the neighborhood fabric that will provide solar access while best promoting the urban effect of walkable pedestrian-oriented, safe, vibrant and active streets. This suggests relatively narrow streets in a low-rise, high-density pattern.



B4 ***INTEGRATED URBAN PATTERNS*** **of streets and blocks can be oriented and sized to integrate concerns for light, sun, wind and shade according to the priorities of the climate. [heating, cooling and daylighting]**

KEY POINTS

- Integrated urban patterns balance needs for heating, cooling and daylighting based on the variables of Use and Climate.
- The pattern of streets and buildings sets the stage for the possibility of passive strategies at the building scale.
- The orientation and layout of streets, combined with the spacing of buildings, has a significant effect on the microclimate around buildings and on the blocking of or access to sun and wind for use in buildings.

FORCES

Different combinations of Use and Climate call for varying weightings of priorities for heating and cooling, as described in the chapter "Navigation by Climate." The mix of heating and cooling needs translates to criteria for the urban pattern to admit sun and block wind (cold climate), to admit wind and block sun (hot climate), or to accommodate some mix of both needs (mixed climate).

In energy terms, one of the jobs of the neighborhood pattern is to admit desirable site resources and when possible to block the undesirable resources. However, especially in mixed climates, these criteria may be at odds. The second major tension in neighborhood layout is the need for compactness versus the need to disperse buildings for access to winter sun or summer wind.

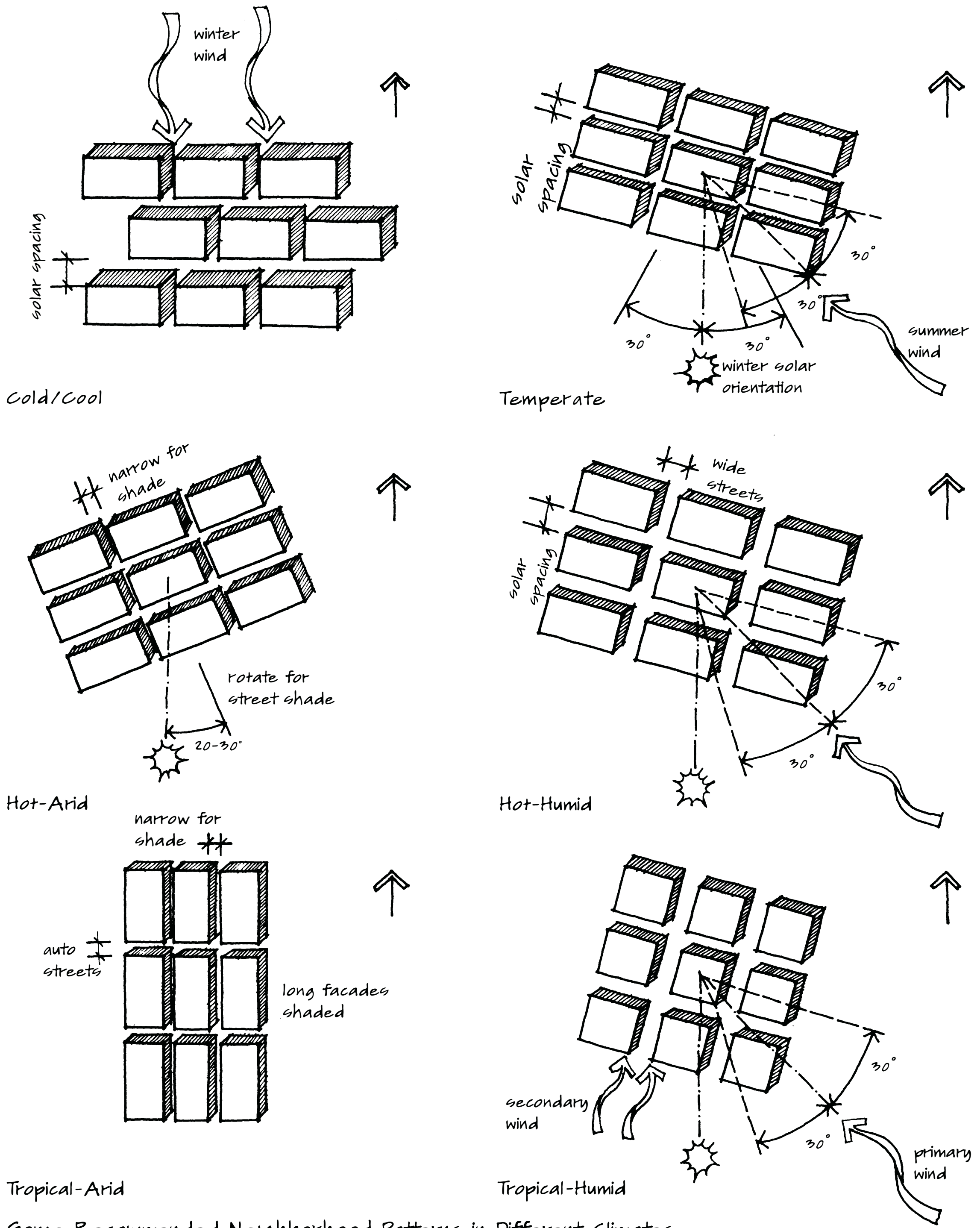
Greater compactness and density is correlated with increased urbanity, walkability and transit effectiveness. It also generally decreases energy for both transportation and buildings. Compact cities are pedestrian friendly and energy efficient. On the other hand, buildings spaced too closely can make solar heat and power ineffective, and buildings can block each other's access to the cooling potential of breezes.

RECOMMENDATIONS

Several phenomena can be observed, and the successful neighborhood pattern will combine these effectively.

- Wider east–west streets give better winter solar access [EAST–WEST ELONGATED BUILDING GROUPS]
- Wider streets in the direction of prevailing wind flows promote better wind movement through the city [BREEZY STREETS].
- Wind speeds can be decreased or increased depending on whether the neighborhood is designed as a LOOSE OR DENSE URBAN PATTERN.
- At high latitudes the sun position and therefore winter radiation is more equatorial-dominant (S in NH and N in SH), while at temperate latitudes, more flexibility in orientation for solar heating is permissible without severe penalties in the amount of radiation collected [ROOMS FACING THE SUN AND WIND].
- Narrow north–south streets can create shade from one building to the next [SHARED SHADE].

Depending on the climate and heat load of buildings, different combinations of strategies may be appropriate. The diagrams show **Some Recommended Neighborhood Patterns in Different Climates** as potential generic solutions.



Some Recommended Neighborhood Patterns in Different Climates

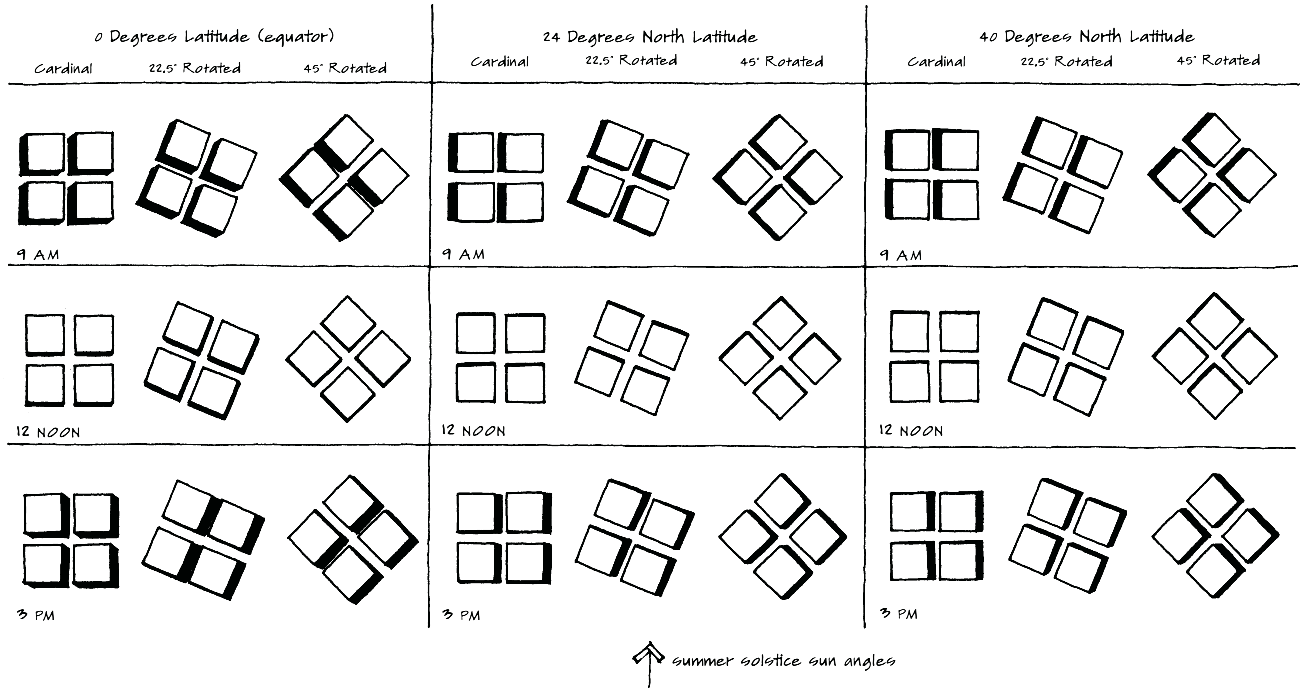
BUILDING TYPE		RESPONSE		
Internal Loaded Buildings	Skin Loaded Building	1st Priority	2nd Priority	COMMENTS
Very Cold	Cold	Lee	Sun	• Strict cardinal orientation for sun. • Discontinuous streets in direction of winter winds. • Space E–W streets for solar access for spring and fall.
Cold	Cool	Sun	Lee	• Cardinal orientation for sun. • Discontinuous streets in direction of winter winds. • Space E–W streets for solar access at solstice.
Cool	Mixed	Winter Sun; Summer Wind	Winter Lee; Summer Shade	• Orient +/- 30 degrees from cardinal for sun. • Adjust orientation 20–30º oblique to summer wind. • Space E–W streets for solar access. Elongate blocks E–W.
Mixed-Arid	Hot-Arid	Summer Shade	Summer Wind; Winter Sun	• Narrow N–S streets for shade. • Rotate from cardinal to increase street shading. • Space E–W streets for solar access, if needed. Elongate blocks E–W.
Mixed-Humid	Hot-Humid	Summer Wind	Summer Shade; Winter Sun	• Orient streets 20–30º oblique to summer wind. • Modify orientation by rotating from cardinal to increase street shading. • Space E–W streets for solar access if needed. Elongate blocks E–W. • Wide streets for wind flow.
Hot-Arid & Tropical-Arid	Tropical-Arid	Shade all seasons	Night Wind; Day Lee	• Narrow N–S streets for shade. • Elongate block N–S, If E–W facades shaded. • Wider auto streets run E–W.
Hot-Humid & Tropical-Humid	Tropical-Humid	Wind all seasons	Shade	• Orient streets 20–30º oblique to predominant wind. • Respond to secondary wind direction. • Maximize street right-of-ways for wind flow, but not paving.

Street Orientation and Layout by Climatic Priority

Refer to the table of* Street Orientation and Layout by Climatic Priority *for specific recommendations by climate.

See the method in "Navigation by Climate" to assess the balance between heating and cooling in mixed climates. Note that, because internal-load-dominated (ILD) buildings have a greater requirement for cooling than skin-load-dominated (SLD) buildings, the effect on the recommendations is to shift these buildings to the next hotter climate type. For related recommendations that vary by Climate and Use, see SITE MICROCLIMATE and SHADING CALENDAR.

The diagrams of* Summer Solstice Shadows as a Function of Street Orientation *show the effect of different street orientations on summer solstice sun and shading patterns at different latitudes. Orientation and building



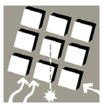
Summer Solstice Shadows as a Function of Street Orientation

spacing can be selected based on the building's mix of needs for heating or cooling.

They represent four-story buildings on 60 ft (18 m) right-of-way streets. Cardinal orientations give more sun to the south facades in winter, whereas rotated organizations tend to reduce winter gains and increase summer gains, especially on easterly and westerly facades. However, for buildings that do not require winter sun for heating, rotated organizations give more evenly distributed sun to more facades.

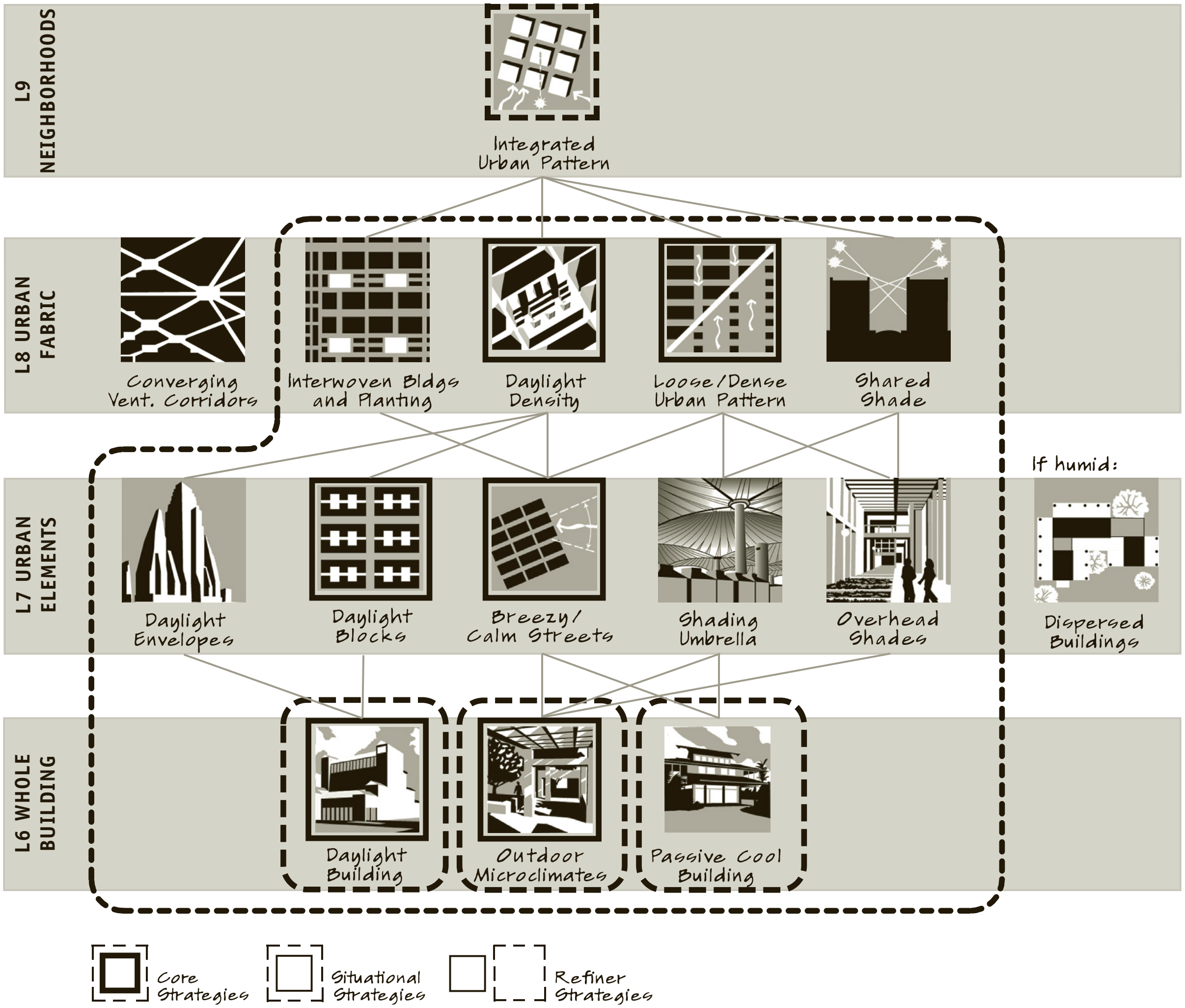
A cardinal orientation will generally cast more shadow on buildings facing north–south streets than a rotated organization, and thus does a better job at shading buildings. In contrast, rotated orientations provide more shade on the streets during more of the day. A cardinal orientation will have one shady street, while cross streets will be sunny. In contrast, rotated orientations will provide shade on at least one side of the street for most of the day. Note that during midday, when the sun is high, buildings cast quite small shadows and the orientation of streets has little effect, indicating that south-facing facades (N in SH) should be shaded at the element scale [DAYLIGHT-ENHANCING SHADES, EXTERNAL SHADING, and INTERNAL AND IN-BETWEEN SHADING] and that streets, open spaces and outdoor rooms must be shaded in the overhead plane [OVERHEAD SHADES].

The 22.5° rotation plans show increase street shading while meeting solar orientation criteria and may be appropriate for a temperate climate. As rotation increases away from cardinal, shadows reach opposite buildings less and thus buildings must provide more self-shading.



CORE STRATEGIES:

Of the five strategies that apply to and enhance the design and energy performance of urban fabrics in all climates, two give guidance on wind and three on light. The strategies for daylight apply to all climates, since most buildings in all climates require lighting and daylight strategies allow for a range of available light levels. The two wind strategies apply to all climates,



INTEGRATED URBAN PATTERN: Hot-Climate Bundle

but in hot and cold climates they are used differently.

LOOSE OR DENSE URBAN PATTERNS sets the basic wind regime in the fabric for streets parallel to the wind. Wider streets, lower buildings and narrower faces to the wind create more wind in the streets. This is especially significant for the windward edge of building groups, which can be designed to allow winds to pass into the neighborhood. This strategy is modified by BREEZY OR CALM STREETS. Good air movement in streets is important in all hot climates.

BREEZY OR CALM STREETS helps designers configure and orient streets to either promote or retard air movement This is important to cool the spaces between buildings and to provide air to buildings for natural ventilation.

DAYLIGHT DENSITY helps the designer configure streets, blocks and buildings to support light to each building. It demonstrates that, while daylighting design may generate urban forms different from those generated by rules that ignore daylight, high density development is indeed

possible. It combines DAYLIGHT BLOCKS and DAYLIGHT ENVELOPES into a composite pattern.

DAYLIGHT BLOCKS helps the designer determine block sizes based on daylighted building form or, conversely, to fit appropriate daylight massing of buildings to existing block dimensions.

Two bundles at the L6 Whole Building scale are common to all its variations. The DAYLIGHT BUILDING and OUTDOOR MICROCLIMATE bundles help build the strategies at the L7 Urban Elements level because buildings are one of the components at that level. Conversely, these bundles are enhanced by and become more possible with a successful INTEGRATED URBAN PATTERN.

DAYLIGHT BUILDING is itself a bundle of numerous strategies in the sequence from sky to interior surfaces. Each scale along the way is critical to effective daylighting. It offers combinations of strategies for THIN PLAN and thick plan buildings [ATRIUM BUILDING and TOPLIGHT BUILDING].

OUTDOOR MICROCLIMATES benefits from the larger heating and cooling neighborhood strategies that form its context and block or admit forces of sun, wind and light. It is also a bundle of smaller strategies that shapes outdoor comfort at smaller scales.

SITUATIONAL STRATEGIES: Variations Based On Hot and Cold Climates

The bundle is varied by "Hot Climate" and "Cold Climate" situations, which have opposing priorities for both sun and wind, or a combination of both may be used.

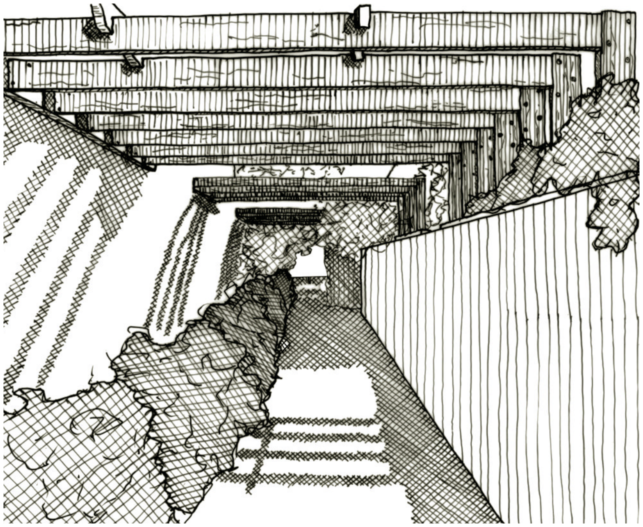
1. Hot Climate INTEGRATED URBAN PATTERN Bundle

The Hot Climate bundle variation focuses on and biases toward reducing solar gain and promoting ventilation while preserving daylight access.

Hot Climate Situational Strategies

INTERWOVEN BUILDINGS AND PLANTING has two components: green areas *concentrated*, such as in parks, and *distributed*, such as street trees. Plants cool by shading and by evaporation.

SHARED SHADE helps designers configure buildings to shade each other, particularly on north-south streets.



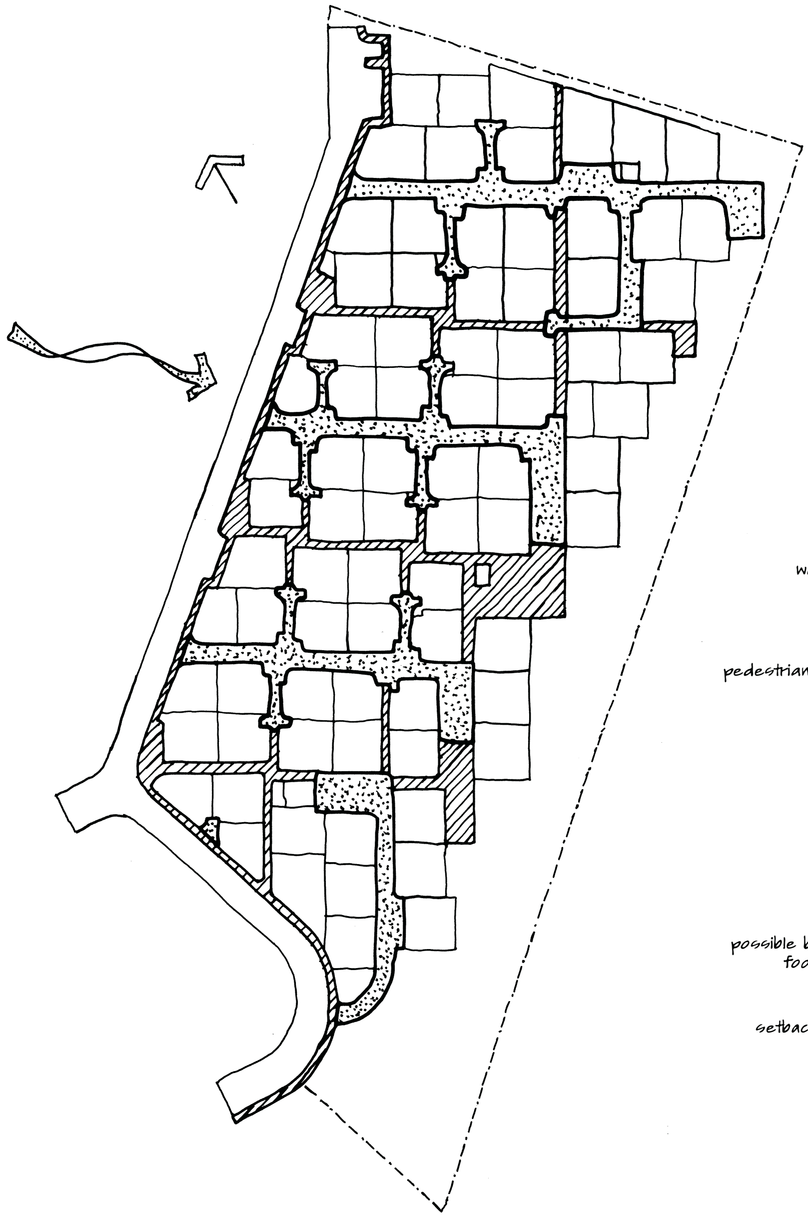
Shaded Pedestrian Alley, Neve-Zin Neighborhood

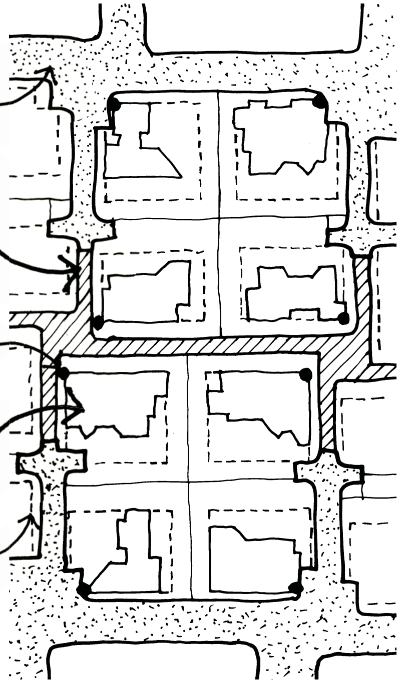
DAYLIGHT ENVELOPES guides designers to create a three-dimensional development envelope that, if building massing is kept within it, insures that all surrounding buildings will get adequate access to daylight. It can be applied at the building or block scale, depending on which adjacent facades are being protected.

SHADING UMBRELLA works similarly to shared shade, but at a smaller scale, by providing shade to particular open spaces or courts by shaping surrounding buildings and edges to cast shadows.

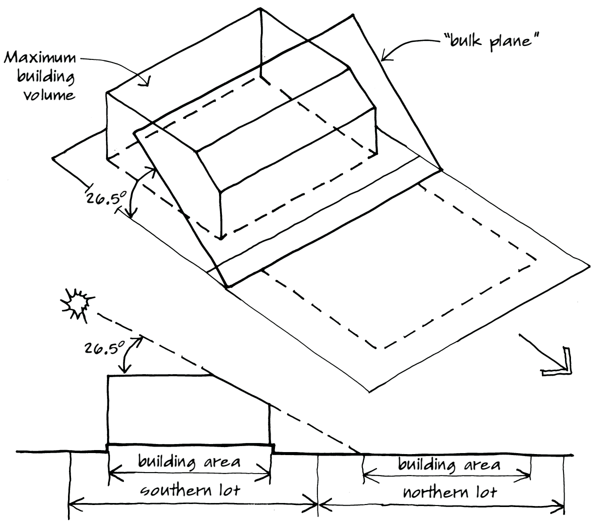
OVERHEAD SHADES is a particularly important strategy for shading of pedestrian circulation, of smaller open spaces and of buildings where the height to width ratio (H/W) admits significant sun, such as the south facade (N in SH). Both built shade, such as arcades, and vegetation, such as street trees, cool the afternoon air, but as the urban canyon (H/W) increases, the cooling effect diminishes.

PASSIVELY COOLED BUILDINGS are both the benefactors of an INTEGRATED URBAN PATTERN and help to create its pattern. This bundle helps build the strategies at the L7 Urban Elements level because buildings are one of





Neve-Zin Neighborhood, Sde-Boqer, Israel,
architects: Desert Architecture Unit, J. Blaustein Institute for Desert Research, Ben-Gurion University



Solar Access Protection,
Neve-Zin Neighborhood, Sde-Boqer, Israel

the components at that level. Conversely, this bundle is enhanced by and becomes more possible with a successful INTEGRATED URBAN PATTERN. It is its own bundle of smaller strategies for cooling buildings in both humid and arid situations.

MIXED ARID CLIMATE EXAMPLE

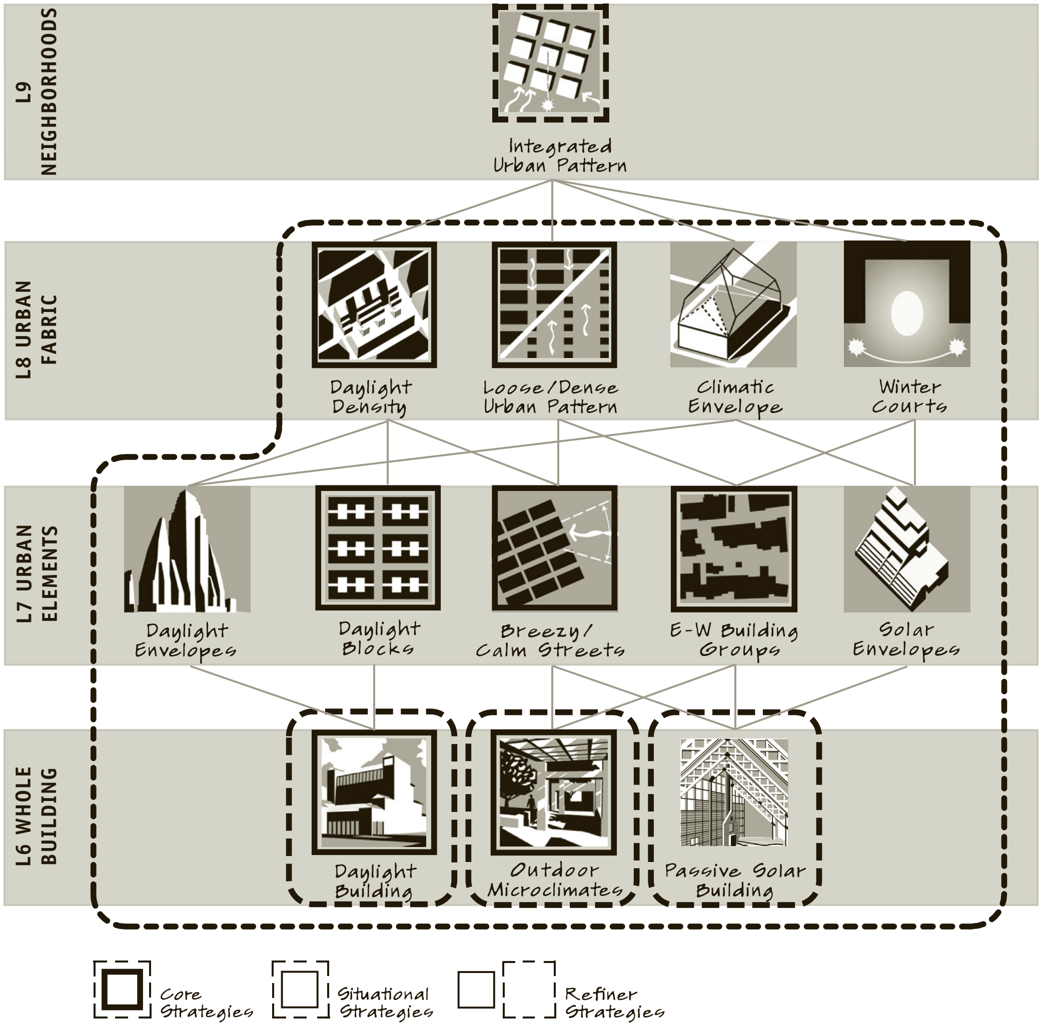
Located at 31° north latitude, the 78-lot **Neve-Zin Neighborhood in Sde-Boqer, Israel,** designed by the Desert Architecture Unit of Ben-Gurion University, is set in a mixed-arid climate with hot summers and cool winters, requiring both heating and cooling (Etzion, 1989, 1992; Pearlmutter, 2000; Erell et al, 2011). As housing, it falls into the skin-load-dominated (SLD) and mixed climate category of the table **Street Orientation and Layout by Climatic Priority** (two spreads back). Summer day temperature ranges from 15–32 °C (59–90 °F) and winter lows average 3 °C (37 °F) with ample sunshine.

The neighborhood's orientation is 17° west of south and was set by existing road and topography, but fits with the guidelines of ROOMS FACING THE SUN AND WIND. This orientation gives the primary streets an orientation that is 28° from the northwest prevailing winds from the Mediterranean Sea, fitting neatly within the 20–30° guideline set in BREEZY STREETS.

Circulation is organized into two main types, mixed traffic *woonerfs* and a separate system of **Shaded Pedestrian Alleys** (previous spread). The *woonerfs* are 8 m (26 ft) wide, primarily in the east-west direction, allowing solar access to south-facing facades, as recommended in EAST–WEST ELONGATED BUILDING GROUPS. Narrow shaded pedestrian alleys run perpendicular to the *woonerf* system where east and west building facades create SHARED SHADE. Development rules require up to two-thirds of the alley length to be covered with OVERHEAD SHADES consisting of trellises and vines.

This combination moderate grid rotation, wider E–W streets for solar access and narrower N–S lanes for shade follows the general pattern for a hot-arid climate as outlined in the diagrams of **Some Recommended Neighborhood Patterns in Different Climates** (located earlier in this bundle).

Solar Access Protection and shading are facilitated by development regulation of building placement and a solar protection plane. Building lots are arranged in sets of four, and each lot has a required perimeter point along its setback line (P-point) where the building footprint is required to touch at its corner. This simple move forced buildings to be located close to the roads and alleys, providing pedestrian shade, and keeps the center of the lots open for usable open space and solar access to houses with their south side facing the backyard. The pattern creates the potential for INTERWOVEN BUILDINGS AND PLANTING. Garages and fences are allowed to break the setback line and be placed at the lot lines, further enhancing the climatic goals. Setback lines are shallow along the streets and deeper in the back yards to promote good solar access. Finally, a solar protection plane creates a simplified SOLAR ENVELOPE that limits building heights. Given the scale of these buildings, all 8 m (26 ft) tall or less, and given that the solar access protections are stricter than the patterns required for daylight access, then access to light is also protected and would not be a problem.



INTEGRATED URBAN PATTERN: Cold-Climate Bundle

2. Cold Climate INTEGRATED URBAN PATTERN Bundle

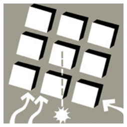
The Cold Climate bundle variation focuses on and biases toward collecting solar gain and blocking cold winds while preserving daylight access.

Cold Climate Situational Strategies

CLIMATIC ENVELOPE combines DAYLIGHT ENVELOPE with SOLAR ENVELOPE (cold climate) or SHADOW UMBRELLA (hot climate) or potentially with both (mixed climate) to generate development envelopes that balance site resources.

WINTER COURTS can be used at the scale of a single outdoor room, for a complex of buildings, or for a town. This strategy helps the designer shape and orient buildings to block wind and create a warm, sunny protected area. WINTER COURTS help build places of MIGRATION. The strategy LOCATING OUTDOOR ROOMS helps define the location of the WINTER COURT and its accompanying outdoor rooms in other seasons.

EAST-WEST ELONGATED BUILDING GROUPS create long sun-facing winter facades and space buildings in the north-south direction so that these long facades get access to winter sun. This is critical in winter heating climates because the radiation available from the lower winter sun arrives mostly in the midday hours when the sun is in the southern sky (N in SH). The urban implication is for east-west elongated blocks with shorter east and west faces and midblock open spaces. In many neighborhood configurations, some east- and west-facing buildings are inevitable. In that case, building design using DEEP SUN sections and rooftop SOLAR APERTURES can solve the solar access problem.



SOLAR ENVELOPES regulate building massing to protect the neighboring buildings' access to winter sun and in some cases, year-round for PV and solar hot water. Since DAYLIGHT ENVELOPES are orientation-neutral and SOLAR ENVELOPES are solar-orientation specific, this relationship is resolved by CLIMATIC ENVELOPES.

B5 A *DAYLIGHT BUILDING* is organized to light itself with the sky using a family of strategies fit to place and purpose. [daylighting]

KEY POINTS

- Room design and room organization are keys to making use of daylight admitted through the envelope.
- Effective daylight design requires strategies at several scales.
- Many building massing alternatives can be effectively daylighted.

CONTEXT

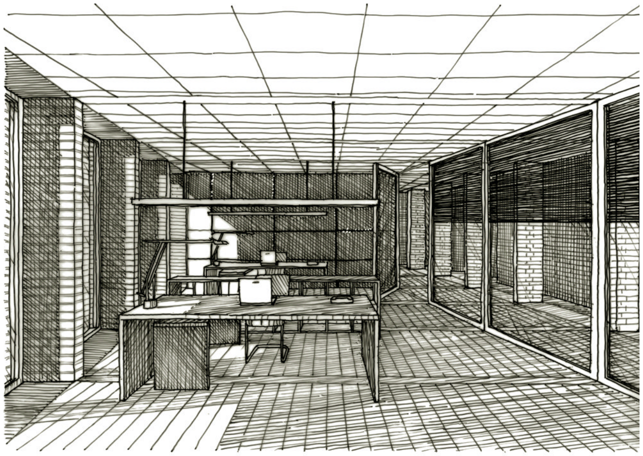
Each bundle helps build one or more larger strategies at the next scale of complexity. The core strategies of this bundle help build the whole building scale strategy of DAYLIGHT BUILDING, which in turn helps build the larger daylighting strategy at the scale of urban elements, DAYLIGHT ENVELOPE.

FORCES

Unlike heat, which can be stored, or cooling, which can be induced by evaporation or stack effect, daylight is available moment to moment during the daytime. It depends heavily on a geometric relationship between building and sky.

The practical questions for the designer are about how to get access to light, how to bring it to every room, how to place openings to admit light, how to shape the rooms to distribute the light, how to avoid glare and how to integrate electric light when daylight is not strong enough.

Designing a building for daylight can seem like a simple task, yet a complex, interrelated series of strategies at multiple scales are needed to bring the desired quantity and quality of light to rooms. If light is blocked or diminished too much along the way, daylighting design can fail.



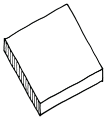
Office, National Parliament Building of Liechtenstein, 2010, Hansjörg Göritz Architekturstudio

RECOMMENDATIONS

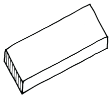
- ***Refer to* NEIGHBORHOOD OF LIGHT *and using strategies found there, determine the building's daylight access context.***
- ***Design at the scales of this bundle to preserve daylight access to each room.***
- ***Select the "Thin Plan" or "Thick Plan" bundle variation, or a combination of thick and thin.*** See the illustration **Daylight Planning Strategies and Building Form.**
- ***If the climate has predominantly clear skies, design for* REFLECTED SUNLIGHT *whenever possible.***

At a basic level, buildings can be thought of as short or tall, thick or thin, or some combination of these. The graphics in **Daylight Planning Strategies and Building Form** show a few possible massing typologies and how

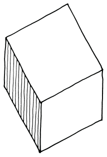
MASSING



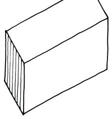
Short/Fat



Short/Thin

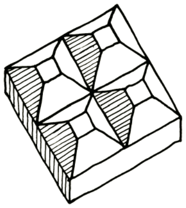


Tall/Fat

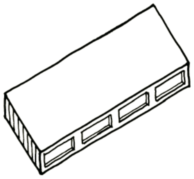


Tall/Thin

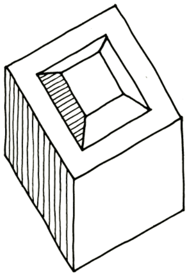
BASIC TYPES



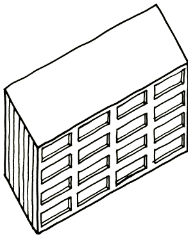
(Toplight)
- Skylight Building
- Toplight Room



(Sidelight)
- Thin Plan
- Sidelight Room Depth

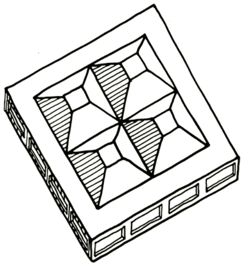


(Atrium)
- Atrium Building
- Toplight Room

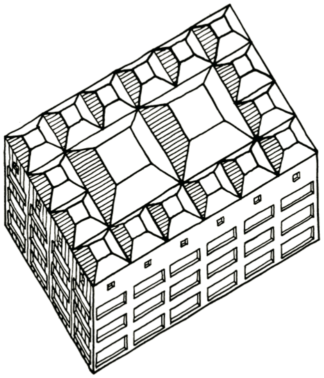


(Sidelight)
- Thin Plan
- Sidelight Room Depth

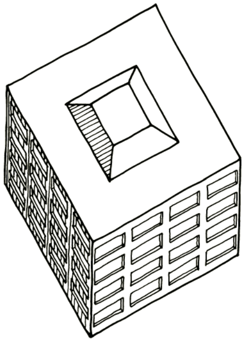
COMBINATIONS OF TYPES



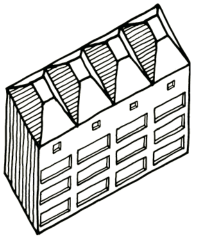
Short/Thin at Perimeter
- Skylight Building
- Toplight Room
- Sidelight Room Depth



Short/Fat on Top + Tall/Thin at Perimeter
- Skylight Building
- Atrium Building
- Toplight Room

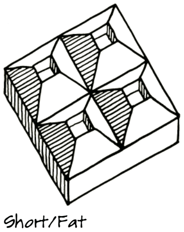


Tall/Thin + Short/Fat on Top
- Atrium Building
- Toplight Room
- Sidelight Room Depth

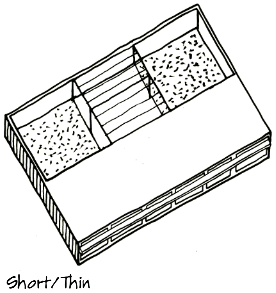


Tall/Thick + Tall/Thin at Perimeter
- Skylight Building
- Thin Plan
- Sidelight Room Depth

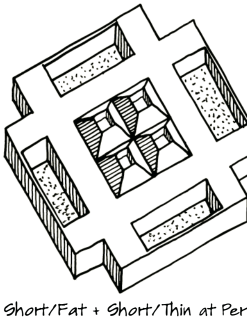
WITH REFLECTION



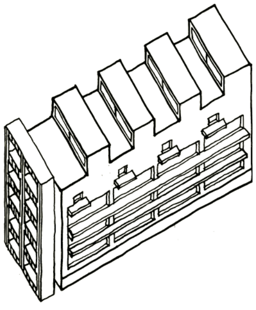
Short/Fat
- Skylight Building
- Toplight Room
- Reflected Sunlight



Short/Thin
- Thin Plan
- Sidelight Room Depth
- Reflected Sunlight

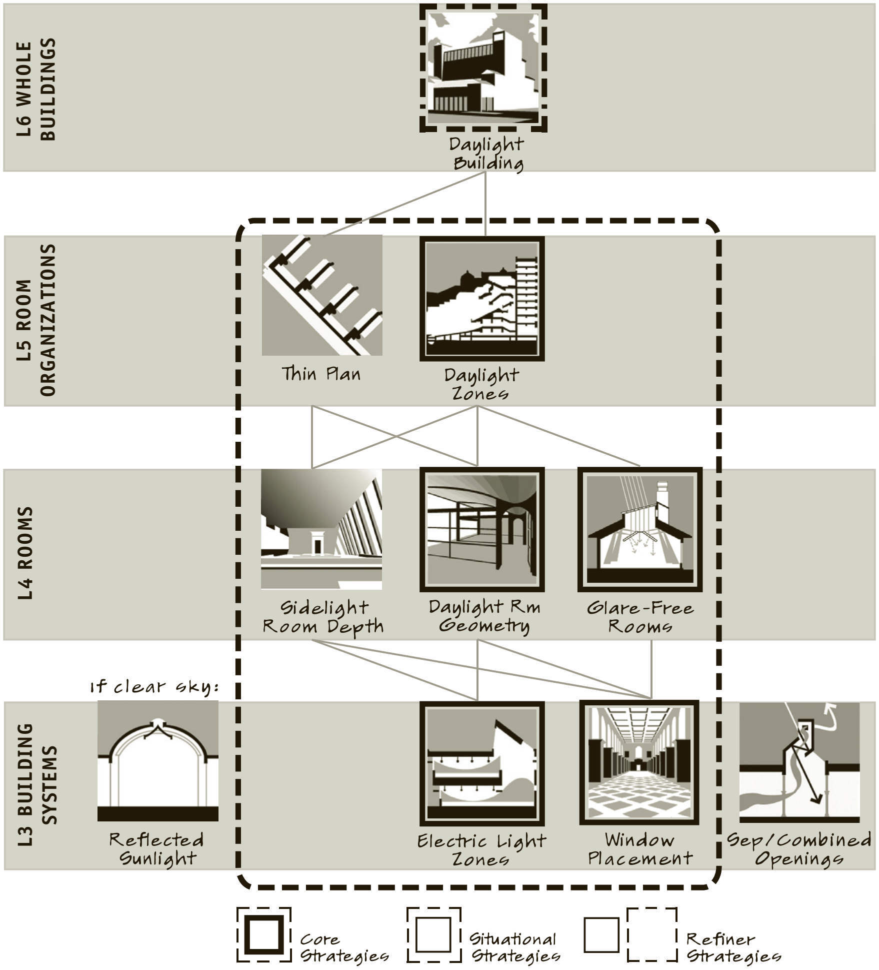


Short/Fat + Short/Thin at Perimeter
- Skylight Building
- Toplight Room
- Thin Plan
- Sidelight Room Depth
- Reflected Sunlight



Tall/Thin + Short/ Fat on Top
- Skylight Building
- Toplight Room
- Thin Plan
- Sidelight Room Depth
- Reflected Sunlight

Daylight Planning Strategies and Building Form



DAYLIGHT BUILDING: Thin Plan Bundle

each might make use of different daylight design strategies. Short/Fat buildings can be toplighted and do not require sidelight. Thin buildings can be sidelighted. The top floor of all tall buildings can be treated like a Short/Fat building by toplighting. Tall/Fat forms need to have a hole cut in the form of an open light court or glazed ATRIUM. Many buildings are combinations of thick and thin forms and strategies. In clear sky climates, REFLECTED SUNLIGHT is most useful. The diagrams show a few schematic alternatives.

CORE STRATEGIES

There are four strategies that can apply to almost any building designed for daylight. In contemporary practice, most American buildings have rather poor daylighting. Such fundamental mistakes could be avoided by paying design attention to each of these four strategies.

DAYLIGHT ZONES: Light is more accessible at the edges of buildings, and in some sites, on upper floors. The

essence of this strategy is to put spaces that need the most light near the sources of the light, and to group spaces with similar needs together so their needs can be met with similar architectural solutions. This is a fundamental building order.

DAYLIGHT ROOM GEOMETRY: One of the most overlooked strategies is to shape the room to become a lighting fixture such that the light is redistributed from the apertures to desired patterns of distribution within the room. The room geometry may differ depending on its daylight zone.

GLARE-FREE ROOMS helps the designer avoid high contrast ratios in a daylighted room by using reflection strategies and obscuring bright window surfaces.

WINDOW PLACEMENT helps the designer place windows to admit light and direct it to reflecting surfaces within the room. It helps build a daylighted room. The effects of alternative window locations on light distribution and intensity are poorly understood by many designers.

ELECTRIC LIGHT ZONES establishes the pattern of electric light placement and switching based on the patterns of daylight distribution within the room. If energy savings are to be gained from daylight design, the electric lighting system has to be synchronized spatially and temporally to the pattern and rhythms of daylight.

SITUATIONAL STRATEGIES

Variations Based on Thin and Thick Plans

The sky condition of a climate is often taken as the starting point for daylight building design. While the nature of the sky is an important variable, in *SWL*, most of the design strategies allow for the variation of sky cover or daylight intensity based on climate. The strategies are, with one exception (and there can be exceptions to that, too), applicable to many climates and to both clear and overcast conditions. Instead, this bundle focuses on the strategies that work best with *thin buildings*, which can use primarily sidelight, and *thick buildings*, which most often require toplight.

This bundle may be varied by whether the building is thick or thin in plan. A particular daylight building may be understood as thin, thick, or a combination of thick and thin. In practice, many buildings are some combination. For example, a large toplighted room may be surrounded by a thin wrapper of sidelighted rooms [see Kahn's First Unitarian Church example in TOPLIGHT ROOM]. The effect is a thick building that uses a combination of think and thin strategies. Similarly, an ATRIUM BUILDING may be thick, but the exterior rooms are most often sidelighted with thin building strategies.

In both thick and thin buildings we recommend REFLECTED SUNLIGHT as a refiner strategy for clear sky dominated climates. This strategy can also be used to avoid glare from low angle sun at high latitudes or on east and west orientations in all climates, or when space is tight. Both of the examples given here make use of use reflected light, although neither is from a clear sky dominated climate.

1. Thin Plan DAYLIGHT BUILDING Bundle

The Thin Plan bundle focuses on sidelighting, so building dimensions are driven by how deeply light can penetrate from the exterior walls.

Thin Plan Situational Strategies

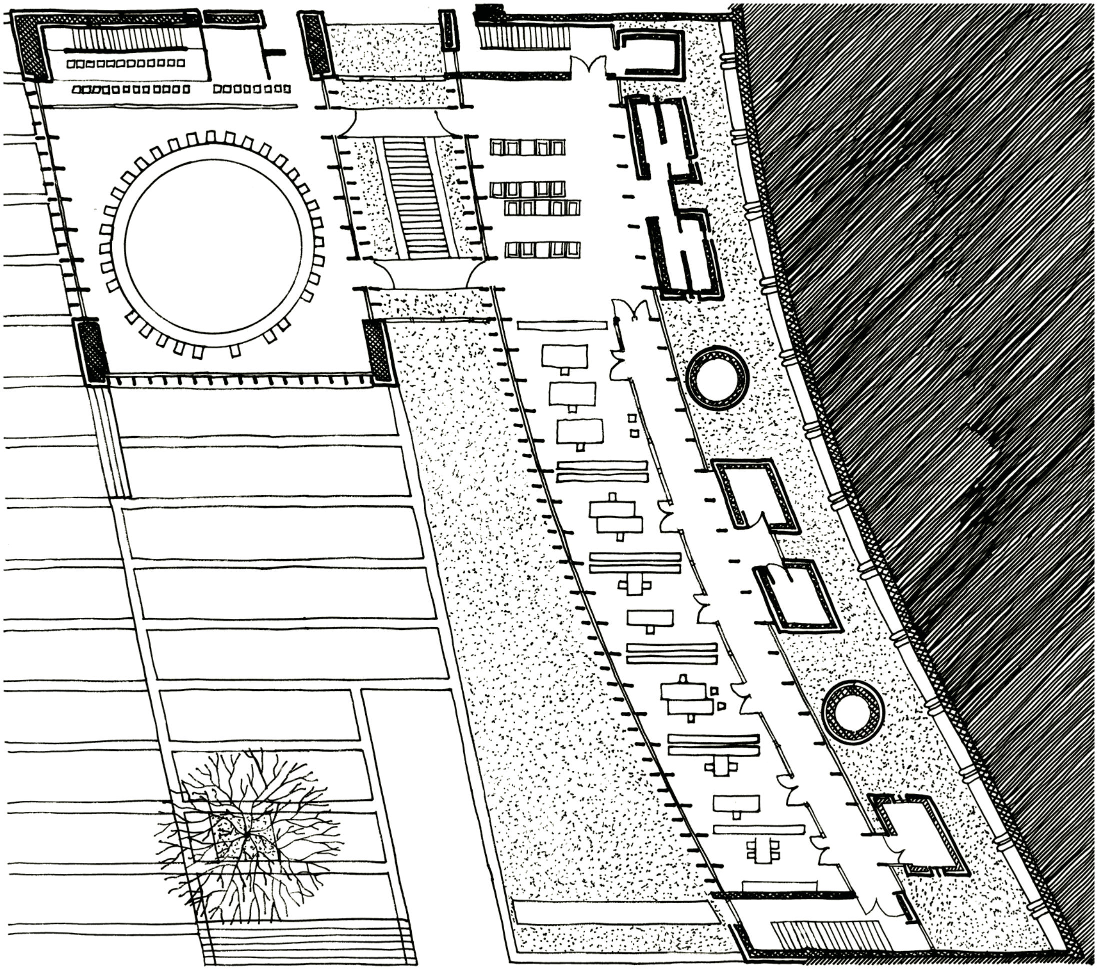
In addition to the five core strategies applicable to all buildings, this situational bundle adds these strategies that will apply to most thin plan buildings or sidelighted rooms:

THIN PLAN is the floor plan implication of the sectional relationship expressed in SIDELIGHT ROOM DEPTH. Recognizing that sidelight has limited penetration generates a fundamental planning module.

SIDELIGHT ROOM DEPTH establishes a critical ratio between window head height and room depth in rooms with unilateral lighting. Depths can be increased in a variety of ways.

Thin Plan Example

The **National Parliament Building of Liechtenstein** (see previous spread and next page), by the Hansjörg Göritz Architekturstudio is an elegant example of a well-daylighted building (ArchDaily, 2011; Weckesser, 2008). It is



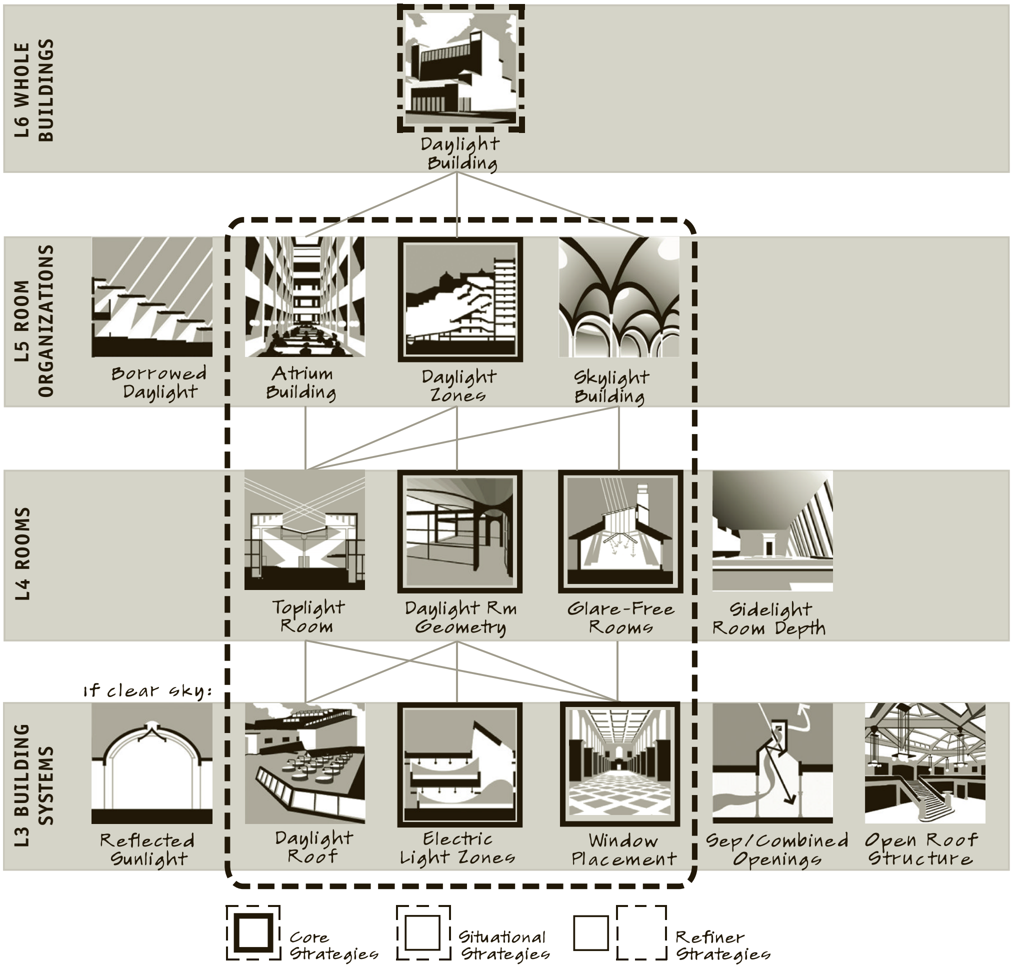
Level 1 plan, National Parliament Building of Liechtenstein, 2010, Hansjörg Göritz Architekturstudio

composed as a THIN PLAN three-story office wing (known as the Long House) married to a tall toplighted meeting house (see section in TOPLIGHT ROOM).

The rooms of the Long House are organized by DAYLIGHT ZONING, placing the offices near the wall that faces the public square, while the service spaces and circulation are located along the back wall. Occupied rooms with less critical lighting needs, such as the lounge, are located in the joint of the building at the north end, where they can use BORROWED LIGHT from the entry hall.

Built against a steep rock cliff, a light-colored concrete retaining wall bounces REFLECTED SUNLIGHT to the service side of the plan. The service elements alternate with glazing to provide daylight to the corridor, which itself has a fully glazed wall that provides a secondary source of light to the offices.

The WINDOW PLACEMENT organizes vertically proportioned windows that extend full height, alternating with light-colored brick piers extending like fins, providing daylight reflection and shading while preserving view. The GLARE-FREE ROOM environment is promoted by a gradient of brightness on the fins from inside to out, and by the



DAYLIGHT BUILDING: Thick Plan Bundle

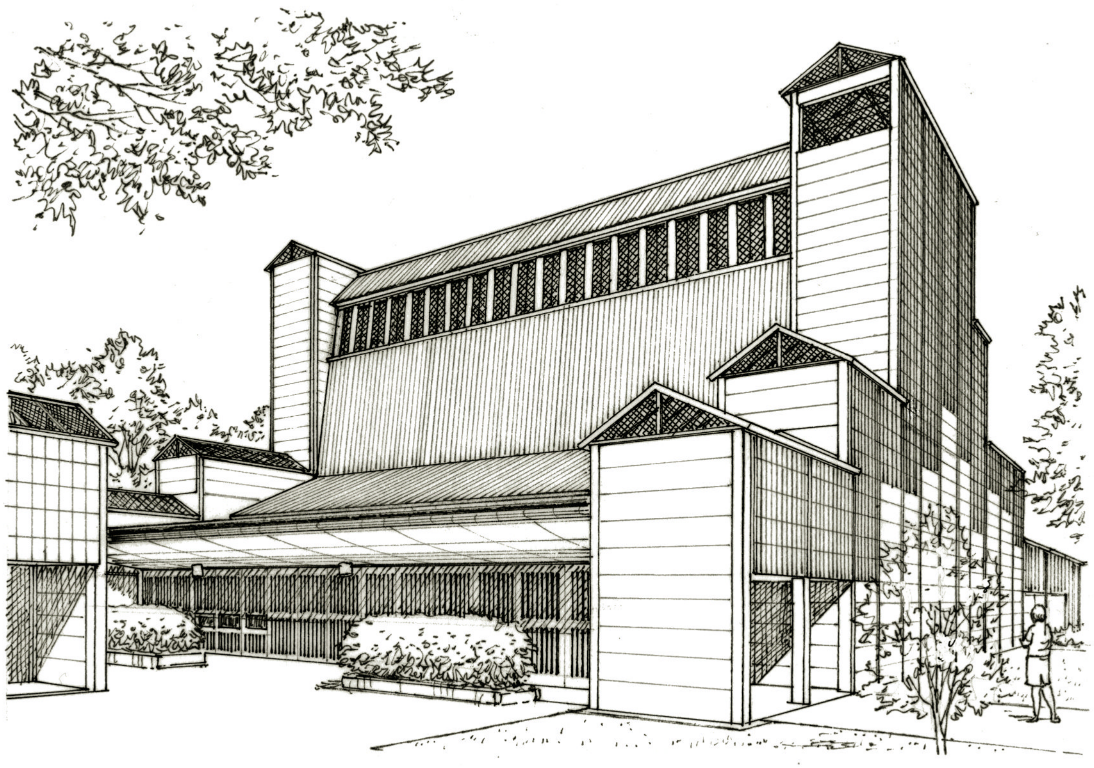
bilateral lighting that keeps contrast ratios close.

The window height is a shallow 3 m (9.8 ft); office depth is 8 m (26.2 ft) [SIDELIGHT ROOM DEPTH]. The DAYLIGHT ROOM GEOMETRY benefits from partitions, desks and shelving organized perpendicular to the window wall.

The electric lights are organized in strips perpendicular to the windows and are flush with the ceiling, eliminating any daylight blockage. The ELECTRIC LIGHT ZONES allow electric light to be switched off by automated controls in the zone closest to the windows in response to changing daylight levels outside.

2. Thick Plan DAYLIGHT BUILDING Bundle

The Thick Plan bundle variation focuses on toplighting in the form of either ATRIUM BUILDING or SKYLIGHT BUILDING. In this situational bundle, one can use one or the other, or both. The distinction is between thick buildings driven by cutting holes for light, which are often more than one or two stories, and those that are one or two stories high and can be daylighted by skylights through the roof or lightwells that penetrate the top floor. The top floor of any building can be treated as a skylight building.



Bagsværd Church, near Copenhagen, Denmark, 1976, Jørn Utzon, architect

Thick Plan Situational Strategies

In addition to the five Core Strategies applicable to all buildings, this situational bundle adds these strategies that will apply to most thick plan buildings or toplighted rooms:

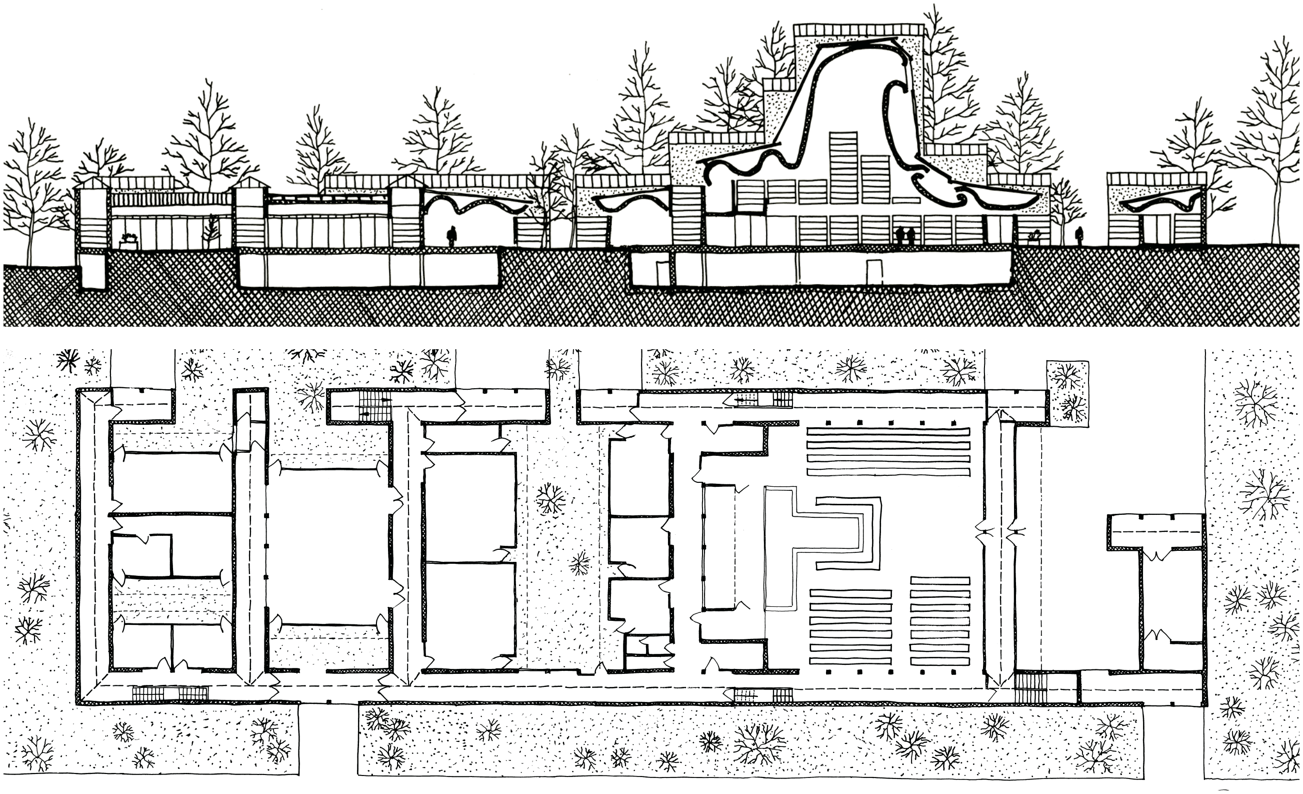
ATRIUM BUILDING organizes rooms around light courts, glazed or unglazed, while TOPLIGHT BUILDING brings light through the roof to short buildings.

TOPLIGHT ROOM offers the designer ways to shape the room to help distribute light from above. TOPLIGHT ROOF provides options for how to shape and organize the roof openings and the roof shape to bring light where the designer intends.

Thick Plan Example

The **Bagsvaerd Church**, near Copenhagen, by Jørn Utzon, is one of the preeminent examples of daylight design (Futagawa, 1981; Weston and Schwartz, 2006). It can be understood as a single story SKYLIGHT BUILDING, as the daylight of each room is either from the top or from the side facing courts. The pattern of rooms organized around courtyards can be also seen as an ATRIUM BUILDING.

Christian Norberg-Schultz (1988) identifies the main sanctuary as a metaphor for the existential condition of man situated between the clouds of heaven and the solid earth. A large west-facing clerestory casts light onto undulating white concrete structural vaults to distribute and diffuse light creating an ethereal TOPLIGHT ROOM. The extra-tall corridors with no windows, topped with a gabled, glassed DAYLIGHT ROOF, form an enclosed compound. Rooms are internally focused, most sharing borrowed light from the corridor skylights and views onto the courtyards through wooden screens. The Danish sun is low in the sky and can be a great source of glare.



Bagsværd Church, near Copenhagen, Denmark, 1976, Jørn Utzon, architect

GLARE-FREE ROOMS are created by placement of the sanctuary and corridor skylights high above the field of view, by multiple reflections on whitish concrete and painted surfaces, and by facing sidelight openings toward walled courts. In this way, all the light becomes indirect such that strong patterns of light and shade are limited to the upper portions of the walls or ceilings.

B6 A *PASSIVELY COOLED BUILDING* is organized to cool itself with wind, sky and earth using a family of strategies fit to place and purpose. [cooling]

KEY POINTS

- Follow a design process hierarchy for passive cooling
- Arid climates can benefit from evaporative cooling strategies, but moisture makes hot-humid conditions worse.

CONTEXT

Each bundle helps build one or more larger strategies at the next scale of complexity. The core strategies of this bundle help build the whole building scale strategy we call PASSIVELY COOLED BUILDING, which in turn helps build five cooling strategies at the scale of urban elements: DISPERSED BUILDINGS, OVERHEAD SHADES, GREEN EDGES, BREEZY OR CALM STREETS and SHADING UMBRELLA.

FORCES

One of the challenges for designers of passively cooled buildings is the selection of appropriate cooling strategies that are effective in the building's climate.

The BIOCLIMATIC CHART shows a basic distinction in cooling options between a hot-humid climate in which natural ventilation is the primary approach and a hot-arid climate in which many more options are available.

A second challenge is that cooling forces during hot periods tend to be weak and dispersed. Passive cooling can be effective for a building only where the heat gains have been minimized.

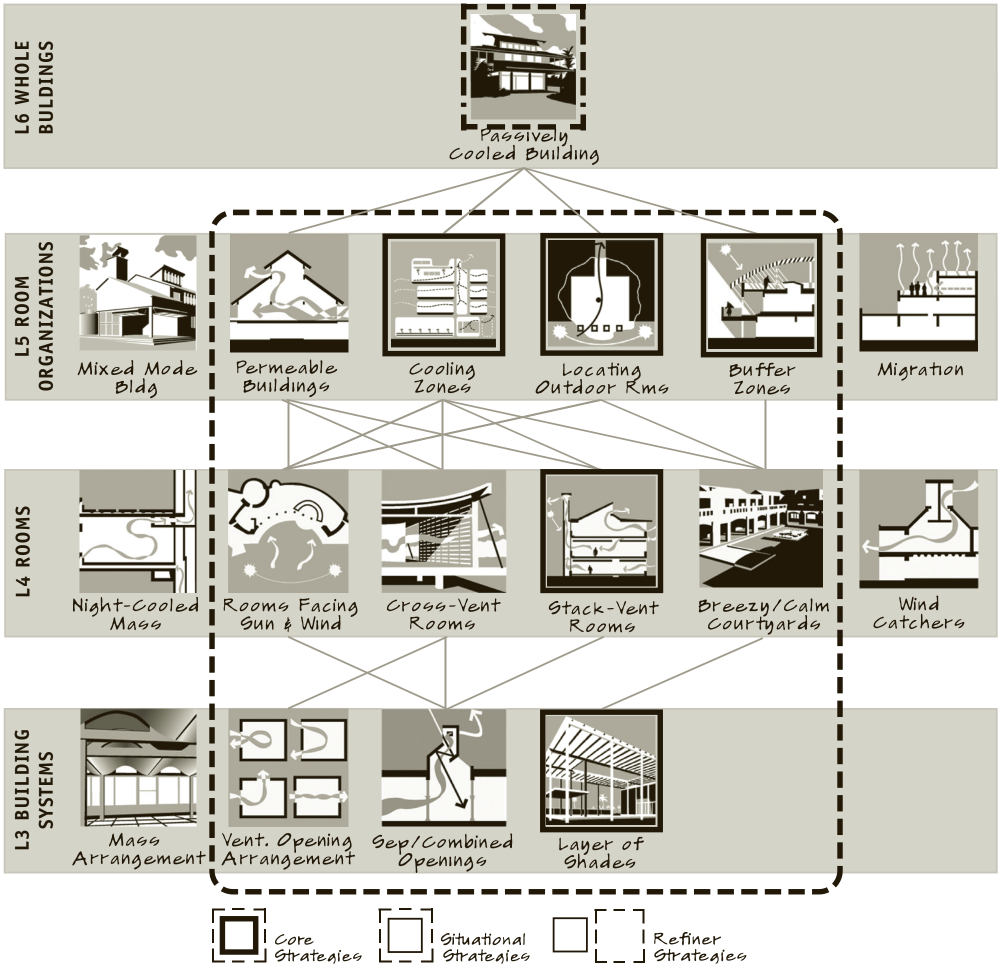
These two challenges mean that a combination of passive cooling approaches must often be used, each effective within a particular range of climate and use conditions.

RECOMMENDATIONS

Take a prioritized and tiered design approach:

1) ***Drastically reduce the cooling loads first.***
2) ***Then meet the remaining loads with good passive design when possible.***
3) ***Supplement with mechanical assistance, such as fans or evaporative coolers.***
4) ***Then use efficient mechanical cooling systems for any remaining loads.***
5) ***Select combinations of strategies based on the matrix criteria.***

The table **Climate Criteria for Cooling Strategies** (next spread) gives guidelines for selecting cooling strategies. In most buildings, a few strategies will be used. A single strategy is rarely effective in all situations throughout the day or in all seasons. The guidelines are general, and exceptions to most of them are possible. Outside temperature is a limit to some passive cooling strategies as natural and cross-ventilation require temperatures lower than those indoors. The sizing tools in VENTILATION APERTURES assume that the outdoor air is 3 °F (5.5 °C) cooler than indoor temperature. This places an upper limit on outdoor temperature at which natural ventilation alone for cooling is effective, depending on comfort criteria. Indoor temperatures can be cooled by 3–4 °F (5.5–7 °C) by the use of ceiling fans. Higher temperatures require the building to be closed for part of the day when it is too hot for ventilation. Heat gains during these closed hours can be stored in THERMAL MASS. NIGHT-COOLED MASS depends on low night temperatures, ideally below the comfort zone, to cool mass after outside temperatures fall. When



PASSIVELY COOLED BUILDING: Hot-Humid Climate Bundle

temperatures are more extreme, the effects of using NIGHT COOLED MASS will often be limited. ROOF PONDS work best when night skies are clear and can cool single-story buildings in extreme climates. If the climate is dry, EVAPORATIVE COOLING TOWERS work well, including under extreme heat. EARTH EDGES can provide some cooling under most outdoor conditions but should not be used if heating outweighs cooling. Similarly, EARTH–AIR HEAT EXCHANGERS can temper incoming ventilation air even in hot conditions. Typically, neither of the ground-based strategies will provide for the entire cooling load.

CORE STRATEGIES

Many factors contribute to TOTAL HEAT GAINS in buildings. In this bundle, strategies at the scales that tend to drive the building's *parti* are addressed. It is assumed that the designer will pay close attention to other important strategies at the material and element scales [see RESPONSIVE ENVELOPE] and that internal gains from lights, people and equipment are carefully addressed.

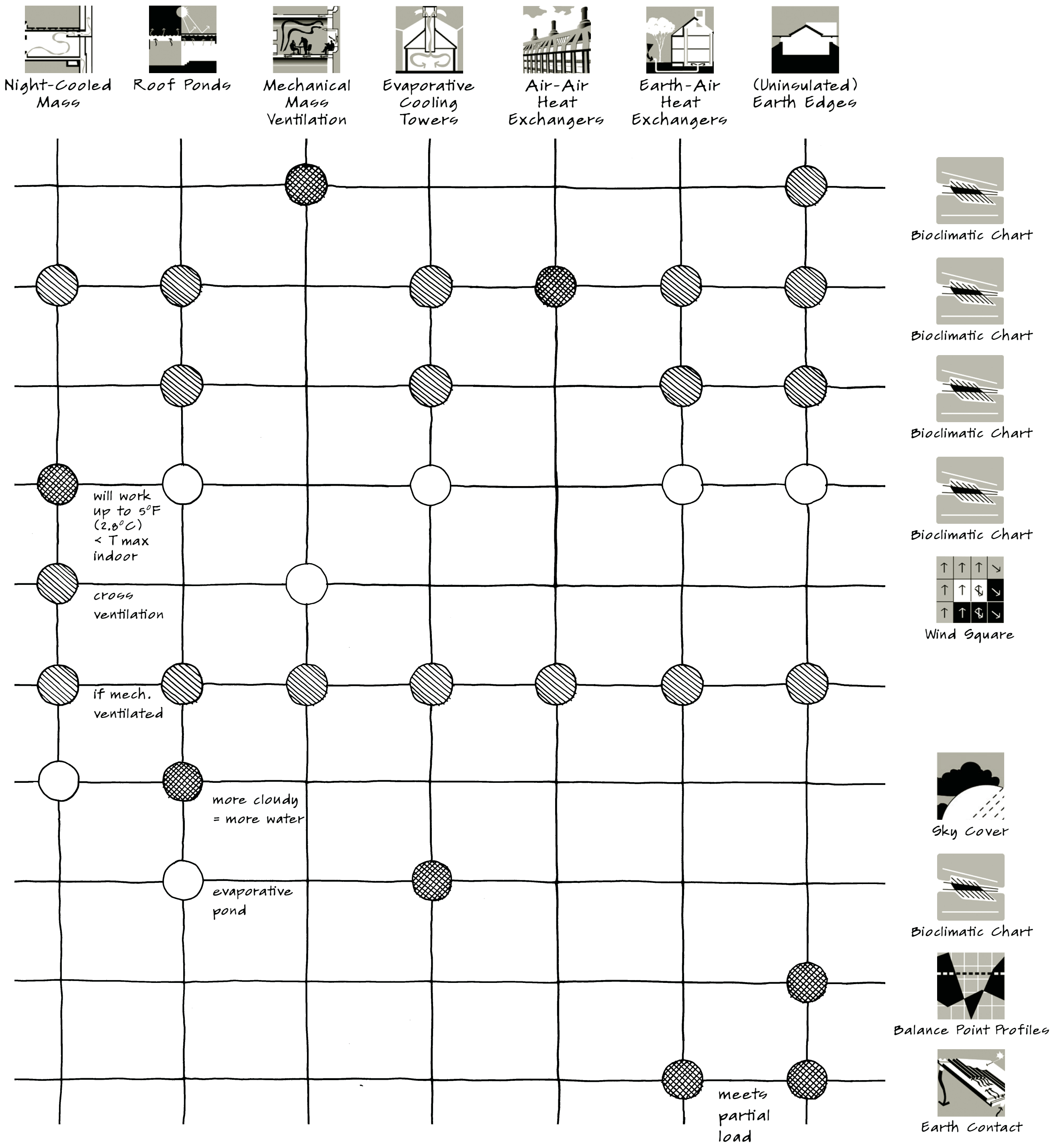
There are **five strategies that are considered invariants in all passively cooled buildings**. While one of

Climatic Criteria for Cooling Strategies

Legend: (hatched circle) Use if answer is YES; (cross-hatched circle) Critical criteria for strategy (YES); (open circle) Use if answer is NO

These strategies are effective once the facts regarding criteria below are determined.

Analysis Techniques	Criteria	Cross-Vent Rooms	Wind Catchers	Stack Vent Rooms	Mechanical Space Ventilation
Bioclimatic Chart	outside temperature is lower than inside temperature	Critical (YES)	Critical (YES)	Critical (YES)	Critical (YES)
Bioclimatic Chart	outside temperature is higher than inside temperature				
Bioclimatic Chart	outside temperature is higher than inside temperature and the comfort zone max.				
Bioclimatic Chart	low temperature at night < 72° F (22 °C)				
Wind Square	wind speed @ building > 3 mph (1.3 m/s); % calm < 10%	Critical (YES)	Critical (YES)	NO	NO
	outdoor air is dusty, polluted (combine with filtration or high inlets)		YES		YES
Sky Cover	sky condition at night > 50% clear				
Bioclimatic Chart	cooling season is arid or semi-arid. overheated hours < 50% RH				
Balance Point Profiles	cooling is more significant than heating; HDD @ T_b < CDD80°F (CCDD 27°C) (also see DD data)				
Earth Contact	ground temperature 5° F (2.8° C) < comfort zone max				



Night-Cooled Mass
Roof Ponds
Mechanical Mass Ventilation
Evaporative Cooling Towers
Air-Air Heat Exchangers
Earth-Air Heat Exchangers
(Uninsulated) Earth Edges
Bioclimatic Chart
Bioclimatic Chart
Bioclimatic Chart
Bioclimatic Chart
Wind Square
Sky Cover
Bioclimatic Chart
Balance Point Profiles
Earth Contact
will work up to 5°F (2.8°C) < T max indoor
cross ventilation
if mech. ventilated
more cloudy = more water
evaporative pond
meets partial load

these strategies might be left out or its function carried out by an alternate strategy, all passively cooled buildings will benefit from each of these five strategies, whether the climate is arid or humid.

LOCATING OUTDOOR ROOMS: Outdoor rooms expand the living space and allow places for MIGRATION. They may support associated occupied floor areas inside the envelope. Designers can ask, *What spaces (such as circulation or morning meeting) can happen in unconditioned outdoor spaces?* This strategy directs the designer to consider the combination of wind and sun directions when locating outdoor rooms. For example, in a hot climate, when the summer sun and wind come from the same direction, admitting the breeze rules, and the designer must admit wind first and provide structured or landscaped shade to minimize harsh sun.

BUFFER ZONES: Some rooms can tolerate temperature swings and can be located between the more protected rooms and undesired heat sources, often the eastern or western sun, or the roof. These spaces can be used as thermal buffer zones between the more extreme outside conditions and spaces that need somewhat more careful temperature control.

COOLING ZONES: If parts of the building can be cooled during only a portion of the day, or with a passive strategy or with a low-energy cooling system such as evaporative cooling, then the overall energy for cooling will be significantly reduced. This strategy directs the designer to consider arranging spaces that have similar cooling needs and occupant schedules together in zones of the plan or section. Its consideration begins with ENERGY PROGRAMMING. If these spaces are in the same zone they can employ the same energy efficient design strategies to maintain the space's comfort. In ENERGY PROGRAMMING, spaces are categorized by allowable temperature range, internal rate of gain and occupant density.

STACK-VENTILATION ROOMS: In almost all climates natural ventilation will provide some or all of the cooling for some portion of the cooling season or for some portion of the day. It is like throwing money away not to employ it. In a significant number of climates, the wind is calm for portions of the day, so CROSS-VENTILATION, while effective when the wind blows, does not always work. In most cooling climates, temperatures during the summer afternoon will be too hot for the outside air to provide much cooling. In such cases, NIGHT-COOLED MASS strategies will often work well, but winds tend to be most calm at night. For all these reasons, we recommend stack-ventilation for almost all passively cooled buildings. This strategy directs the designer to consider the sectional quality of the building to enhance this gravity-driven ventilation system. In a room cooled by stack-ventilation, warm air rises, exits through openings at the top of the room, and is replaced by cooler air entering low in the room.

LAYER OF SHADES: One of the greatest design opportunities in hot climates is to expand the idea of the envelope from a thin construction (conceptually a line) to a broader spatial zone of elements. Solar heat gain on the roof is greatest in the middle of the day, when the sun is overhead in summer. In most hot climates, the sun is high enough in the sky for much of the day that a horizontal structure of overhead elements is effective at shading outdoor spaces, roofs, or entire buildings (except in the early morning and evening, where vertical shades or adjacent buildings [SHARED SHADE] would be more effective). This strategy gives recommendations for the size and location of overhead shades. On east and west walls in very hot climates, consider the related DOUBLE SKIN MATERIALS strategy.

SITUATIONAL STRATEGIES
Variations Based on Hot-Humid and Hot-Arid Climates

This bundle may be varied by the climatic context of aridity or humidity. To select which bundle variation to use for your combination of climate and use, refer to the table for **Bundle Variations by Climate and Internal Gains** in the chapter “Bundles Explained: Relationships Among Strategies.”

1. Hot-Humid PASSIVELY COOLED BUILDING Bundle (diagram, opening spread)

The hot-humid bundle focuses on reducing solar gain and maximizing ventilation across all scales.

NIGHT-COOLED MASS will be effective in many situations for some portions of the year and should be carefully evaluated.

Hot-Humid Situational Strategies

In addition to the five core strategies applicable to all buildings, this bundle variation adds these situational strategies that will apply to most buildings in hot-humid climates:

PERMEABLE BUILDINGS: Because humid climates depend so greatly on ventilation for cooling, it is critical to promote *both* cross- and stack-ventilation by making plans and sections open as a pathway for air.

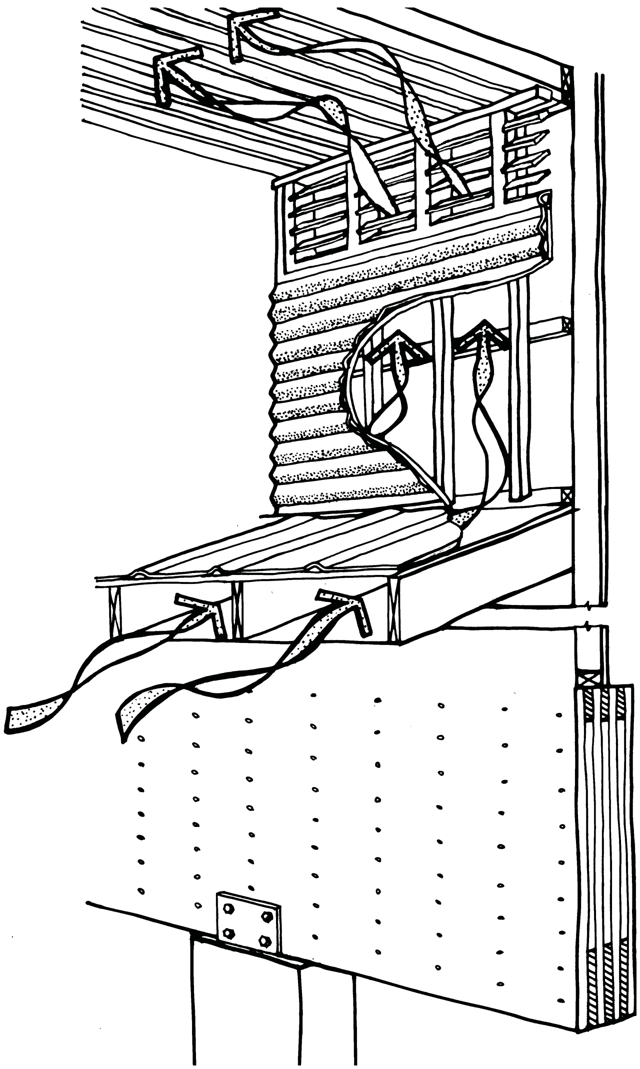
CROSS-VENTILATION ROOMS: More than arid climates, humid climates can use wind-driven cross-ventilation when the wind is available. Wind driven ventilation is, in general, more effective than stack-ventilation. However, because the wind is not always available, most humid-climate buildings should also design for STACK-VENTILATION ROOM.

ROOMS FACING THE SUN AND WIND: To support cross-ventilation, face inlets towards the prevailing breezes and be aware of secondary wind directions [WIND ROSE]. Cross-ventilation outlets *and* stack ventilation outlets should face *away* from the prevailing wind.

BREEZY COURTYARDS: A fully enclosed courtyard is one of the least comfortable outdoor spaces in a humid climate. It cannot be cooled by the breeze and air becomes stagnant. Therefore, like indoor rooms, outdoor rooms and courts used in the hot season can be designed with shade and partial enclosure that promotes good ventilation.

VENTILATION OPENINGS ARRANGEMENT: A good cross-vented plan only works if the ventilation apertures are placed so that all of the floor space is cooled by moving air and there are no dead air zones. Similarly, an elegant stack-ventilation section can not work for cooling if the openings are misplaced for a full-coverage air flow path through each space.

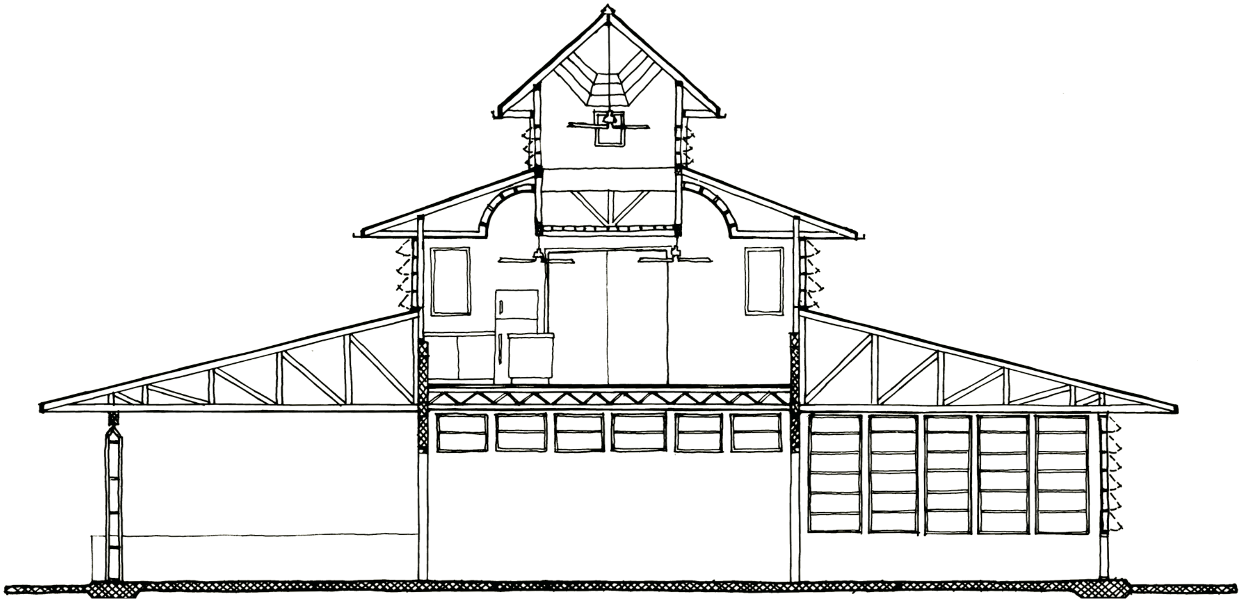
SEPARATED OR COMBINED OPENINGS: Because ventilation apertures may be larger than solar or daylight apertures, and because there are so many places they are required to be, consider whether in some cases, ventilation openings may be handled separately, thus avoiding overlighting or overheating from glazed apertures.



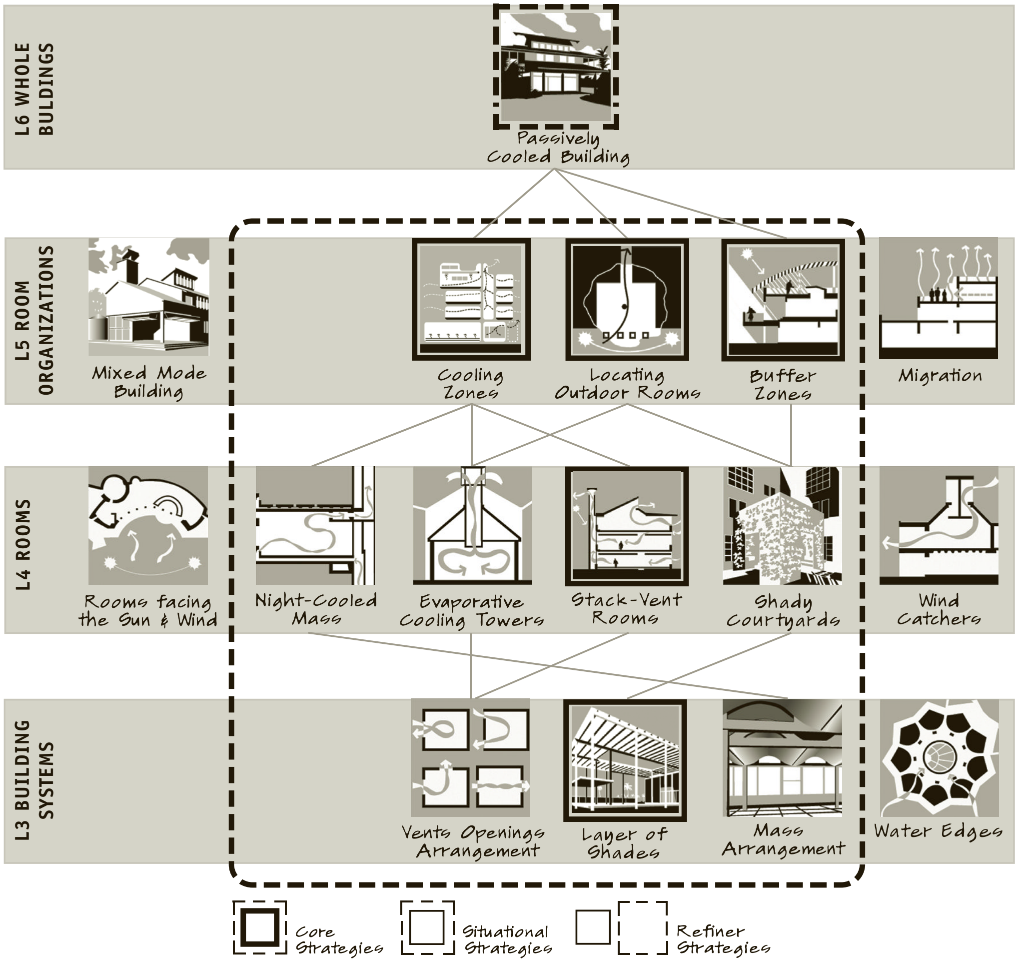
Vented Wall + Roof System, Palmetto House

Hot-Humid Example

The elegant **Palmetto House** in Redland, Florida, by Jersey Devil Design/Build, near the Everglades, is a fine example of a passively cooled building in a hot-humid

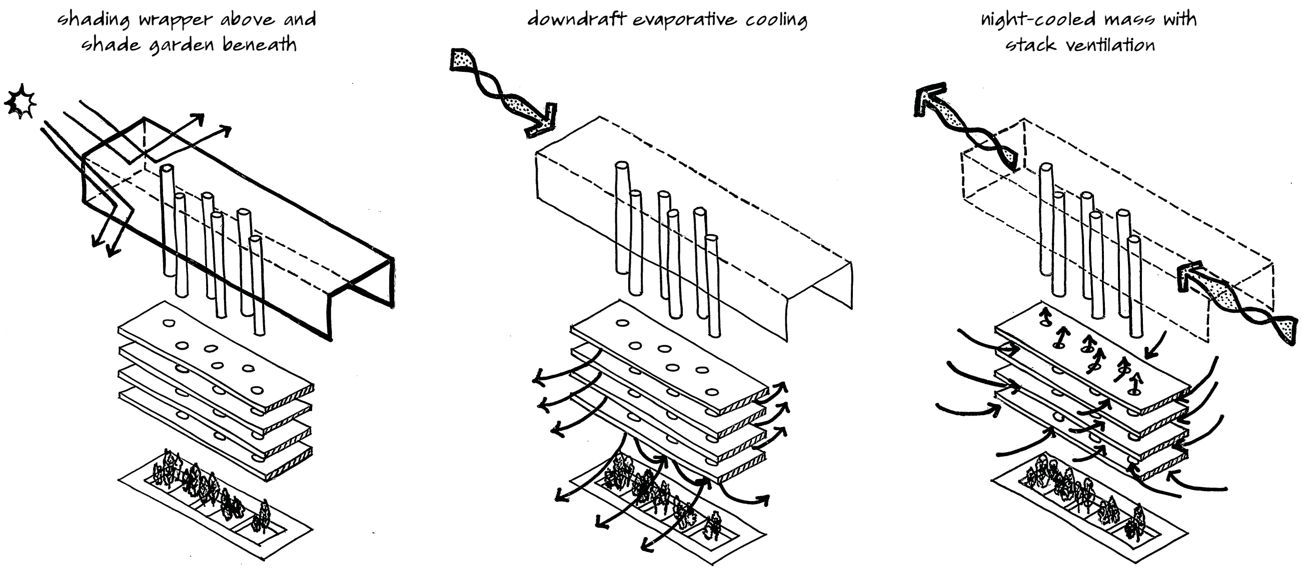


Palmetto House, Redland, Florida, 1989, Jersey Devil Design/Build



PASSIVELY COOLED BUILDING: Hot-Arid Climate Bundle

climate (Piedmont-Palladino and Branch, 1997; Badanes, 1989). Raised off the ground to catch breezes [ROOMS ORIENTED TO THE SUN AND WIND], it uses a double skin **Vented Wall and Roof System** with radiant barriers [DOUBLE SKIN MATERIALS] to reduce solar gains. On the main (second) level, it is designed with shaded screened porches [LOCATING OUTDOOR ROOMS] at both ends [MIGRATION, BUFFER ZONES]. The house is zoned vertically with a ground floor professional woodworking shop in the shadiest zone [COOLING ZONES] and the more sedentary writing office on the top floor. Designed as a PERMEABLE BUILDING, the main floor is a large single room with partitions less than ceiling height and a metal grated ceiling, allowing for STACK-VENTILATION, which can exit though even higher outlets in the long cupola. The plan is one room thick, promoting CROSS-VENTILATION. VENTILATION APERTURES are plentiful and opposite each other to maximize cross flow [VENTILATION OPENINGS ARRANGEMENT]. The large overhanging porches and extensive overhangs and roofs create a LAYER OF SHADES for outdoor patio and work spaces.



Experimental Office Building, Catania, Sicily, Mario Cucinella Architects (MCA), 1998

2. Hot-Arid PASSIVELY COOLED BUILDING Bundle

The hot-arid bundle focuses on reducing solar gain and exploiting a range of strategies orchestrated to address the often extreme temperatures. Arid climates open the possibility of evaporative cooling and large daily temperature swings align very well with NIGHT-COOLED MASS.

Hot-Arid Situational Strategies

In addition to the five core strategies applicable to all buildings, this situational bundle adds these strategies that will apply to most buildings in hot-arid climates:

SHADY COURTYARDS offer a respite from intense sun. Their proportions are biased toward shade rather than wind, as in hot-humid climates.

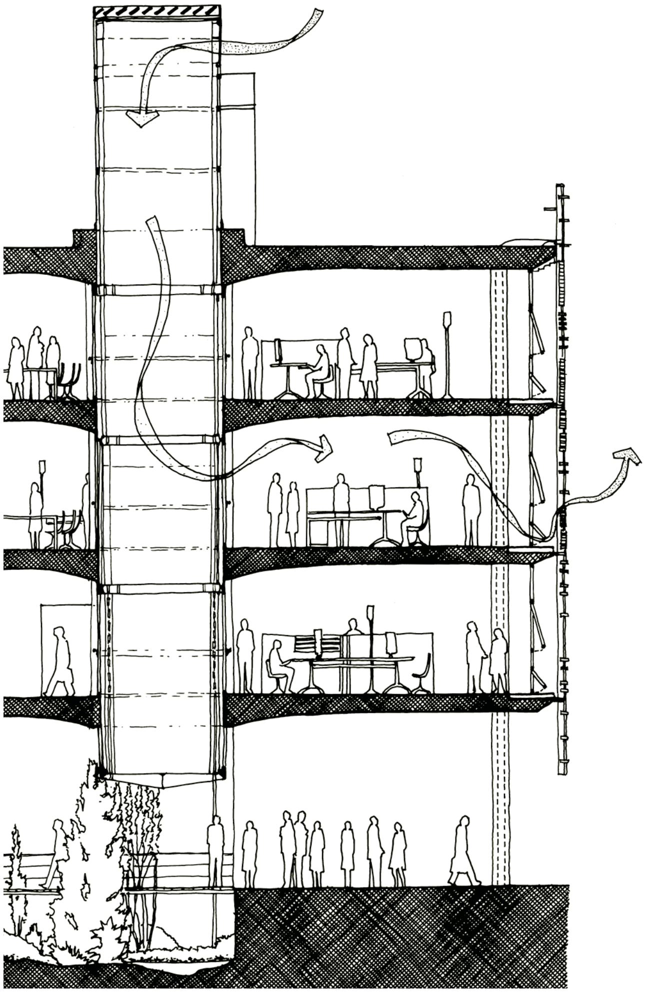
EVAPORATIVE COOLING TOWERS, not a viable option in an already humid climate, work well in arid conditions by using gravity to drive air flow without wind or fans and to cool and humidify air. They can cool when the air is much too hot for natural ventilation cooling alone. Substantial new research is available to guide designers (Ford et al, 2010).

NIGHT-COOLED MASS ROOMS are a great fit in arid climates where temperature ranges tend to be high and straddle the comfort zone. This is a good combination with evaporative cooling, which can be used to supplement mass cooling or can be used during the day, depending on conditions.

MASS ARRANGEMENT assures that thermal mass for cooling is located where it can absorb the most heat during the day and give that heat up to ventilation air during the night. The location of massive and nonmassive elements can be a major driver of building order.

Hot-Arid Example

Mario Cucinella Architects designed a prototype design for an **Experimental Office Building** in Catania, Sicily, as part of the EU's Passive Downdraft Evaporative Cooling (PDEC) research project (Ford et al, 2010). The building is organized into cooling zones with spaces clustered around a series of central cylindrical, glazed **Downdraft Evaporative Cooling Towers** that function when the air is too hot outside for natural ventilation (see also EVAPORATIVE COOLING TOWERS strategy). The shape of the towers is derived



Downdraft Evaporative Cooling Towers, Experimental Office Building, Catania, Sicily, Mario Cucinella Architects (MCA), 1998

from the form of the cool air plume. The cooling towers can also operate as updraft shafts for STACK-VENTILATION ROOMS during the day when outside air is cooler than inside or at night while employing NIGHT-COOLED MASS.

The building's MASS ARRANGEMENT is in the form of concrete floors and ceilings. The VENTILATION OPENINGS ARRANGEMENT was carefully studied with predictive models to provide the proper and controllable amount of cooling to each floor and zone. A LAYER OF SHADES over the entire building reduces solar gain to the roof and provides a shady/breezy roof terrace [LOCATING OUTDOOR ROOMS], while the raised building provides a shady cooled garden below [SHADY COURTYARDS]. The building is predicted to use only 15% of the cooling energy of a conventional office building (Cucinella et al, 2004; Cucinella, 1998).

B7 A *PASSIVE SOLAR BUILDING* is organized to heat itself with the sun using a family of strategies fit to place and purpose. [heating]

KEY POINTS

- Creative design in section and of heat distribution can solar heat even thick building plans.
- A combination of solar heating systems is usually better than employing a single approach.
- All solar heating systems combine collection, storage and distribution.

CONTEXT

Each bundle helps build one or more larger strategies at the next scale of complexity. The core strategies of this bundle help build the whole building scale strategy SOLAR HEATED BUILDING, which in turn helps build three heating strategies at the scale of urban elements: SOLAR ENVELOPE, EAST–WEST BUILDING GROUPS, which set the context for solar access to buildings (yours and others), and WINDBREAKS, which reduces convective heat loss and infiltration to buildings.

FORCES

Whereas a mechanical system shapes the climate to fit the building, a passive solar building shapes the building to fit the climate. The thicker the plan relative to the sunny winter orientation, the more difficult it is to collect the sun and get its heat to each room.

A passive solar heated building uses the configuration of the architecture to collect, store and distribute heat from the sun. Each of the five solar system types at the scale of rooms [DIRECT GAIN ROOMS, SUNSPACE, THERMAL STORAGE WALLS, ROOF PONDS and THERMAL COLLECTOR WALLS AND ROOFS] are combinations of collection, distribution and storage.

The prerequisite for solar heating is to minimize TOTAL HEAT LOSS. The solar resource is relatively weak and distributed. It is sufficient, but only with a highly efficient building envelope.

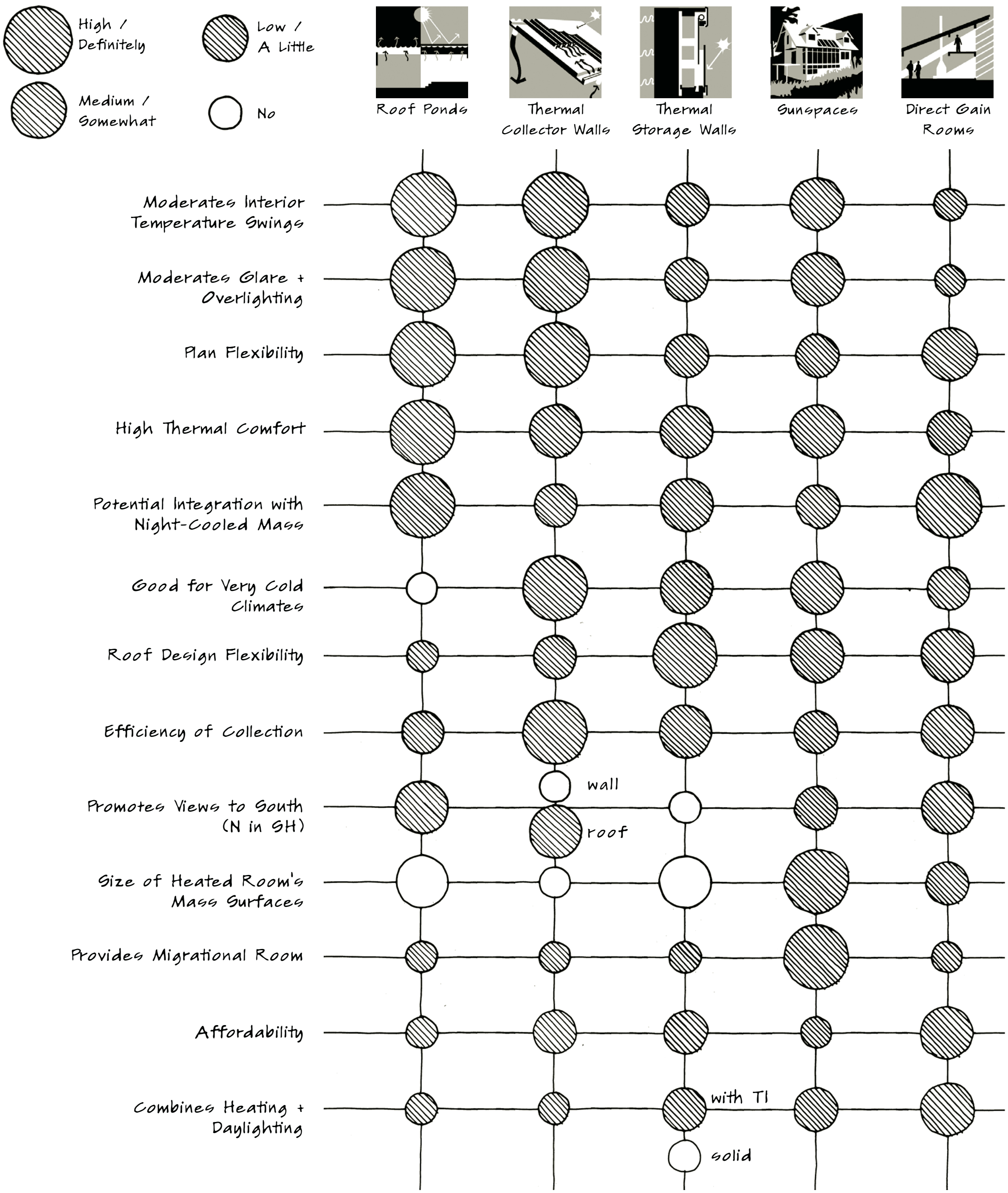
Storage [THERMAL MASS, MASS ARRANGEMENT] can be near the collection aperture, in the same room, in an adjacent room, or remote from the collection. The farther away the thermal storage is from the collection, the more MOVING HEAT TO COLD ROOMS will have to be employed. Some amount of mechanically assisted movement is common in thick buildings.

RECOMMENDATIONS

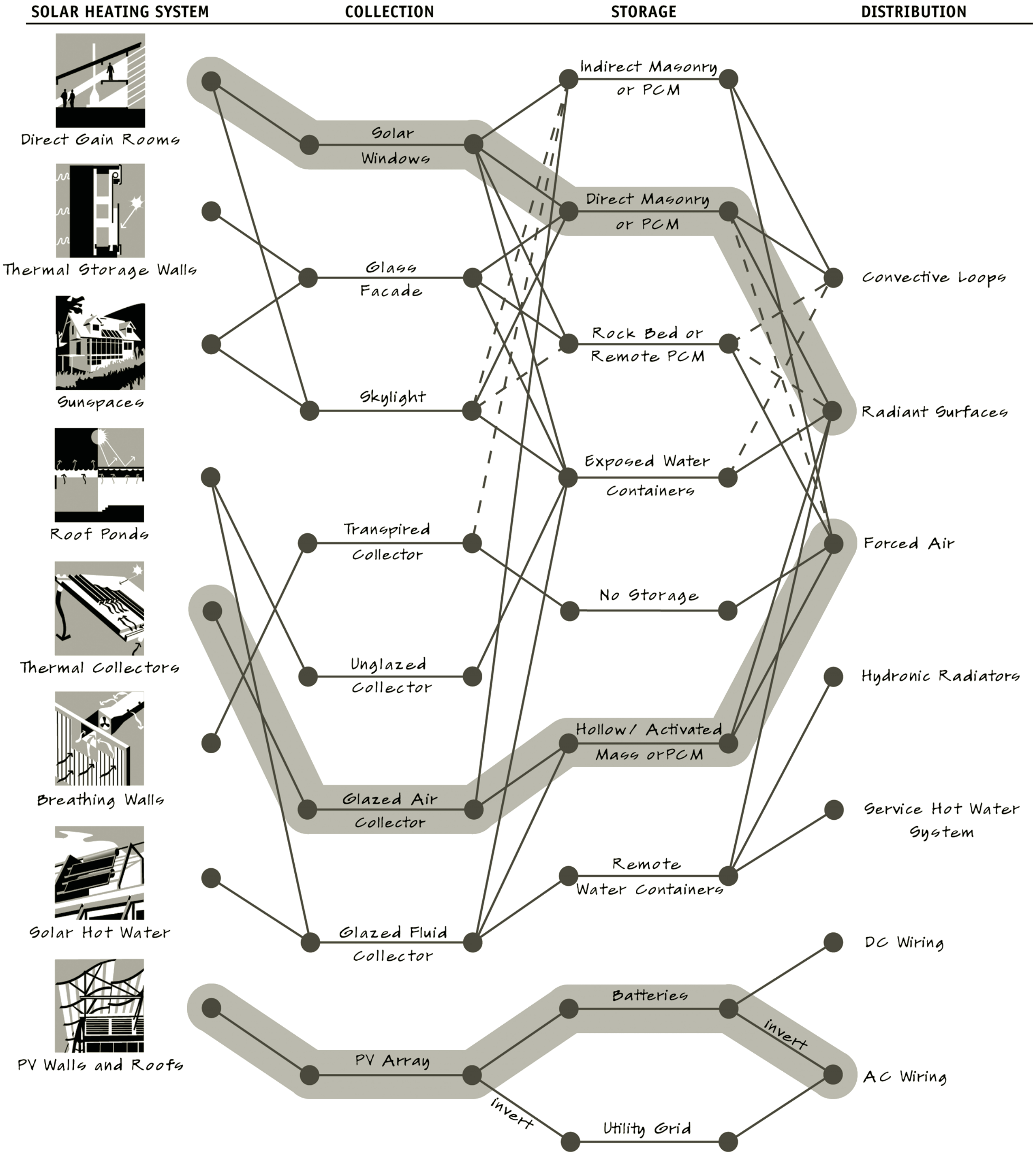
In shaping the architecture to become a kind of heat exchanger, use and site combine to influence the basic building massing and choice of systems.

- ***If the site and program allow, begin with the "Thin Plan" bundle variation and employ* EAST–WEST PLAN *with* DIRECT GAIN ROOMS*, the simplest solution. If the plan requires more than two rooms in the north-south direction, also use the "Thick Plan" bundle variation, beginning with* DEEP SUN.**
- ***If the site dictates a short face toward the equator, or a plan with three or more rooms in the north-south direction, begin with the "Thick Plan" bundle variation and employ* DEEP SUN.**
- ***Where possible, combine* DIRECT GAIN ROOMS *with other room-scale solar heat strategies, such as* THERMAL STORAGE WALLS *or* SUNSPACES*, to balance heat gains with daylight needs, controlling glare and offering control options.***
- ***Tightly control heat loss. Be sure to pay attention to all of the elements given in* TOTAL HEAT LOSSES.**

To utilize the diagram **Characteristics of Different Solar Heating Systems**, select the system that best fits the desired characteristics of the building's rooms. Remember



Characteristics of Different Solar Heating Systems



Combining Collection, Storage, and Distribution to Create Solar Heating Systems

that different systems can be used for different HEATING ZONES and that more than one system can be combined in a single zone.

The diagram **Combining Collection, Storage and Distribution to Create Solar Heating Systems**, shows alternative configurations of the elements needed in any solar system design. The diagram shows systems for passive solar heating, active solar thermal (space heat), solar hot water and photovoltaics. The links show the most common options and relationships among elements. Many other variations and less common combinations are also possible. The shaded pathways indicate the prototypical configuration for each system. For example, [DIRECT GAIN ROOMS] is the simplest and most common passive solar system and its prototypical configuration collects sun through solar windows [see SOLAR APERTURES], stores heat in direct masonry or PCM [THERMAL MASS] placed in wall and floors [see MASS ARRANGEMENT] and redistributes heat as the room cools primarily via natural radiation to cooler room surfaces.

CORE STRATEGIES

There are five strategies that are so pervasive in passive solar buildings that they can be considered invariants. Each of these five strategies will be effective in any solar design.

HEATING ZONES: Organize the plan and section to place rooms with similar needs for heat together. Rooms that need more heat get access to more sun while rooms that are less occupied, make their own heat, or can be cooler can get less access to sun.

ROOMS FACING THE SUN AND WIND: Orientation is critical to solar heating success and, surprisingly, often overlooked by many designers. Orienting within about 30° of south (N in SH) maximizes winter solar gain.

DIRECT GAIN ROOMS: This is in many ways the simplest and, as the name implies, most direct means of solar heating. Because most rooms have windows and some rooms in most buildings can face the equator, this strategy works for at least a part of the solar concept in almost all buildings.

MASS ARRANGEMENT: Thermal mass stores heat, and to be effective, it has to be located where it can absorb solar heat that is collected and discharge that heat later to warm the room. Critical to this placement is the distinction between *direct mass* (in the solar space) and *indirect mass* (remote from collection), which is about one-third as effective.

WELL-PLACED WINDOWS recognizes that winter sunny windows can collect heat, but other orientations are net heat losers. As windows lose much more heat than opaque walls or roofs, the key is to locate just enough window area for daylight and views on east, west, and polar sides.

SITUATIONAL STRATEGIES

Variations Based on Thin Plan and Thick Plan Buildings

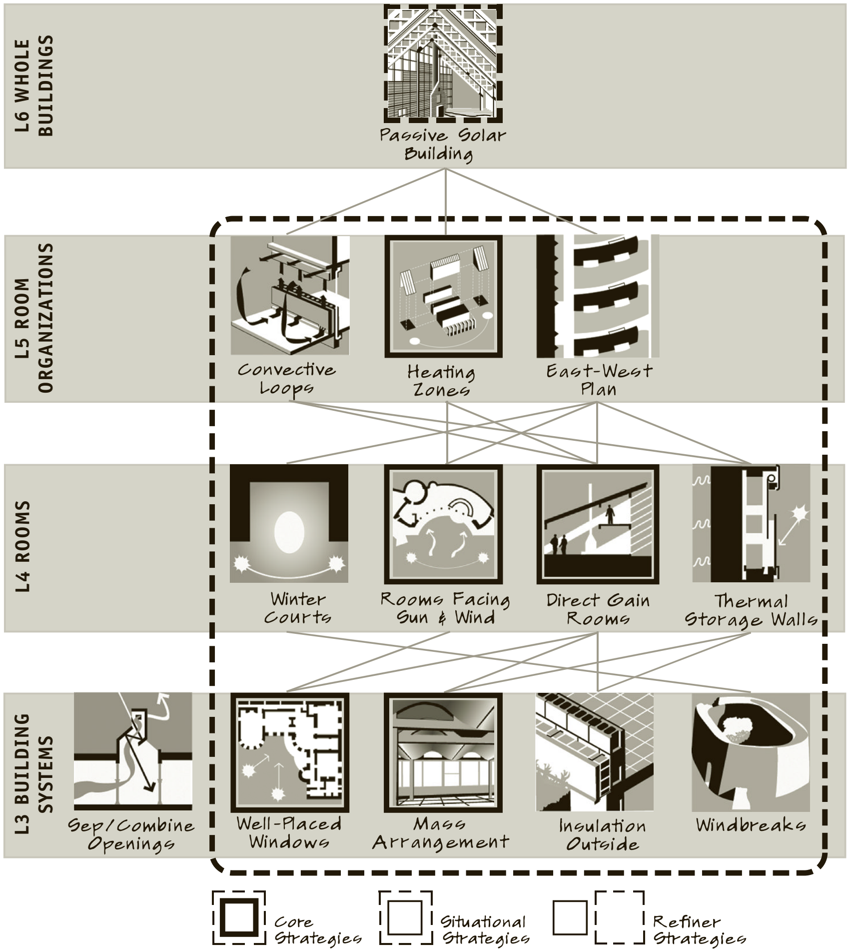
This bundle distinguishes two families of strategies, one for “Thin Plan” buildings and “Thick Plan” buildings.

1. Thin Plan SOLAR HEATED BUILDING Bundle

The “Thin Plan” bundle (diagram, next page) focuses on building organizations and plans with an east-west orientation and a combination of direct gain with other solar systems.

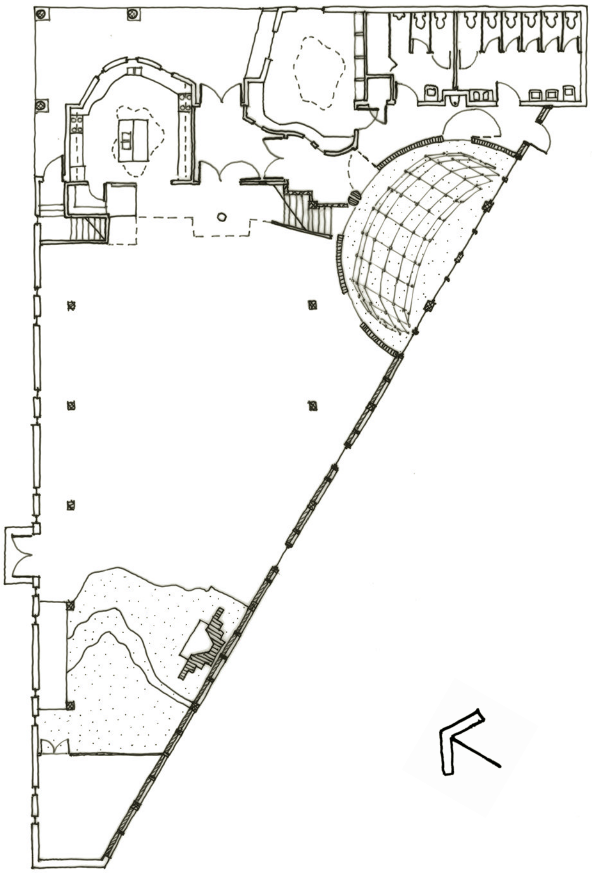
Thin Plan Example

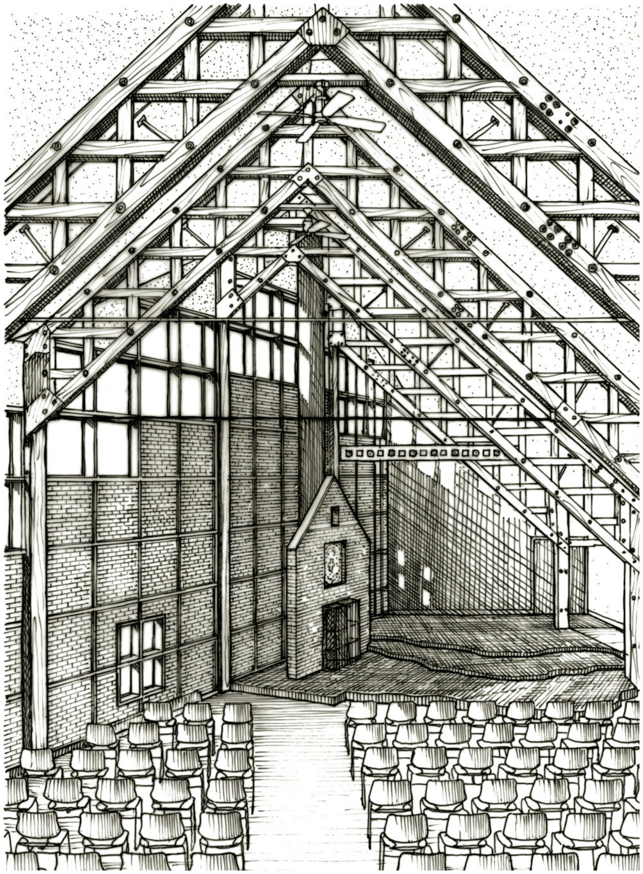
Architects Bohlin Cywinski Jackson designed the **Shelly Ridge Girl Scout Center** in Miquon, Pennsylvania (next spread) is an excellent example of a passive solar building with multiple system types (Dean, 1984; Architectural



PASSIVE SOLAR BUILDING: Thin Plan Bundle

Record, 1985; Bohlin Cywinski Jackson, 1984). The building is thin in that its large room stretches in a sophisticated interpretation of EAST–WEST PLAN, having a long south facade, while, along the east side, rooms without south exposure can share heat from the large sunny room. HEATING ZONES are simple: The semicircular lobby takes direct sun, becoming a sunspace; the most occupied room, the great hall, has the most access to south sun; and the entry, circulation, kitchen, etc. are along the east edge. The south facade is oriented due south [ROOMS ORIENTED TO THE SUN AND WIND] while other walls respond to the site and other buildings. The organization is a combination of a thin masonry THERMAL STORAGE WALL and a DIRECT GAIN ROOM, with daylight windows puncturing the brick, supplemented by the SUNSPACE. Openings are configured as WELL-PLACED WINDOWS, with the majority of glazing on the south, daylight and view windows to the east, and very little glass on other orientations. MASS ARRANGEMENT is a well-distributed combination of a large brick stage and fireplace, a tall brick mass wall and a concrete floor with arcing brick partition wall for the sunspace lobby. With its low north face and sloping roof, the building itself forms a WINDBREAK for a south-facing, if loosely defined WINTER COURT.





Shelly Ridge Girl Scout Center, Miquon, Pennsylvania, 1984, Bohlin Cywinski Jackson, architects

Thin Plan Situational Strategies

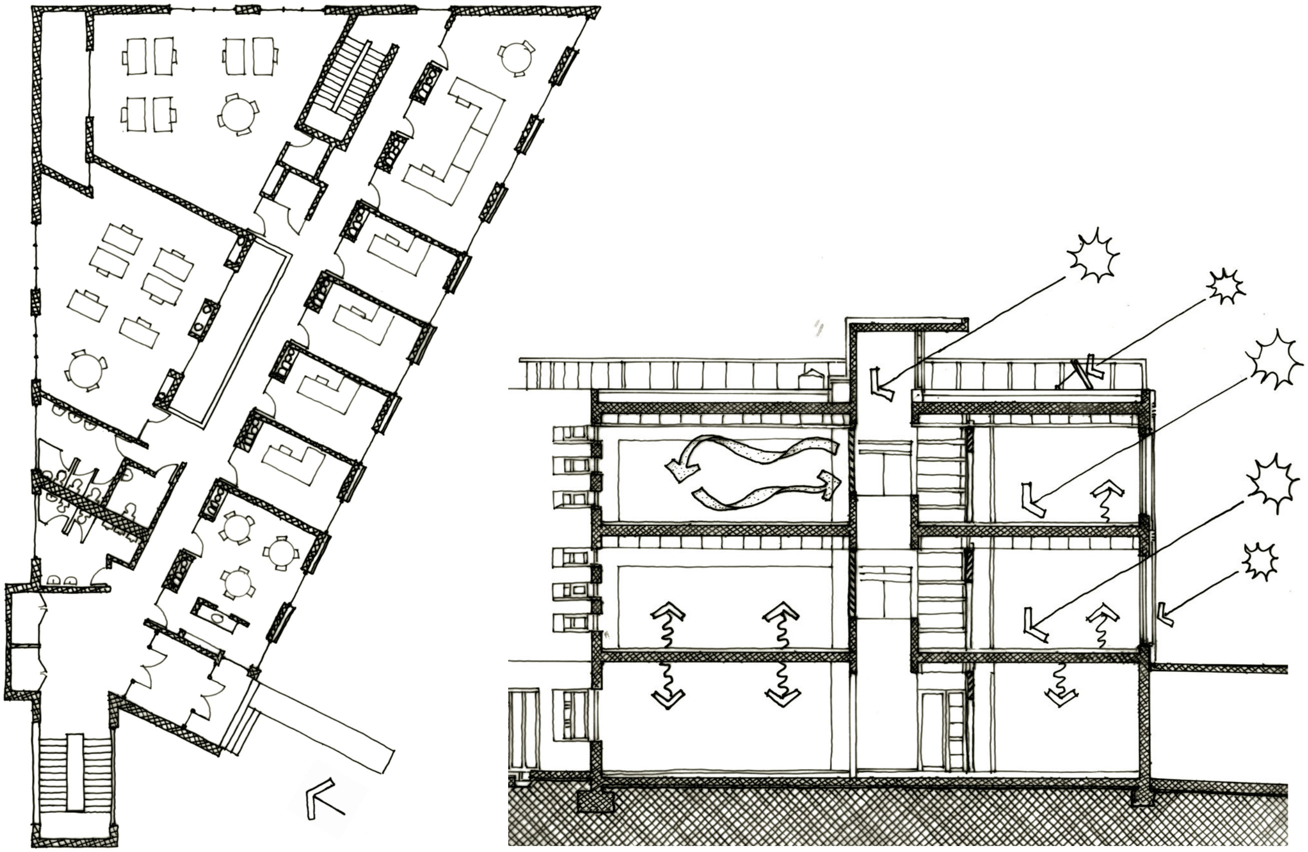
In addition to the five core strategies applicable to all passive solar buildings, this situational bundle adds these strategies that will apply to most thin plan buildings:

EAST-WEST PLAN directs the designer to, when possible, spread rooms along an east-west axis to maximize exposure to winter sun while also minimizing exposure to harsh east and west heat gains in summer.

CONVECTIVE LOOPS, which are driven by hot air rising and cool air falling in the section, are one means to distribute heat within a room or to move heated air from a sunny room to an adjacent space. Heat distribution by natural convection works best when the distances are small, such as in a thin building.

THERMAL STORAGE WALLS are a good complement in many buildings to DIRECT GAIN ROOMS. When direct gain alone is used, south glazing may be quite large and glare can become an issue if not handled properly. The mass in walls delays heat to later in the day or evening, whereas direct gain heats the space up in the morning.

WINTER COURTS: Thin building plans, particularly those that shield outdoor spaces from the wind, are a good fit



Edifício Solar XXI, National Laboratory for Energy and Geology (LNEG), Lisbon, Portugal, 2006, Pedro Cabrito and Isabel Diniz, architects

with sunny, south-facing outdoor rooms. The building massing can be configured to create a microclimate favorable to an extended outdoor use season.

INSULATION OUTSIDE of the mass is required any time THERMAL MASS is located in the exterior envelope, such as on an exterior wall, or in a floor raised over outdoor air.

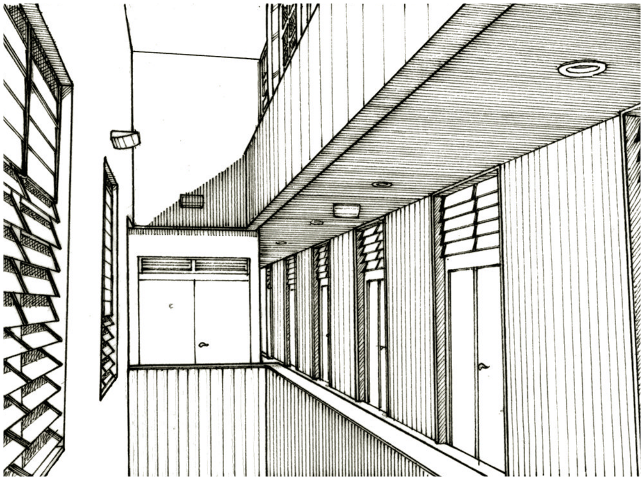
WINDBREAKS can reduce wind-driven heat loss. As thin buildings have larger exposed perimeter areas, reducing cold winds is worth considering seriously. Similarly, the building itself can become a windbreak for outdoor rooms or for other buildings in a complex.

2. Thick Plan SOLAR HEATED BUILDING Bundle

The "Thick Plan" bundle variation (diagram, next spread) focuses on building organizations with three or more rooms in the north-south direction, requiring sectional strategies and more sophisticated distribution logics to bring sun to each room.

Thick Plan Example

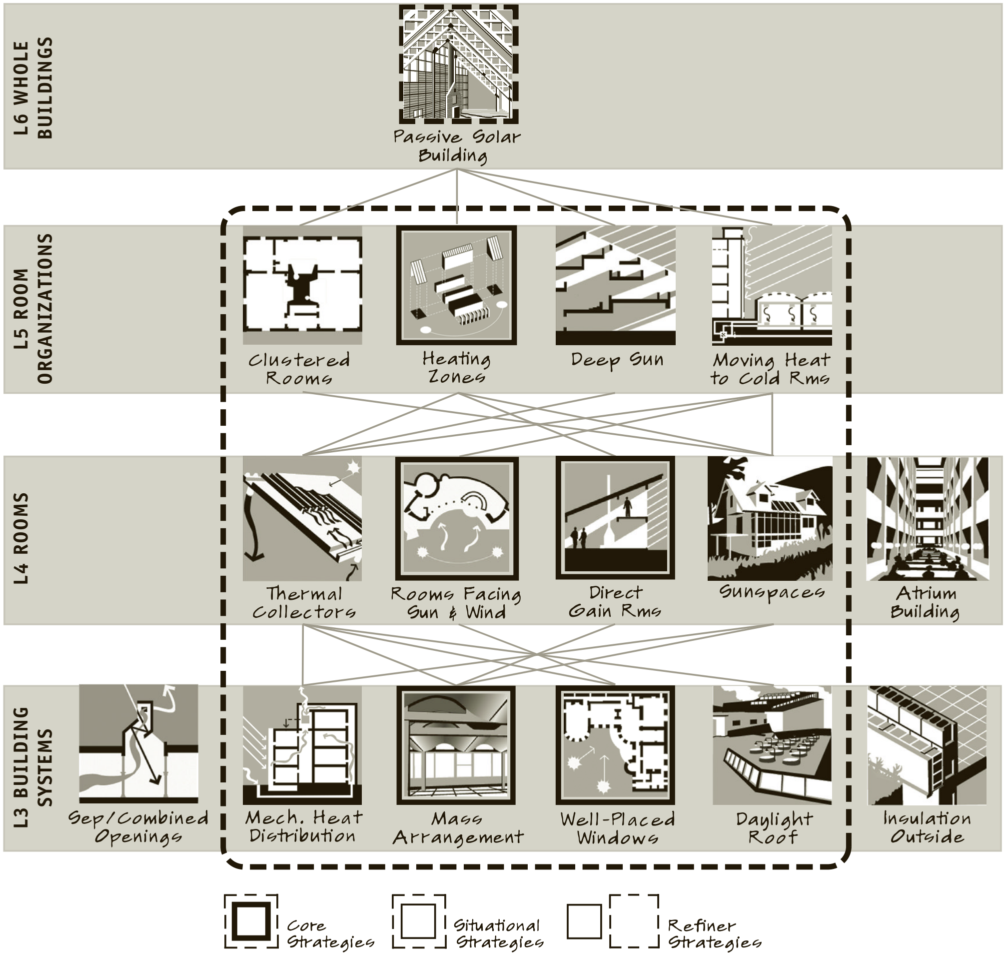
In Lisbon, Portugal, architects Pedro Cabrito and Isabel Diniz designed the **Edifício Solar XXI building** using simple architectural strategies to heat a relatively thick building (Gonçalves & Cabrito, 2006; Gonçalves, et al,



Edifício Solar XXI, interior louvers for natural convection in winter and stack ventilation

2012). The plan is organized according to HEATING ZONES by locating rooms that are most occupied to the south and labs that generate more heat and are less occupied to the north. The section admits DEEP SUN by raising a south-facing clerestory over a three-story light well and circulation zone (also serves as a STACK-VENTILATION ROOM).

Passive CONVECTIVE LOOPS are made possible by large doors to the offices, **interior louvers** at the top of the office wall, and even larger louvers in the lab walls facing the light well. In this way, solar heat can be moved from the south rooms to the corridor and from the corridor to the labs [MOVING HEAT TO COLD ROOMS]. The atrium and south offices are heated as DIRECT GAIN ROOMS, and the offices are supplemented by a CONVECTIVE LOOP in the wall that makes use of waste heat from the PHOTOVOLTAIC WALL, making it essentially a THERMAL COLLECTOR WALL. The offices and clerestory SOLAR APERTURES are organized due south, for ROOMS FACING THE SUN AND WIND. As suggested in WELL-PLACED WINDOWS, south glazing is large (12% of the floor area), and other orientations are limited to glazing for daylight and ventilation. MASS ARRANGEMENT serves both heating and cooling, with hollow brick mass walls, including behind the PVs, coffered concrete ceilings with INSULATION OUTSIDE and mass floors.



PASSIVE SOLAR BUILDING: Thick Plan Bundle

An active solar thermal system is used for SOLAR HOT WATER and back-up heating. The building is cooled by EARTH–AIR HEAT EXCHANGERS and NIGHT-COOLED MASS, and has no mechanical air-conditioning.

Thick Plan Situational Strategies

In addition to the five core strategies applicable to all passive solar buildings, this situational bundle adds these strategies that will apply to most thick plan buildings:

DEEP SUN helps the designer find sectional concepts that admit sun past the first sun-facing room to get solar heat deeper into the building.

CLUSTERED ROOMS reduce heat loss through the exterior skin. A thick building will tend to have a lower skin to volume ratio than a thin building. Clustered room organizations fit well with SUNSPACES, which concentrate solar collection and storage.

MOVING HEAT TO COLD ROOMS: If the building must be ordered such that each room cannot get direct sun, then several strategies are available for getting the heat from where it is collected to the rooms lacking their own. In some cases, MECHANICAL HEAT DISTRIBUTION, integrated with the HVAC system, is required.

THERMAL COLLECTOR WALLS AND ROOFS are a good way to collect heat efficiently when air will be the heat distribution medium to storage and use in remote spaces, which is a common requirement in thick buildings.

SUNSPACES face the equator, can be multistory and lend themselves to collecting a large amount of heat with a small orientation toward the sun. They are also a good fit with the less linear, more clustered room organizations found in thicker buildings.

TOPLIGHT ROOM in an atrium building, thick by definition, may also function as a SUNSPACE for passive solar heating if it has substantial glazing facing the equator.

DAYLIGHT ROOF brings in light to areas of thick buildings where sidelight does not reach. Some portion or all of its aperture can be oriented to the sun for winter solar gain.

B8 Comfortable *OUTDOOR MICROCLIMATES* adjacent to buildings are organized using a family of strategies fit to place and outdoor use. [heating and cooling]

KEY POINTS

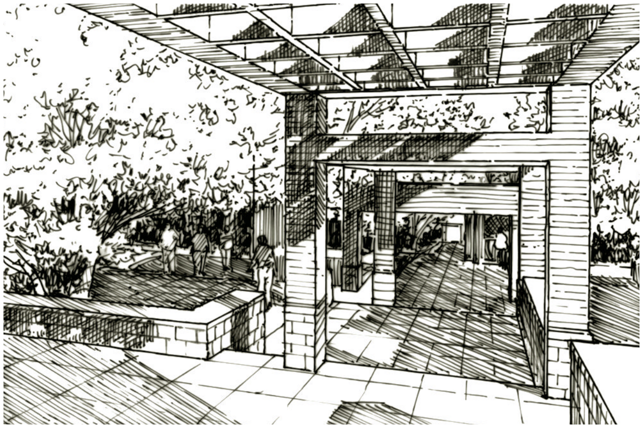
- Outdoor space has a rich design language available and needed to support net-zero energy design.
- The period of comfort in outdoor spaces can be greatly expanded by appropriately admitting or blocking sun and wind.
- Outdoor heating and cooling goals have conflicting design implications.
- In mixed heating and cooling climates, careful design may allow for seasonal adaptation to both conditions.

CONTEXT

The OUTDOOR MICROCLIMATE bundle operates at the local scale of a building and its site to organize a group of smaller strategies for outdoor rooms. It also creates conditions that help to build the urban scale strategies related to outdoor climate, such as SHADOW UMBRELLA, OVERHEAD SHADES and the urban scale application of WINDBREAKS. By setting the location of cool and warm outdoor rooms in relation to buildings and climates, this bundle sets criteria for these and other urban fabric strategies, such as SOLAR ENVELOPE and TALL BUILDING CURRENTS.

FORCES

Most contemporary North American buildings exhibit a strong separation of inside from outside. The rich traditional form language of outdoor rooms and transitional in-between spaces has increasingly disappeared. Most outdoor places are used only for a small fraction of the year because they are thermally uninhabitable. Few designers program outdoor space. Partly because of this, people think they need more conditioned indoor space.



Entry, Center for Environmental Education, Ahmedabad, India

John Lyle termed buildings and landscapes typically designed in the age of fossil fuels as *paleotechnic* (relating to old technology). In contrast, he used the term *neotechnic* for buildings and landscapes tuned to climate and local ecology to meet human needs (Lyle, 1985). In paleotechnic buildings, dominated by indoor mechanical conditioning, people have come to expect that outdoor comfort is a matter of a narrow range of conditions. Neotechnic sustainable designers have the opportunity to change our relationship to Nature, in terms of both resources and pollution and by creating places where outdoor and transitional spaces can be inhabited and in which Nature is cared for. As Robert Brown puts it in his *enduring microclimate hypothesis,* "landscapes that create positive microclimates are likely to endure, while negative microclimates are likely to be removed or replaced over time" (Brown, 2010).

	J	F	M	A	M	J	J	A	S	O	N	D
1 am	CH	CM	CM	CM	CH	CH	OH	CH	CH	CM	CH	CH
2	CH	CM	CM	CM	CH	CH	CH	CH	CH	CM	CH	CH
3	CH	CM	CM	CM	CH	CH	CH	CH	CH	CM	CH	CH
4	CH	CM	CM	CM	CH	CH	CH	CH	CH	CM	CH	CH
5	CH	CM	CM	CM	CH	CH	CH	CH	CH	CH	CH	CH
6	CH	CM	CM	CM	CH	CH	OH	CH	CH	CH	CH	CH
7	CH	CM	CM	CM	CM	CH	OM	CM	CH	CM	CH	CH
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11 am	CM	CM	CM	CM	CM	OM	OM	OM	CM	CM	CM	CM
12 noon	CM	CM	CM	CM	OM	OM	OM	OM	OM	CM	CM	CM
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10	CH	CM	CM	CM	CM	CM	OM	CM	CH	CM	CH	CM
11	CH	CM	CM	CM	CM	CH	OH	CH	CH	CM	CH	CM
12 mid	CH	CM	CM	CM	CM	CH	OH	CH	CH	CM	CH	CM

Humidity	Temperature: Hot	Temperature: Comfort	Temperature: Cold
Dry	HD	OD	CD
Moderate	HM	OM	CM
Humid	HH	OH	CH

Bioclimatic Calendar (Outdoors)
based on temperature + humidity, referenced to bioclimatic chart

	J	F	M	A	M	J	J	A	S	O	N	D
1 am	CH	CM	CM	CM	CH	CH	OH	CH	CH	CM	CH	CH
2	CH	CM	CM	CM	CH	CH	CH	CH	CH	CM	CH	CH
3	CH	CM	CM	CM	CH	CH	CH	CH	CH	CM	CH	CH
4	CH	CM	CM	CM	CH	CH	CH	CH	CH	CM	CH	CH
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6	CH	CM	CM	CM	CH	CH	OH	CH	CH	CH	CH	CH
7	CH	CM	CM	CM	CM	OH	OM	OM	CH	CM	CH	CH
8	CM	CM	CM	CM	OM	OM	OM	OM	OH	CM	CH	CM
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10	CM	CM	CM	OM	OM	OM	OM	OM	OM	OM	CM	CM
11 am	CM	CM	CM	OM	OM	OM	OM	OM	OM	OM	CM	CM
12 noon	CM	CM	CM	OM	OM	OM	OM	OM	OM	OM	CM	CM
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10	CH	CM	CM	CM	CM	CM	OM	CM	CH	CM	CH	CM
11	CH	CM	CM	CM	CM	CH	OH	CH	CH	CM	CH	CM
12 mid	CH	CM	CM	CM	CM	CH	OH	CH	CH	CM	CH	CM

Humidity	Temperature: Hot	Temperature: Comfort	Temperature: Cold
Dry	HD	OD	CD
Moderate	HM	OM	CM
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Bioclimatic Calendar (Expanded for Wind and Radiation)
based on temperature + humidity, referenced to bioclimatic chart

	J	F	M	A	M	J	J	A	S	O	N	D
1 am	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
2	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
3	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
4	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
5	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
6	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
7	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
8	CH	CH	CM	OH	OM	OM	HH	OH	OM	OH	CH	CH
9	CM	CH	CM	OM	OM	HM	HM	HM	OM	OH	CH	CH
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12 noon	CM	CM	OM	OM	HM	HM	HM	HM	HM	OM	OM	CM
1 pm	CM	CM	OM	OM	HM	HM	HM	HM	HM	HM	OM	CM
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4	CM	CM	OM	OM	HM	HM	HM	HM	HM	OM	OM	CM
5	CM	CM	OM	OM	HM	HM	HM	HM	HM	OM	OM	CM
6	CM	CM	OM	OM	OM	HM	HM	HM	HM	OM	OM	CM
7	CM	CM	CM	OM	OM	HM	HM	HM	OM	OH	CM	CH
8	CM	CM	CM	OM	OM	HM	HM	HM	OM	OH	CM	CH
9	CM	CM	CM	OH	OM	OM	HH	OM	OM	OH	CH	CH
10	CM	CH	CM	OH	OH	OH	OH	OH	OM	OH	CH	CH
11	CM	CH	CM	OH	OH	OH	OH	OH	OH	OH	CH	CH
12 mid	CM	CH	CH	OH	OH	OH	OH	OH	OH	CH	CH	CH

Humidity	Temperature: Hot	Temperature: Comfort	Temperature: Cold
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Bioclimatic Calendar (Outdoors)
based on temperature + humidity, referenced to bioclimatic chart

	J	F	M	A	M	J	J	A	S	O	N	D
1 am	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
2	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
3	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
4	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
5	CH	CH	CH	CH	OH	OH	OH	OH	OH	CH	CH	CH
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12 noon	OM	OM	OM	OM	OM	HM	HM	HM	OM	OM	OM	OM
1 pm	OM	OM	OM	OM	OM	HM	HM	HM	OM	OM	OM	OM
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11	CM	CH	CM	OH	OH	OH	OH	OH	OM	OH	CH	CH
12 mid	CM	CH	CH	OH	OH	OH	OH	OH	OM	CH	CH	CH

Humidity	Temperature: Hot	Temperature: Comfort	Temperature: Cold
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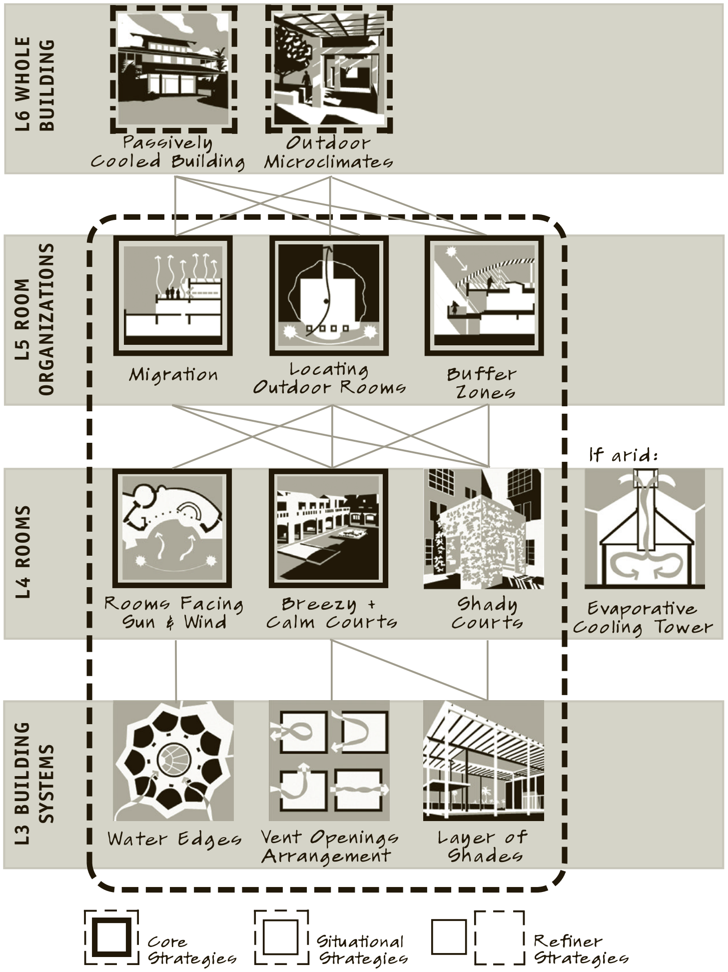
Humid	HH	OH	CH

Bioclimatic Calendar (Expanded for Wind and Radiation)
based on temperature + humidity, referenced to bioclimatic chart

Expansion of the Comfort Zone in Outdoor Spaces by Designing with Climate
Left: hourly conditions; Right: conditions after manipulating available hourly sun and wind. Top row: Madison, WI; Bottom: Houston, TX



OUTDOOR MICROCLIMATES: Hot Climate Bundle

RECOMMENDATIONS

Imagine the indoor and outdoor environments as a continuum of climatic contexts and criteria.

- ***Develop a brief architectural program for all outdoor spaces on the site.*** Set goals and criteria for use, size, experiential qualities, occupancy periods and thermal conditions. In most cases, this will require designers to expand on and rethink the conventional program.
- ***Create a building and site organization with three kinds of rooms:*** 1) indoor rooms, 2) outdoor rooms, 3) rooms that are in-between indoors and outdoors.
- ***Use combinations of strategies in this bundle to locate and shape a family of outdoor rooms*** habitable in different seasons and at different times of day.
- ***Refine these outdoor rooms using building systems level strategies*** to provide in each room varying degrees of engagement and retreat from the climatic forces.

The analysis shown in **Expansion of the Comfort Zone in Outdoors Spaces by Designing with Climate** (previous page) demonstrates the effectiveness of working with the site forces of sun and wind to effect changes in outdoor

conditions. On the left side, find the existing typical comfort conditions based on temperature and humidity in Madison Wisconsin, mostly cool (top row); and in Houston, Texas, mostly warm–humid (bottom row). The climate calendars on the right show expanded comfortable hours for outdoor spaces designed with climate. The existing conditions are determined from the BIOCLIMATIC CHART. If there is enough radiation (determined from hourly radiation data) at a given underheated hour, the existing condition may change from Cold to Comfort. If there is enough wind (determined from hourly wind speed data) at a given overheated hour, the existing condition may change from Hot to Comfort. The level of wind or radiation required to produce comfort is obtained from the BIOCLIMATIC CHART. ***This expanded zone of comfort represents the potential for passive design to improve comfort in outdoor rooms.*** Of course, changing clothing levels or activity could also increase or decrease comfort at any hour. The method is indicative only. Comfort and Hot conditions are assumed to be fully shaded. For details of the method and examples from other climates, see the "Comfort" section of the *Climatic Context* reports provided in *SWL Electronic*.

CORE STRATEGIES

Four strategies form the core of this bundle and apply to almost all outdoor rooms. The basic motives are reversed in hot and cold conditions. In general, in a cooling condition, provide access to wind and block the sun; in a heating condition, admit the sun and block the wind. For more detailed criteria by climate, see SITE MICROCLIMATES.

LOCATING OUTDOOR ROOMS is the most fundamental move that places built form and open space relative to each other. It recognizes that the microclimate around buildings is impacted by the buildings themselves. They create shade or reflect sun; they block wind or intensify it. Outdoor rooms can be located to make use of this fact.

MIGRATION is often a good strategy because it is difficult to design a single outdoor space that is comfortable in all conditions. This strategy suggests creating multiple spaces designed to create different conditions (such as a summer room and a winter room) that allow users to move between them and find conditions that suit them. Another variation is to create a gradient of conditions in a single space, such as full sun, partial shade and full shade. Given that people have different thermal tolerances and preferences, each will find the combination of conditions that best suits that individual.

BUFFER ZONES create a third condition of tempering between inside and outside that reduces thermal stresses on the indoor space and can provide for occupied spaces at the edge of buildings, which are more comfortable than being in the open. BUFFER ZONES can be used for both cold and hot conditions.

BREEZY AND CALM COURTYARDS helps the designer determine the dimensions of open spaces, such as courtyards, based on whether wind is an asset or a liability. Breezy courts are relatively wide and permeable, while calm courts are more protected.

ROOMS FACING THE SUN AND WIND applies equally to indoor and outdoor rooms. If a partially enclosed outdoor room is to be ventilated, it needs both inlets facing the wind and outlets away for the wind. If an outdoor room is to receive sun, building massing cannot block the sun reaching the ground. This strategy is often at odds with rigid formal symmetry that creates mirrored orientations.

SITUATIONAL STRATEGIES
Variations Based on Hot and Cold Climates

Since the response to site forces of sun and wind for cooling and for heating are fundamentally opposite in most cases, the variations on this bundle are marked for hot climates and cold climates.

1. Hot Climate OUTDOOR MICROCLIMATE Bundle

Hot climates can be mostly humid, mostly arid or a mix of humid and arid in different seasons or, in some climates, when major weather patterns shift. In all these conditions shade is desirable during selected periods according to the SHADING CALENDAR. In arid conditions, additional humidity can improve comfort, while in hot-humid conditions it generally does not. The remaining distinction is whether or not admitting wind is desirable.

In hot-humid conditions air movement over people will improve their comfort. In arid conditions, there is debate on the matter, usually centering on either the drying effects of wind or on its dust content. Take care to use strategies that will reduce dust (if it is a local issue) when ventilating outdoor spaces. In the authors' experiences, light breezes are usually desirable in hot-arid conditions, as they promote even greater evaporation of perspiration. Therefore, we generally recommend admitting moderate breezes while excluding the extremely hot ones in hot-arid climates, but not at the expense of shading.

Hot Climate Situational Strategies

SHADY COURTYARDS helps the designer choose proportions where the building helps shade the outdoor room and its facades. Tall narrow courts create more shade but reduce wind flows. In general, wider courts that admit wind, coupled with arcades and layers of shades, such as found in the **Entrepreneurship Development Institute** [in BREEZY OR CALM COURTYARDS], work better in humid climates. Taller, narrower courts, particularly in the east-west direction, are advised in arid climates. This may be coupled with a more sunny court to induce ventilation, such as shown in the **Housing in Alice Springs, Australia** [in BREEZY OR CALM COURTYARDS].

WATER EDGES is a strategy mostly useful in arid climates to increase humidity. Ponds can also create a “cool island” effect during the day and can have an evaporative cooling effect when used in relatively enclosed areas.

VENTILATION OPENINGS ARRANGEMENT is important for good air distribution in both indoor and outdoor rooms, although many designers overlook this critical strategy. This strategy helps with placing inlets and outlets.

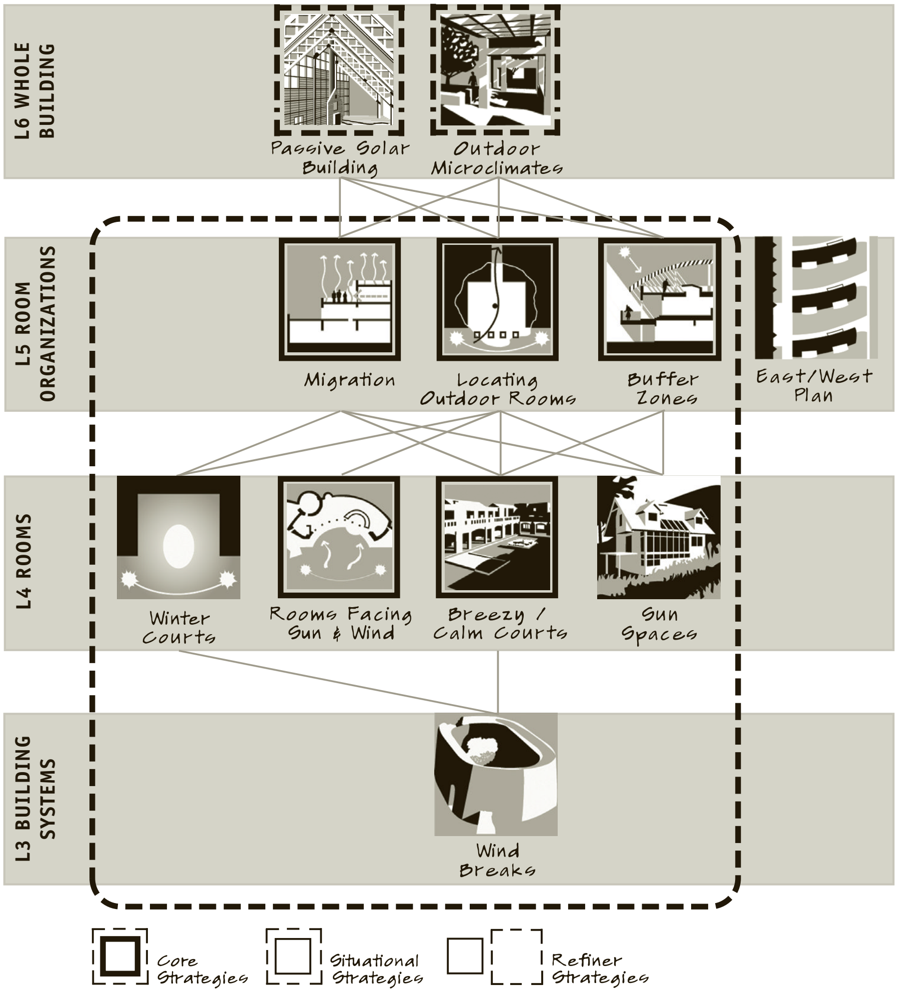
LAYERS OF SHADES helps to size overhead shading to shade an open space during specified shading criteria. Its horizontal elements can also be combined with the vertical elements of SHADY COURTYARDS.

Hot Climate Example

In the hot composite climate of Ahmedabad, India, which shifts from arid to humid seasonally, architects Neelkanth Chhaya and Kallol Joshi designed a thermal oasis at the

Center for Environmental Education, Ahmedabad, India, 1990, Neelkanth Chhaya and Kallol Joshi, architects

Center for Environmental Education (CEE) (Chhaya, 1990). An amazing diversity of outdoor rooms (see also the **Entry at the CEE** on first page of this bundle) is organized as a series of linked courts, along topographic ridges with axial views through the site. Offering a wealth of opportunity for daily and seasonal MIGRATION, the variations include sunny roof terraces, pergola-covered and tree-lined courts and shady recessed porches that serve as BUFFER ZONES. To accommodate the humid season, the BREEZY COURTYARDS are also protected with LAYERS OF SHADES above, a strategy also used over much of the



OUTDOOR MICROCLIMATES: Cold Climate Bundle

primary outdoor circulation. The outdoor rooms become SHADY COURTYARDS by the combination of buildings acting as vertical shades and a concert of trees, pergolas and trellises at the building edges working to create shade in the horizontal plane. The wall and roof sections are elegantly designed with planting beds for vines at the roof edges and also forming an inboard fixed shade adjacent to the cantilevered trellises. Many courts have open corners towards the breeze [ROOMS FACING THE SUN AND WIND] and the whole heavily vegetated complex can be described as relatively DISPERSED BUILDINGS, combined with lower buildings in the windward direction. In a scheme in which habitable outdoor space seems equal to indoor space, the designers have crafted an architectural language that grows out of climate and culture.

2. Cold Climate OUTDOOR MICROCLIMATE Bundle

The core strategies for this bundle cover both hot and cold conditions, but the choices the designer makes are opposite, for example, designing migrational spaces that are warmer, locating outdoor rooms that are

sunny and wind protected, and buffering from the cold rather than from the sun. In addition to the core strategies for this bundle, this variation adds three new strategies that can be used in cold climates or in any climate that has a winter period.

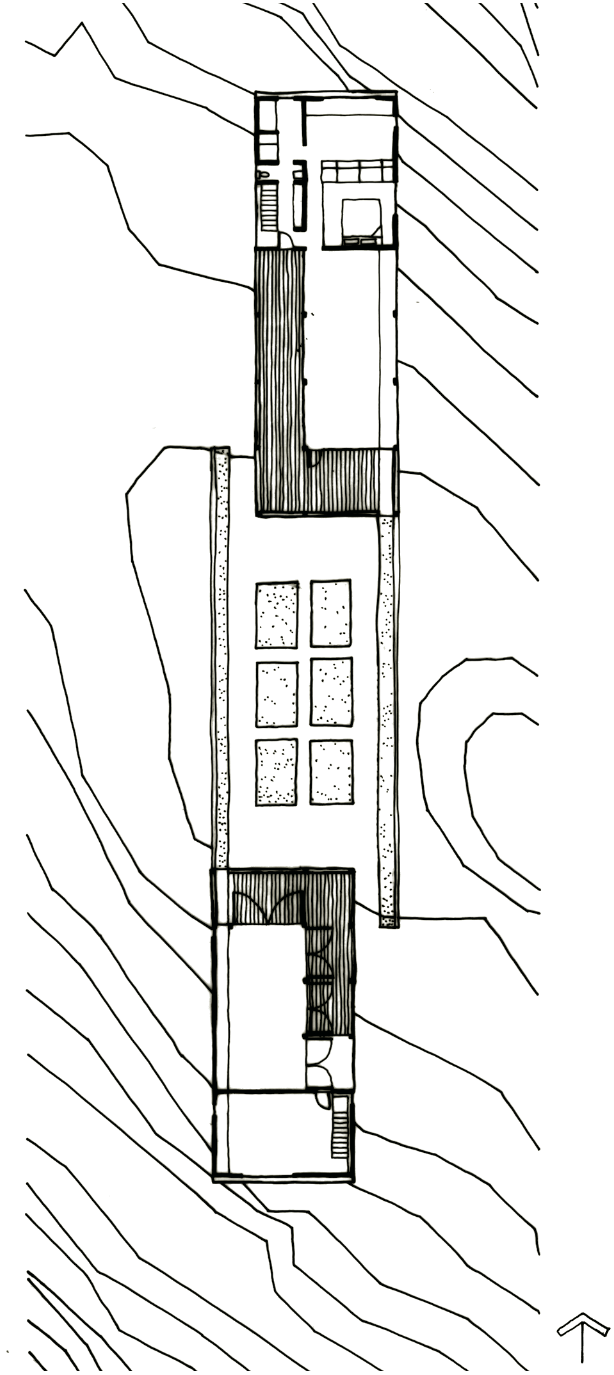
WINTER COURTS can be used at the scale of a single outdoor room, for a complex of buildings, or for a town. This strategy helps the designer shape and orient buildings to block wind and create a warm sunny protected area. WINTER COURTS help build places of MIGRATION. The larger strategy LOCATING OUTDOOR ROOMS helps define the location of the WINTER COURT and its accompanying outdoor rooms in other seasons.

SUNSPACES, in addition to their role in a passive solar heating system, are also spaces that can be inhabited during certain periods and are a special case of buffer zone. Sometimes their temperature is above the comfort zone (such as in the middle of a sunny day), sometimes within the comfort zone (such as on a winter morning) and sometimes below the comfort zone (typically, at night). However, the sunspace will always be warmer than the colder outdoor temperatures in winter and will have a daily temperature variation that is greater than indoors but less than outdoors.

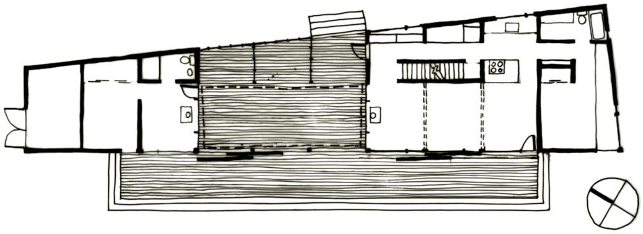
WINDBREAKS are especially important in outdoor microclimates when the temperatures are cool. The BIOCLIMATIC CHART assumes that when conditions fall within the comfort zone, that the wind is blocked. If it is not, there is a cooling effect and even mild conditions can be experienced as cold. Windbreaks can be buildings, walls, fences, or vegetation; in any variety, they help build WINTER COURTS and calm courts [BREEZY AND CALM COURTYARDS].

Cold Climate Example

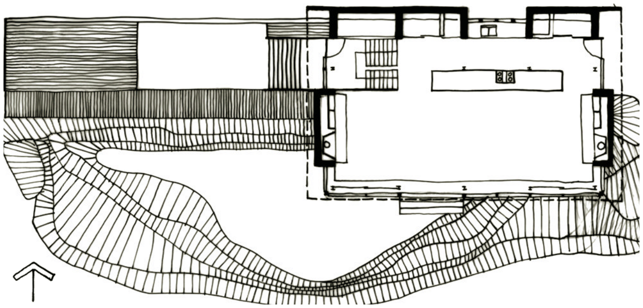
The houses of Bryan Mackay-Lyons, set in the relatively cold maritime climate of Nova Scotia, provide a rich set of examples for configuring buildings and outdoor space to modify the outdoor microclimate. At the **Kutcher House,** in Herring Cove, the courtyard is protected by a 120 ft (37 m) long concrete wall (Carter, 2001; Quantrill, 2005). An almost equally long, but lower granite boulder protects



Hill House, 2004, Nova Scotia, Brian Mackay-Lyons, architect



Messenger House II, 2003, Upper Kingsburg, Nova Scotia, Brian Mackay-Lyons, architect



Kutcher House, 1998, Herring Cove, Nova Scotia, Brian Mackay-Lyons, architect

the southerly side to form a WINTER COURT. The **Messenger House II,** in Upper Kingsburg, Nova Scotia, covers the outdoor room with a daylighted roof and encloses it between the main house and a guest house, widening the deck on the sunny southwest side, while partially closing the space on the northwest with a slatted wind fence (Canadian Architect, 2002; Quantrill, 2005). Large sliding barn doors can switchably protect from sun and wind.

Situated on a windy hilltop, the **Hill House** locates a courtyard between house and barn-like structure, wrapped on the other two sides by protective concrete walls, but leaving openings for views across the court and into the landscape (Kolleeny, 2005; Architectural Review, 2004; Quantrill, 2005).

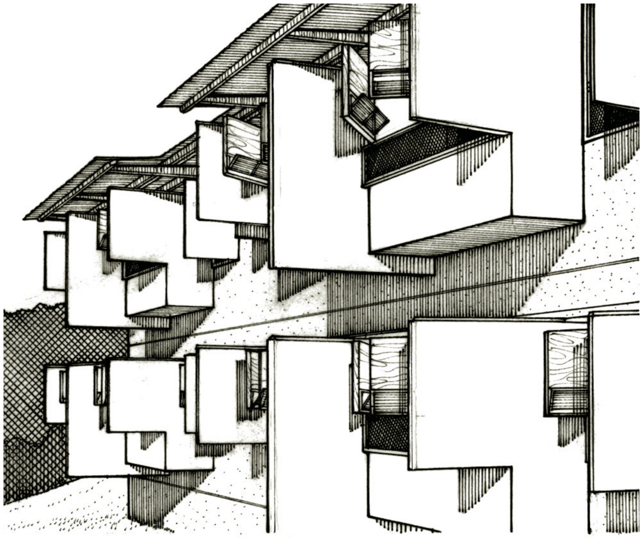
B9 A *RESPONSIVE ENVELOPE* regulates comfort and energy use by adapting to changing patterns of sun, light and air movement. [cooling, heating, lighting, ventilation and power]

KEY POINTS

- Orientation dramatically affects apertures, shading and power production.
- Depending on the situation, lighting, cooling or heating may govern aperture size.
- When aperture sizes conflict, functions may be separated into specialized apertures.
- The choice of whether or not to place thermal mass in the envelope can drive its design.

CONTEXT

Each bundle helps build one or more larger strategies at the next scale of complexity. The strategies of this bundle help build DAYLIGHT ROOM GEOMETRY. Because these strategies address both heating and cooling, they also help build one or more heating or cooling strategies (see the situational bundle diagrams).



Education Center, Illaroo, New South Wales, Australia, Glenn Murcutt, architect

FORCES

The essential problem of the climatic envelope exists because of the tensions among its multiple functions and the variable nature of its design criteria over time. In most buildings, the envelope must resist conductive heat flow, admit and control daylight and either collect sun or admit outdoor air for cooling. In most cases, the envelope also admits fresh air. During overheated periods, its glazing needs shading, and in extreme heat, even its insulated opaque elements may require shade. Combine these common multiple objectives with a dynamic climate of seasonal and daily variability across a range of temperature, humidity, radiation, luminance, wind and sun angles and the designer has a challenging problem! The size of apertures may depend on whether daylighting, ventilation or solar heating governs, whether openings are separated or combined, and whether the ventilation and solar apertures admit light to the room.

RECOMMENDATIONS

- *Using the table* **Bundle Variations by Climate and Internal Gains**, *in the section "Bundles Explained" (see Part IV), determine which climate variation of this bundle fits the building best and whether the situation is "heavily dominated" in that climatic direction (i.e., H2 or C2).*
- *Using the tools in* SOLAR APERTURES *and* VENTILATION APERTURES, *determine for each orientation whether aperture sizing for heating, cooling or ventilation governs. Consult the table* **Design Responses to Aperture Size Conflicts.**

Largest Required Aperture	Possible Integrated Design Responses
HEATING	• Limit direct gain apertures to that required for daylighting. • Supplement direct gain rooms with other solar heat strategies that admit less or no daylight. • Shade solar apertures in summer or totally isolate the heat gains (i.e., separately vented sunspace or thermal storage wall). • Use seasonal solar reflectors to increase winter gain through smaller solar apertures.
VENTILATION	• Separate ventilation from solar and daylight apertures using openings with opaque covers, indirect or baffled pathways, under-floor openings, or low-reflectance louvers. • Fully shade ventilation apertures to reduce heat and light gains. • Select daylight and solar apertures that are fully operable (casements rather than awning windows).
DAYLIGHTING	• Use direct gain solar apertures on equator-facing facades. Limit daylight openings to those required for heating. • Combine fixed glass with an operable percentage that meets ventilation needs. (reduces cost.) • Use exterior daylight reflection to reduce required size of daylight apertures.

Design Responses to Aperture Size Conflicts

- ***Only after solving for passive HCLV issues, size and locate collection for* PHOTOVOLTAIC WALLS AND ROOFS *on equator-facing roofs and facades to meet or exceed* NET-ZERO ENERGY BALANCE *criteria.***

CORE STRATEGIES

There are five strategies that are so pervasive in climatically responsive building envelopes that they can be considered invariants. Each of these five strategies is so critically important that ignoring just one is a recipe for a failed responsive envelope.

WELL-PLACED WINDOWS: The designer is directed to consider the size of windows for each orientation, relative to the site forces of sun and wind, for both heating and cooling seasons.

SEPARATED OR COMBINED OPENINGS: The designer recognizes that any apertures in the envelope can specialize in ventilation, light, or solar gain, or can perform more than one role simultaneously.

SKIN THICKNESS: This strategy recommends insulation thickness, depending on climate and building type, which creates greater or lesser conductive loads on the envelope. More insulation is needed in skin-loaded buildings and in cold climates.

DAYLIGHT APERTURES: This strategy helps the designer size openings based on the external daylight resource present in the climate as well as the interior lighting needs of the rooms enclosed by the envelope.

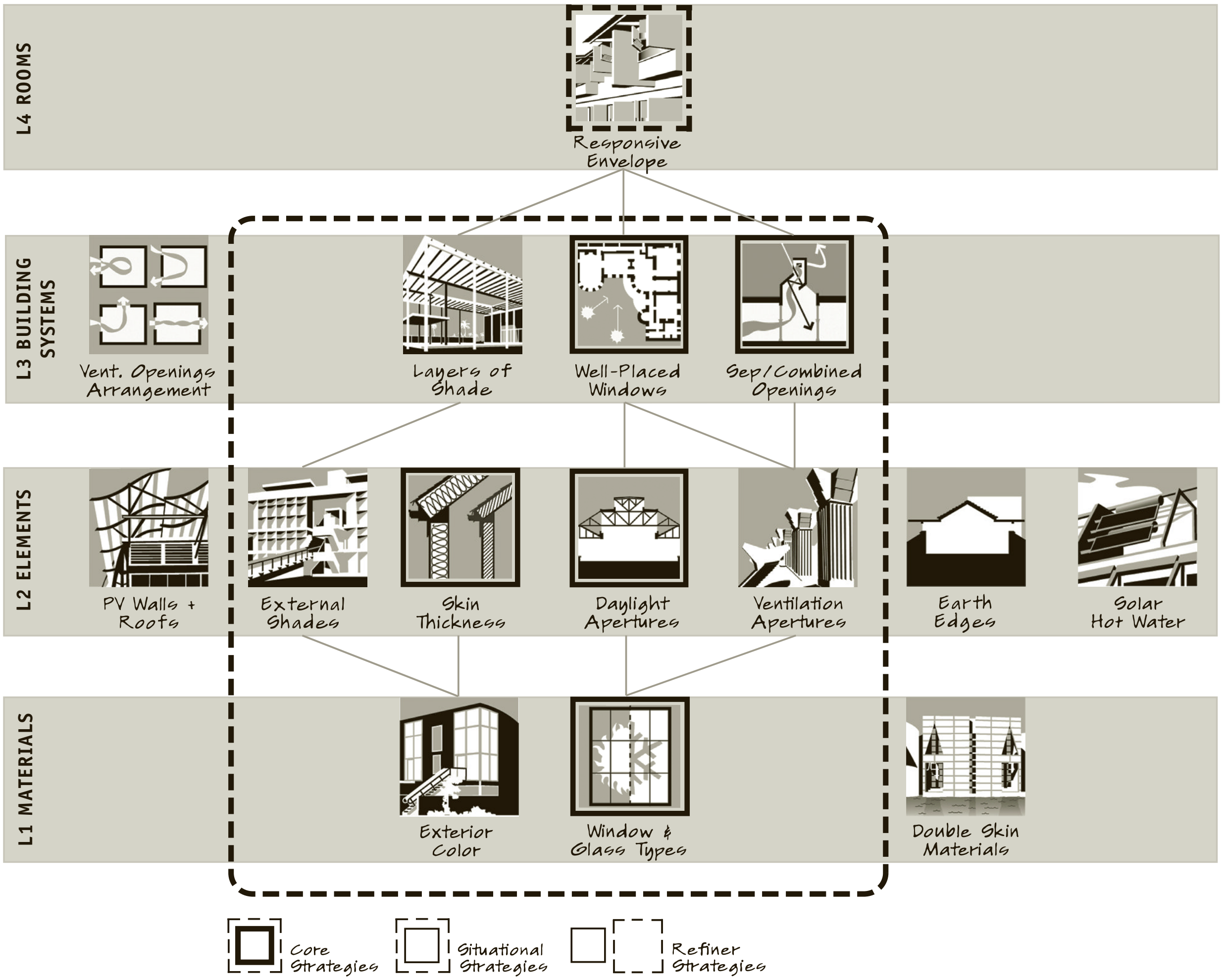
WINDOW AND GLASS TYPES: This strategy gives recommendations for important thermal and lighting characteristics to consider when choosing windows.

REFINERS FOR ALL STRATEGIES

The following are recommended for all envelopes in all climates, but not for all surface orientations:

PHOTOVOLTAIC WALLS AND ROOFS: Photovoltaics for production of electricity are most efficient on south-facing (N in SH) pitched roofs. Proportionally larger PV arrays can also be used on south-facing walls and on flat roofs with racks. On south walls, PV's compete for space with solar apertures, breathing walls and air collectors. Remember to leave enough space for SOLAR HOT WATER collectors.

SOLAR HOT WATER: Collectors for heating hot water are most efficient on south-facing (N in SH) roofs.



RESPONSIVE ENVELOPE: Hot-Humid Climate Bundle

Proportionally larger collectors can also be used on south-facing walls and on flat roofs with racks.

SITUATIONAL STRATEGIES: Variations Based on Hot-Humid, Hot-Arid and Cold Climates

The bundle may be varied by the need for heating, cooling or a combination of both, and by the climatic context of aridity or humidity. The bundle diagrams show three variations and mark out the extremes: "Cold Climate," "Hot-Arid Climate," and "Hot-Humid Climate." In temperate climates, which shift seasonally from heating to cooling, the designer will need to construct a project-specific bundle using a combination of the Cold Climate bundle variation plus either the Hot-Arid or the Hot-Humid bundle variation (see **Bundle Variations by Climate and Internal Gains** in the section "Navigation by Climate"). In practice, most climates in the continental US require some mix of heating and cooling. Phoenix and Miami have a short heating season, while Minneapolis and Boston have a short cooling season.

To select which bundle variation to use for your combination of climate and use, refer to the **Bundle Variations by Climate and Internal Gains** in the section "Navigation by Climate."

1. Hot-Humid RESPONSIVE ENVELOPE Bundle

The hot-humid RESPONSIVE ENVELOPE bundle focuses on and biases toward reducing solar gain and promoting ventilation.

Context

The hot-humid variation of the bundle helps to build both CROSS-VENTILATION and STACK-VENTILATION ROOMS (both are recommended). The options for passive cooling are more constrained in humid climates, yet in most hot-humid climates, NIGHT-COOLED MASS will work for some of the cooling months. In some cases, this bundle may support WIND CATCHERS, a variation for urban settings, or ROOF PONDS, which work in some hot-humid climates. To help determine the context, see the PASSIVELY COOLED BUILDING bundle.

Hot-Humid Situational Strategies

In addition to the five core strategies applicable to all RESPONSIVE ENVELOPES, this Hot-Humid variation of the bundle adds these situational strategies that will apply to most buildings in hot-humid climates:

LAYER OF SHADES AND EXTERNAL SHADING: To reduce high solar load and make passive cooling possible, external shading is required. Fixed EXTERNAL SHADES can be combined with movable external shades for the swing seasons, or combined with movable INTERNAL OR IN-BETWEEN SHADES.

VENTILATION APERTURES: Natural ventilation alone can often handle the cooling load for many months. Most hot-humid climates are moderate for all but a few weeks. During more extreme periods, CROSS-VENTILATION ROOMS and STACK-VENTILATION ROOMS can support NIGHT-COOLED MASS.

EXTERIOR SURFACE COLOR: The color and materials of the outside skin can contribute to comfort, in this case by reducing solar gains and quickly releasing absorbed heat.

Hot-Humid Refiner Strategies

EARTH EDGES: Green roofs and earth-berm walls can reduce or eliminate solar gain on their surfaces. In hot-humid climates, the ground may be one of the only heat sinks capable of absorbing excess heat. If summer condensation and ventilation issues can be resolved, this is often a good cooling strategy.

DOUBLE SKIN MATERIALS: Hot-humid climates have intense east, west and overhead sun in the summer (or all year in the tropics). A ventilated double skin strategy works particularly well here and can eliminate the solar load on opaque envelope surfaces.

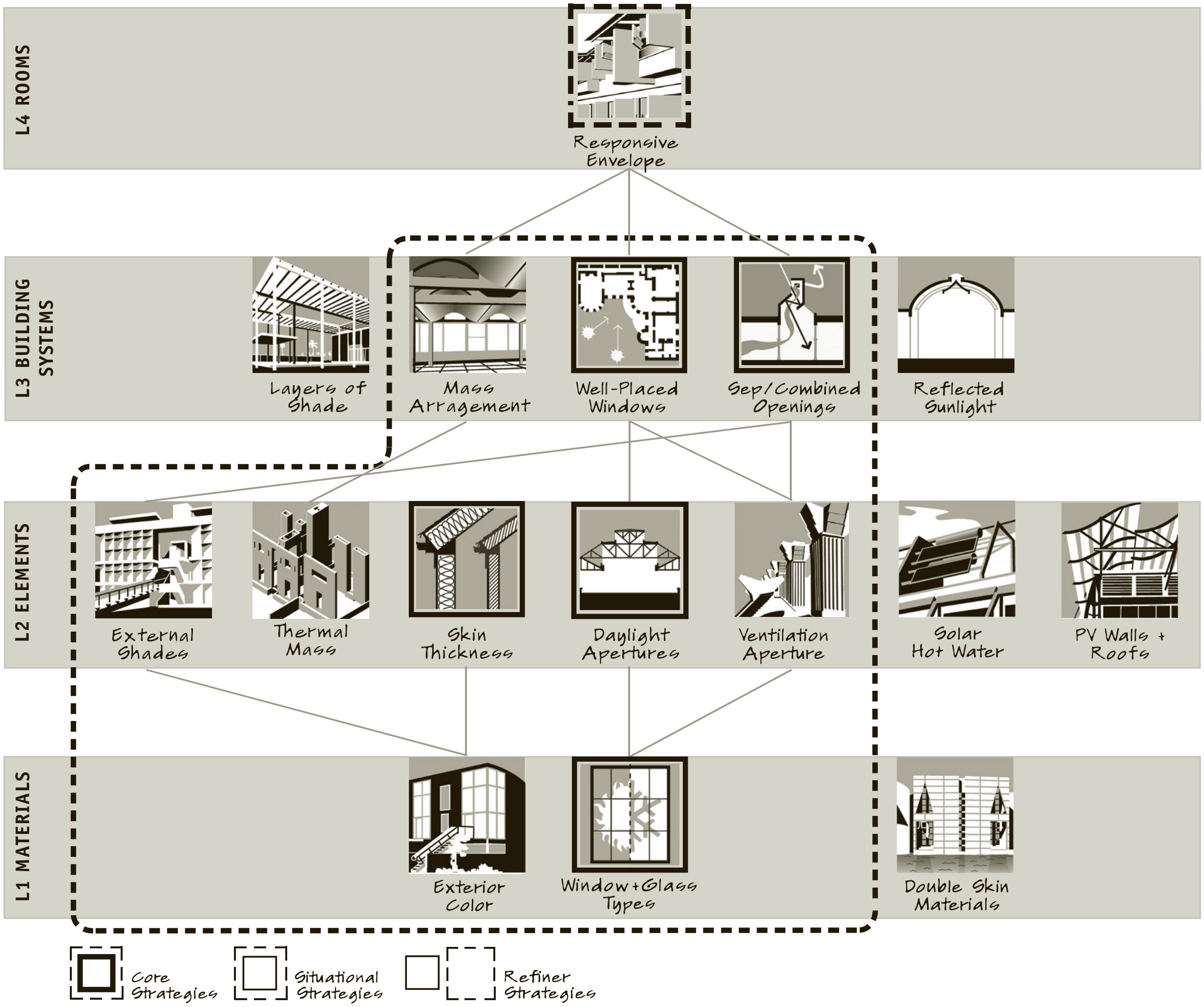
VENTILATION OPENINGS ARRANGEMENT: Humid climate cooling is all about moving air where and when it is needed. This strategy increases air velocity in the room and decreases stagnant zones in naturally ventilated rooms.

MASS ARRANGEMENT: To support NIGHT-COOLED MASS requires large surface areas of thermal mass located where it can absorb heat and be cooled by night ventilation.

Warm-Humid Example

In the mild temperate-humid climate of Illaroo, New South Wales, Australia, Glenn Murcutt designed the sunny northerly facade of the guest rooms for the **Arthur and Yvonne Boyd Education Centre** to address a combination of shade, sun, light, ventilation and view (see illustration on first page of this bundle) (Murcutt, 2006; Drew, 1999; Fromonot, 2000, 2003). The cantilevered sleeping alcoves are shaded by a combination of a deep roof overhang and projecting blades [EXTERNAL SHADING] that also reflect light in to the room [REFLECTED SUNLIGHT], catch breezes and frame views. The upper glazing, which admits light deep into the space, is fixed, as is the lower view window [DAYLIGHT APERTURES]. Solar heat is admitted from this north facade in winter [SOLAR APERTURES].

The midsection of the wall is configured with opaque operable panels that pivot out for maximum ventilation or remain closed for the use of smaller ventilation panels that slide to reveal wood louvers [VENTILATION APERTURES]. The functions of view, light, sun and ventilation



RESPONSIVE ENVELOPE: Hot-Arid Climate Bundle

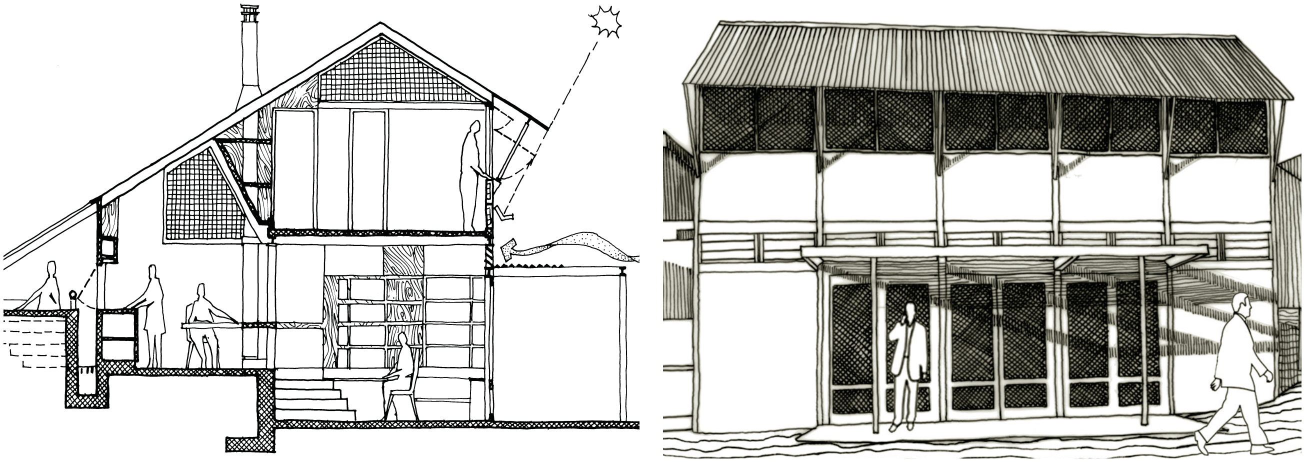
are separated for individual control [SEPARATED OR COMBINED OPENINGS]. The sides of the projections subject to east and west sun are opaque [WELL-PLACED WINDOWS], and along with the lower, unshaded portions of the north face, are insulated [SKIN THICKNESS]. The RESPONSIVE ENVELOPE contributes to a building that requires no mechanical heating or cooling system.

2. Hot-Arid RESPONSIVE ENVELOPE Bundle

The hot-arid bundle focuses on and biases toward reducing solar gain, creating thermal lag and storing daytime heat gains for night ventilation.

Context

The hot-arid climate bundle helps to build NIGHT-COOLED MASS and either CROSS-VENTILATION ROOMS or



Nxumalo House, Johannesburg, South Africa, 1988, Jo Noero, architect

STACK-VENTILATION ROOMS (or both). The options for passive cooling in arid climates are many. In some cases, this bundle may support WIND CATCHERS, a variation for urban settings, or EVAPORATIVE COOLING TOWERS or ROOF PONDS, both of which work well in hot-arid climates. To help determine the context, see the PASSIVELY COOLED BUILDING bundle.

Hot-Arid Situational Strategies

In addition to the five core strategies applicable to all RESPONSIVE ENVELOPES, the Hot-Arid bundle variation adds these situational strategies that will apply to most buildings in hot-arid climates:

MASS ARRANGEMENT: To support NIGHT-COOLED MASS requires large surface areas of thermal mass located where it can absorb heat and be cooled by night ventilation. For cooling, mass is best placed in the ceiling or walls.

THERMAL MASS: Mass surface must be sized to store adequate cold. Since its area is often twice that of the floor area, some or all of the mass will be in the envelope.

EXTERNAL SHADING: To reduce high solar load and make passive cooling possible, external shading is required. Fixed external shades can be combined with movable external shades for the swing seasons, or combined with movable INTERNAL OR IN-BETWEEN SHADES.

VENTILATION APERTURES: Natural ventilation alone can often handle the cooling load for many months. Many hot arid climates are moderate for all but a few weeks. During more extreme periods, CROSS-VENTILATION ROOMS and STACK-VENTILATION ROOMS can support NIGHT-COOLED MASS. In buildings with EVAPORATIVE COOLING TOWERS, ventilation apertures will be used for outlets only.

EXTERIOR SURFACE COLOR: More than in any other climate, the color and materials of the outside skin in hot-arid climates can contribute to comfort, in this case by reducing solar gains and quickly releasing absorbed heat.

Hot-Arid Refiner Strategies

REFLECTED SUNLIGHT: Hot-arid climates tend to have bright clear skies in which daylight from the direct sun or bright sky can come with a heat gain liability. Using reflected lighting strategies can provide a cooler light and works better here than in a more diffuse overcast sky.

DOUBLE SKIN MATERIALS: Hot-arid climates have intense east, west and overhead sun in the summer (or all year in the tropics). A ventilated double skin strategy works particularly well here and can eliminate the solar load on opaque envelope surfaces.

DAYLIGHT-ENHANCING SHADES: Because a good passively cooled building will have extensive external shading

and because the outside sky is bright, glare can be an issue. This strategy resolves the tensions between shade and daylight.

Hot-Arid Example

In the sunny, semi-arid climate Johannesburg, South Africa, Jo Noero's **Nxumalo House** organizes the sunny north side with deep eaves protecting the upper floor glazing, and on the lower floor, louvered vents [VENTILATION APERTURES] and an external trellis [LAYER OF SHADES] (Noero Wolff, 2012), The majority of openings are on the easily shaded north and south exposures, while east and west windows are kept small [WELL-PLACED WINDOWS]. VENTILATION APERTURES are provided by small awning windows on the top floor and high louvers on the lower floor. When more air flow is needed, larger awning windows on the top floor and glazed doors below the trellis can be employed. Daylight is provided by fully shaded clear glazing on the upper floor, the louvered apertures above the trellis, and the larger glazing beneath the trellis [DAYLIGHT APERTURES]. Unshaded portions of the wall are insulated and opaque [SKIN THICKNESS]. Winters are sunny but mild, so partial sun is admitted when the sun's altitude is lower [SOLAR APERTURES]. In contrast to the Murcutt building, each opening serves more than one purpose [SEPARATED OR COMBINED OPENINGS]. The EXTERIOR SURFACE COLOR is white stucco on the lower floor and natural wood below the windows of the second floor. Because windows are well-shaded, they can be made of clear glass to admit more cool daylight [WINDOW AND GLASS TYPES]. The deep shading means that most of the interior light comes from REFLECTED SUNLIGHT. THERMAL MASS is located not in the north envelope, but in the massive floor and EARTH EDGES on other orientations.

3. Cold Climate RESPONSIVE ENVELOPE Bundle

The Cold Climate bundle variation focuses primarily on capturing and retaining both winter sun and interior heat. DAYLIGHT APERTURES will be larger than VENTILATION APERTURES and on equator-facing orientations, SOLAR APERTURES will be larger than daylight or ventilation requirements.

Context

The Cold Climate bundle variation helps to build ROOMS FACING SUN AND WIND and either DIRECT GAIN ROOMS or THERMAL STORAGE WALLS. The primary orientation in the cold climate is to the winter sun for collecting heat and away from winter winds. Orientation toward summer breezes is secondary.

Cold Climate Situational Strategies

In addition to the five core strategies applicable to all buildings, this situational bundle adds:

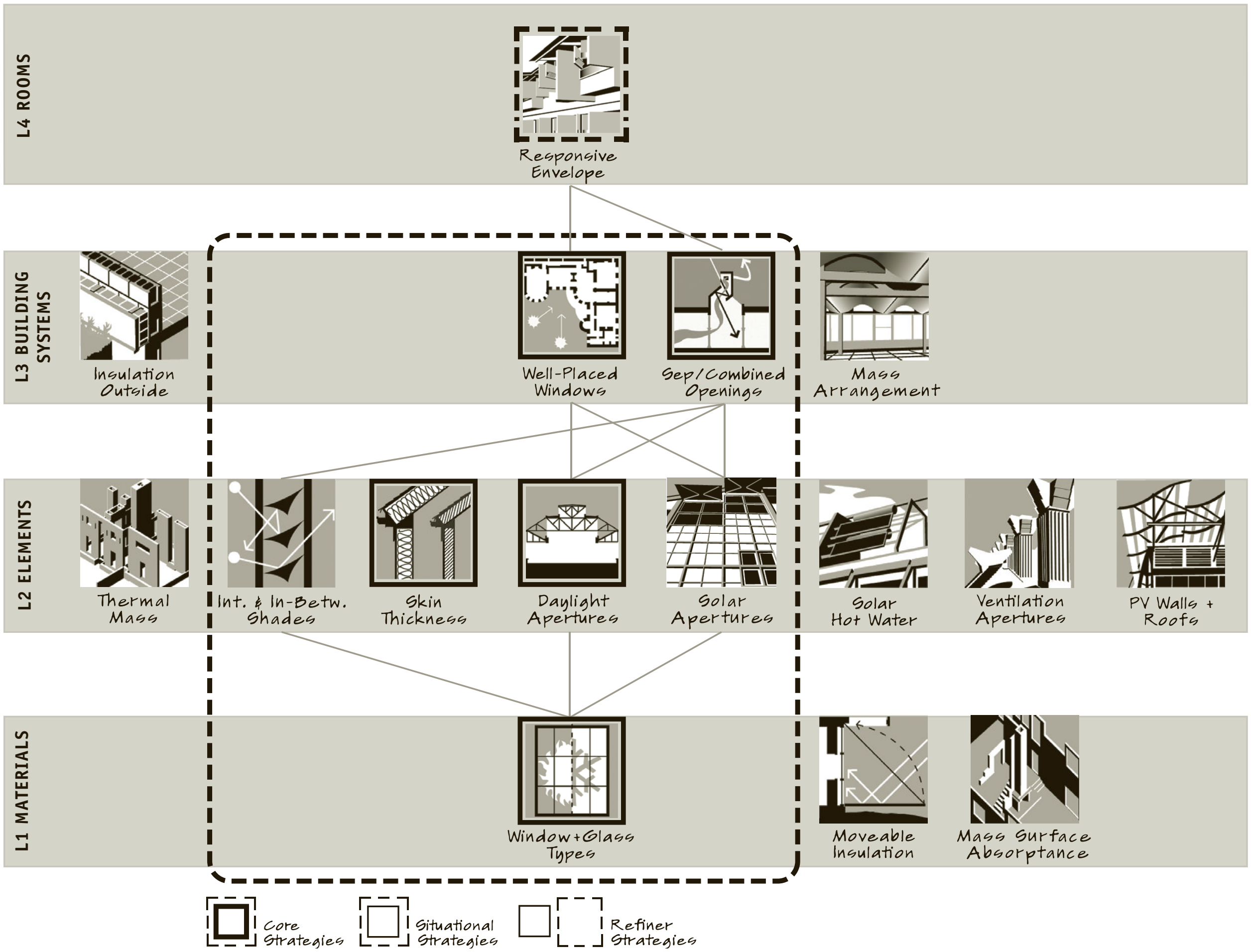
SOLAR APERTURES: This strategy establishes a general relationship between equator-facing glazing and how much heat the building can get from the sun annually using passive solar design.

INTERNAL AND IN-BETWEEN SHADES: To reduce load and prevent the need for air-conditioning in mild summer climates, remember the shading. Large solar apertures for winter heat and larger daylight apertures that adjust for dimmer or more overcast skies can easily create summer or clear day overheating. Since exterior shades can partially shade the solar glass, in cold climates designers often choose internal shades.

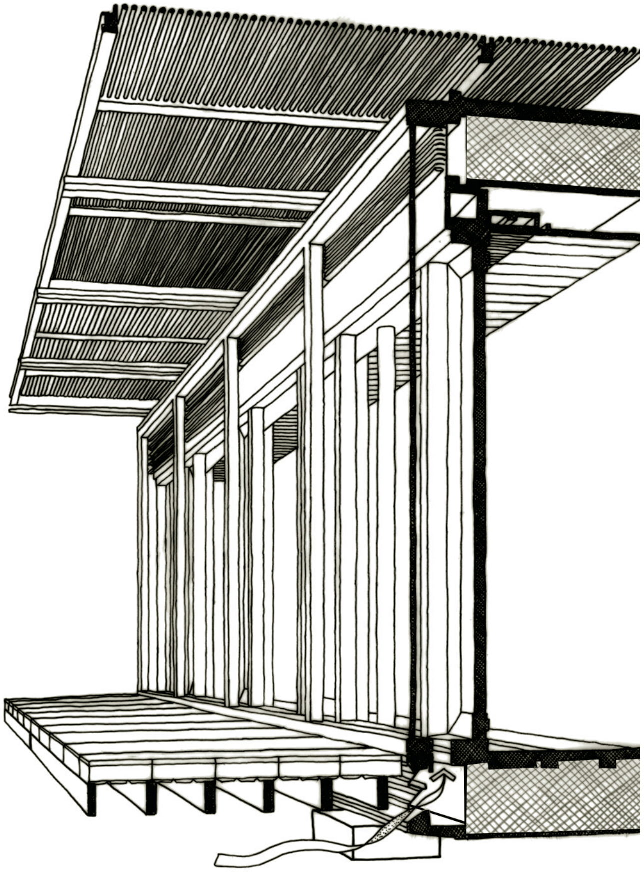
Cold Climate Refiner Strategies

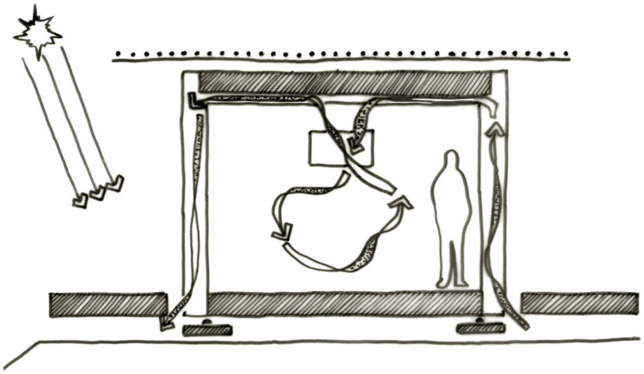
VENTILATION APERTURES: Apertures can be sized to remove heat gain by cross-ventilation based on the design wind-speed. They can also be sized to remove heat by stack-ventilation based on the stack height. It is the rare building where ventilation in inappropriate, however, this strategy is a refiner in a cold climate because windows sized for daylight and solar gain are also usually more than adequate for ventilation.

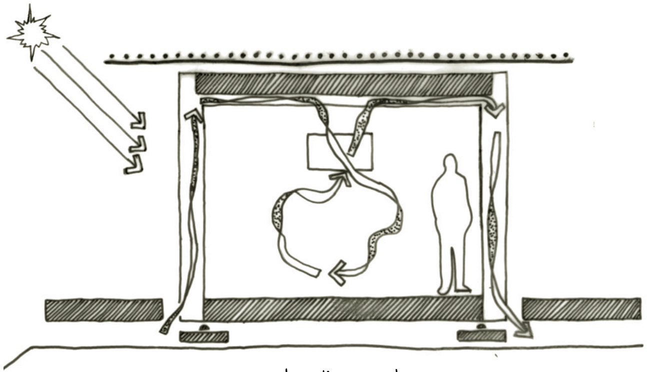
THERMAL MASS: The larger solar apertures required in cold climates create overheating without the use of thermal storage. In some cases, mass for DIRECT GAIN or mass for THERMAL STORAGE WALLS can be placed in the envelope. Although thermal mass is important in all passive solar buildings, it is included in this bundle as a Refiner Strategy because mass in the exterior envelope is less common and not required. Whenever THERMAL MASS is used, consult



RESPONSIVE ENVELOPE: Cold Climate Bundle







Smart Facade, Living Light House, 2011 Solar Decathlon competition entry, Prof. Edgar Stach, Prof. James Rose, and University of Tennessee students

the strategies for MASS ARRANGEMENT and MASS SURFACE ABSORPTANCE.

INSULATION OUTSIDE: When THERMAL MASS for DIRECT GAIN ROOMS is used in the exterior envelope, it should always be exposed to the room air and wrapped with insulation.

MOVABLE INSULATION: In the great majority of cold climates and in many temperate climates, the solar heating performance of the building is greatly improved by insulating the glazing at night. Alternatively, systems with various types of high-performance glazing, translucent insulations, or translucent phase change materials, may perform as well as moveable insulation.

Cold Climate Example

Although designed to address both heating and cooling, the **The Living Light House** (Stach and Rose, 2011; DOE, 2011; Casely, 2011; Rybak, 2011; Hoyt, 2011) is optimized more for cold conditions. On both the north and the south side, its **Smart Facade** uses a dynamic double layer system, made up of suspended film, highly insulated (*R*-11) interior glass and single-pane exterior glass [SOLAR

APERTURES; WINDOW AND GLASS TYPES]. Alternating translucent and transparent panes serve as DAYLIGHT APERTURES, allowing for views of the landscape while maintaining a sense of privacy for the occupant.

The PHOTOVOLTAIC ROOF, made up of cylindrical modules extends to form EXTERNAL SHADING sized to protect the glass in summer and admit winter sun. Sandwiched between the two panes of glass is a motorized horizontal blind system which blocks sunlight before it reaches the conditioned space [INTERNAL AND IN-BETWEEN SHADING] and can be used to absorb solar radiation in winter. The blind system is programmed to provide proper lighting and shading throughout the year. It also provides more privacy when desired.

The cavity within the wall is integral to the HVAC system [supply AIR FLOW WINDOWS] and constitutes a combination of THERMAL COLLECTOR WALL (when warm air is extracted) and apertures for DIRECT GAIN ROOMS (when sun passes directly into the space). During colder months, the black face of the horizontal blind absorbs solar radiation within the south cavity, similar to MASS SURFACE ABSORPTANCE. Outside air is drawn through low louvers [VENTILATION APERTURES], preheated in the cavity and directed to an energy recovery ventilator (ERV) [AIR–AIR HEAT EXCHANGER]. Warm exhaust air from indoors is directed outside, through the north cavity, reducing conductive envelope heat loss [exhaust AIR FLOW WINDOWS], and out another set of low louvers [VENTILATION APERTURES].

During warmer months this process is reversed, pulling fresh air in from the cooler north facade cavity (which now becomes supply AIR FLOW WINDOWS) via the ERV, precooling the fresh air with the indoor exhaust air stream, and exhausting air through the south facade (which now functions as exhaust AIR FLOW WINDOWS) to cool the cavity and reduce heat gain through the south envelope. When outside temperature and humidity is acceptable, operable windows [VENTILATION APERTURES] on the interior facade layer can be opened to allow fresh air inside. In this mode, HVAC systems turn off except for a small fan for MECHANICAL SPACE VENTILATION.

Daylighting, solar gain, ventilation and cooling functions are sometimes addressed with SEPARATED OPENINGS and sometimes with COMBINED OPENINGS. While the same glass admits solar heat and daylight, the majority of solar heat can be admitted (blinds up) or captured in the cavity (blinds down) and either used or rejected to the outside, while daylight is admitted to the interior. While the same outer layer openings are used for fresh air ventilation and for ventilative cooling, outside air can be admitted directly to the interior space for both ventilation and cooling (inner windows) or directed to the HVAC system (for ventilation with heat recovery).

Part V
FAVORITE DESIGN TOOLS
condensed

Despite the fact that *Sun, Wind & Light* is a knowledge base built of preliminary design strategies that take typically five minutes or less to use, the sheer volume of information can be daunting. While we have tried to make the process of design with climate as clear and easy as possible, the book assumes some proficiency with the basics of energy and buildings and that the user is not a beginner in the practice of designing buildings.

This chapter gathers our favorite and most useful design rules of thumb. Some tools, we have found, are so often used that we wanted a quick way to find them without wading through all the other associated material.

Part V "Favorite Design Tools" help the designer make quick decisions early in the design process when specific information is hard to come by. Most of the design strategies in *SWL3* give design guidelines in the form of a quick decision tool. Often a complex design situation is simplified by fixing several variables and leaving the most significant architectural variables up to the designer. Be sure to read the accompanying text, which explains the assumptions, and make sure that your scheme fits these assumptions in a reasonable way.

Each design tool helps tie a design decision to its energy or lighting performance consequence. These tools are meant to be quick and dirty. Some precision is sacrificed in favor of speed.

The design tools presented here are also included in ⌁ *SWL Electronic* in their full form and in the context of the full design strategy, which includes a fuller explanation of the context of its use, the forces at work in the situation and examples of how the strategy that the tool supports has been used in an elegant way by other architects. In some cases, for brevity, we have condensed the tool or its explanation. We suggest that the first time you use the design tool you read the entire strategy. After you understand its context and application, the quick version in the printed book can be used for ready reference.

From DAYLIGHT ENVELOPES

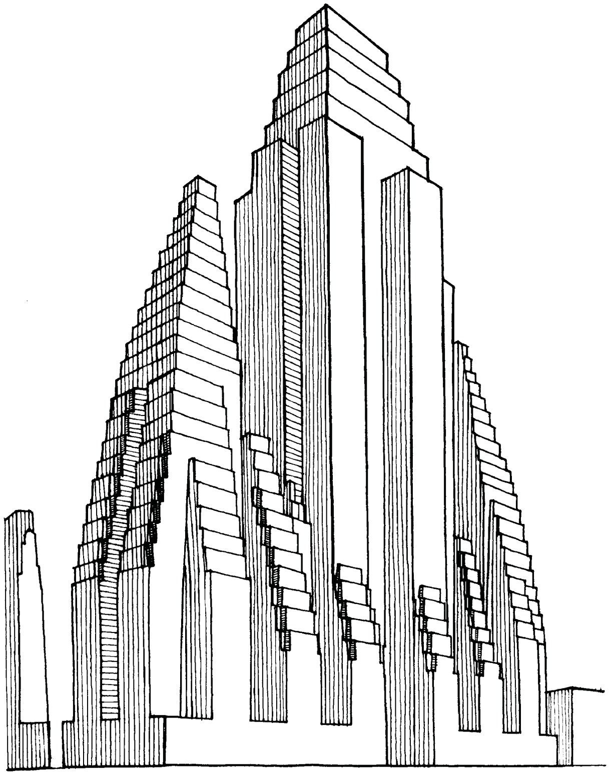
14 *DAYLIGHT SPACING ANGLES* set the criteria to assure adequate daylight access to buildings and determine the daylight envelope. [daylighting]

Daylight access is a precondition to the use of daylight in buildings. In dense contexts, limitations on building massing are necessary to insure daylight access to every building. Hugh Ferriss' **Study of the 1916 New York Zoning**, designed to protect access to light and air, predicted the impact of the law in his book *The Metropolis of Tomorrow* (Ferriss, 1928).

The table **Daylight Spacing Angles for Different Latitudes** indicates rule–of–thumb daylight spacing angles recommended for different latitudes.

The table assumes overcast sky conditions typical of the latitudes listed and continuous building rows. Daylight factors shown are sufficient to provide an average of 20 foot–candles (215 lux) indoors, a moderate level of ambient lighting that would require TASK LIGHTING for activities such as reading or drawing. At low latitudes, higher levels of exterior illuminance are available for more of the year, while at high latitudes nearer the poles, very short winter days prevent high interior daylight levels from being achieved year–round. The table shows the percentage of annual hours between 9 AM and 5 PM during which the 20 fc (215 lux) interior daylight level will be met or exceeded. Three angles are given (in degrees):

- *The Low column*, representing shallower spacing angles (wider streets/shorter buildings) can be generally associated with small windows and darker (low–reflectance) exterior walls.
- *The Medium column*, the recommended values, can generally be associated with medium–sized windows and light–colored (higher reflectance) exterior walls.
- *The High column*, representing steeper spacing angles (narrower streets/taller buildings) can be generally associated with large windows and light–colored (high–reflectance) exterior walls.



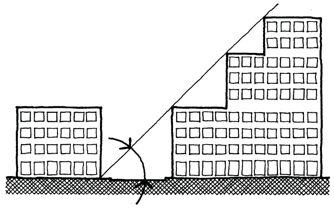
Study of the 1916 New York Zoning, Hugh Ferriss

Study of the 1916 New York Zoning, Hugh Ferriss

As the comments in the table indicate, at low latitudes, large windows are unnecessary for lighting and may cause excessive glare and heat gains, while at high latitudes, low–reflectance walls are not recommended (NR).

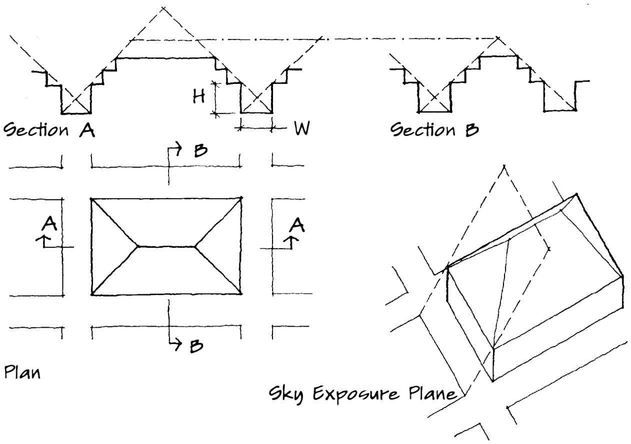
The relationships among sky condition, latitude, surface reflectivity, building spacing and continuity, building shape and height are complex and the spacing angles in the table may be more restrictive than necessary under some circumstances. Remember that many low–latitude climates may be dominated by clear skies and thus the spacing angles would generally be more restrictive than necessary. However, designers may wish to use the overcast sky as a design condition for spacing buildings and sizing windows, while providing controls at the windows

Latitude N. or S.	Required Daylight Factor	H/W range	Min. Spacing Angle Low	Medium	High	% ann. hours 9AM–5PM	COMMMENTS
0–8	1.0	1.7–2.0	60	70	NR	95	large windows NR
12–16	1.0	1.7–2.0	60	70	NR	90	large windows NR
28–32	1.5	1.5–2.0	50	65	70	85	
34–38	2.0	0.8–2.0	39	60	65	85	
40–44	2.5	0.5–1.8	24	52	61	85	
46–48	3.0	0.4–1.5	22	45	56	85	
52	4.0	0.2–1.0	11	31	45	85	low reflect walls NR
56	4.0–5.5	0.3–1.0	NR	23	37	80–85	low reflect walls NR
60	4.0–6.0	0.2–1.0	NR	21	35	70–80	low reflect walls NR
64	4.5–6.0	0.2–0.8	NR	18	32	60–70	low reflect walls NR
68	5.0–6.0	0.2–0.7	NR	15	30	60–70	low reflect walls NR
70	6.0	0.2–0.5		11	24	60	low reflect walls NR



Spacing Angle (degrees)

Daylight Spacing Angles for Different Latitudes
(for 20 fc interior illuminance & overcast sky) NR = not recommended



Construction of a Daylight Access Envelope

to keep out excess sun and light on clear days [see DAYLIGHT AVAILABILITY]. A DAYLIGHT ENVELOPE is the maximum volume that can be built on a given site while still protecting daylight access to neighboring buildings or sites. Daylight envelopes offer a prescriptive development control. Their geometry is illustrated in **Construction of a Daylight Access Envelope**.

After the **spacing angle** *is known from the table, a* ***daylight envelope may be constructed: Determine street width and building height along the street. Then strike a sky exposure plane from one side of the street at ground level through the top of the street wall on the other side, as illustrated. When this is done on all four sides of a block, a hip-roof–shaped pyramid is formed above the street-wall–defined rectangular volume.***

This is a daylight envelope. As long as a window cannot "see" a part of the building across the street that is above the specified street wall height, its daylight access will not be impacted further. Because sky luminance varies with latitude, higher latitudes require using higher daylight factors to achieve the same effect as in lower latitudes [see table in DAYLIGHT APERTURES].

From

EAST–WEST ELONGATED BUILDING GROUPS

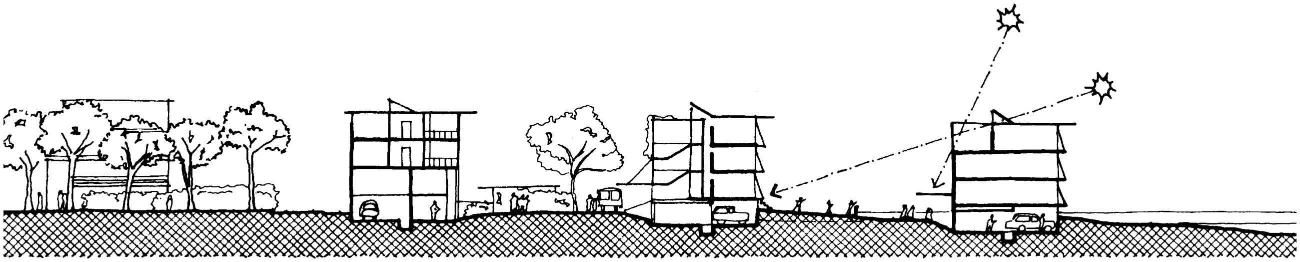
20 ***BUILDING SPACING FOR SOLAR ACCESS* sets criteria for insuring winter solar gain to building rows spaced in the north–south direction. [heating]**

The placement of a building such that it has access to the sun without shading other buildings has important implications for the form and arrangement of groups of buildings.

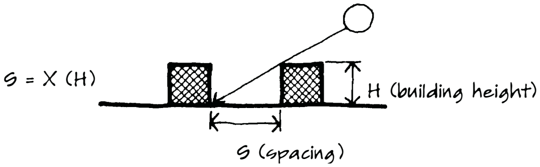
The appropriate spacing between buildings is determined by the profile angle of the low altitude winter sun. Multiply the height of the building,* H*, by the value* X *from the table* Building Spacing for Winter Solar Access *to determine the spacing,* S*, that will provide optimum winter exposure for a cluster of buildings. Also, see EAST–WEST PLAN.

The table is based on the sun position on Dec 21 and Jan/Nov 21 for Northern Hemisphere latitudes between 0° and 52°. Corresponding Southern Hemisphere months are also given at the bottom of each part of the table. Because at high latitudes the sun in midwinter is very low or below the horizon, full solar access all winter may be impossible. Therefore, for 56–60° latitude, the solstice month is omitted, and for 64–70° latitude, the three winter months with the lowest sun are omitted. The most intense solar radiation falls between the hours of 10 AM and 2 PM (solar time).

In planning the **Solar City Pilching,** a new district for Linz, Austria, architects Foster, Herzog and Rogers planned two of the district's sectors as east–west–elongated, roughly parallel rows (Herzog, 1996, pp. 180–191; Treberspurg, 2008). As shown in the section, the buildings of the south sector are spaced with an 18° angle, giving solar access on Jan/Nov 21 between 10 AM and 2 PM. Additionally, the spacing distance between the buildings has been reduced by raising the first floor with parking below, and by cutting back the north side of the upper floor on some buildings.



Solar City Pilching, Linz, Austria, Norman Foster & Partners, section through south sector housing

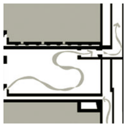


VALUES of X for BUILDING SPACING

LATITUDE North lat.	9 AM		10 AM		11 AM		12 Noon		1 PM		2 PM		3 PM	
	Dec	Jan/ Nov	Dec	Jan/ Nov	Dec	Jan/ Nov	Dec	Jan/ Nov	Dec	Jan/ Nov	Dec	Jan/ Nov	Dec	Jan/ Nov
0	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.6	0.5
4	0.7	0.6	0.6	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.6	0.5	0.7	0.6
8	0.8	0.7	0.7	0.6	0.6	0.5	0.6	0.5	0.6	0.5	0.7	0.6	0.8	0.7
12	0.9	0.8	0.8	0.7	0.7	0.6	0.7	0.6	0.7	0.6	0.8	0.7	0.9	0.8
16	1.1	0.9	0.9	0.8	0.8	0.7	0.8	0.7	0.8	0.7	0.9	0.8	1.1	0.9
20	1.3	1.1	1.1	0.9	1.0	0.9	0.9	0.8	1.0	0.9	1.1	0.9	1.3	1.1
24	1.5	1.2	1.2	1.1	1.1	1.0	1.1	1.0	1.1	1.0	1.2	1.1	1.5	1.2
28	1.7	1.4	1.4	1.2	1.3	1.1	1.3	1.1	1.3	1.1	1.4	1.2	1.7	1.4
32	2.0	1.7	1.6	1.4	1.5	1.3	1.5	1.3	1.5	1.3	1.6	1.4	2.0	1.7
36	2.4	2.0	1.9	1.7	1.7	1.5	1.7	1.5	1.7	1.5	1.9	1.7	2.4	2.0
40	3.0	2.4	2.3	1.9	2.1	1.8	2.0	1.7	2.1	1.8	2.3	1.9	3.0	2.4
44	3.9	2.9	2.8	2.3	2.5	2.1	2.4	2.1	2.5	2.1	2.8	2.3	3.9	2.9
48	5.4	3.8	3.6	2.9	3.1	2.6	3.0	2.5	3.1	2.6	3.6	2.9	5.4	3.8
52	8.8	5.3	5.0	3.7	4.1	3.2	3.9	3.1	4.1	3.2	5.0	3.7	8.8	5.3
South lat.	**Jun**	**May/ Jul**	**Jun**	**May/ Jul**	**Jun**	**May/ Jul**	**Jun**	**May/ Jul**	**Jun**	**May/ Jul**	**Jun**	**May/ Jul**	**Jun**	**May/ Jul**
North lat.	**Jan/ Nov**	**Feb/ Oct**	**Jan/ Nov**	**Feb/ Oct**	**Jan/ Nov**	**Feb/ Oct**	**Jan/ Nov**	**Feb/ Oct**	**Jan/ Nov**	**Feb/ Oct**	**Jan/ Nov**	**Feb/ Oct**	**Jan/ Nov**	**Feb/ Oct**
56	8.4	2.9	5.0	2.5	4.2	2.4	4.0	2.3	4.2	2.4	5.0	2.5	8.4	2.9
60	20.7	3.8	7.9	3.2	6.1	2.9	5.7	2.9	6.1	2.9	7.9	3.2	20.7	3.8
South lat.	**May/ Jul**	**Apr/ Aug**	**May/ Jul**	**Apr/ Aug**	**May/ Jul**	**Apr/ Aug**	**May/ Jul**	**Apr/ Aug**	**May/ Jul**	**Apr/ Aug**	**May/ Jul**	**Apr/ Aug**	**May/ Jul**	**Apr/ Aug**
North lat.	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**
64	5.2	2.1	4.1	2.1	3.8	2.1	3.7	2.1	3.8	2.1	4.1	2.1	5.2	2.1
68	8.3	2.5	5.9	2.5	5.2	2.5	5.1	2.5	5.2	2.5	5.9	2.5	8.3	2.5
72	19.7	3.1	10.2	3.1	8.4	3.1	7.9	3.1	8.4	3.1	10.2	3.1	19.7	3.1
South lat.	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**	**Feb/ Oct**	**Mar/ Sep**

Building Spacing for Winter Solar Access: Values of X for Calculating Building Spacing
Dates are for 21st of each month

From NIGHT–COOLED MASS



54 The *NIGHT VENTILATION POTENTIALS MAP* shows the months for which night ventilation of thermal mass is likely to provide cooling. [cooling]

Cooling a building using nighttime ventilation of the thermal mass depends on a twofold process. First, during the day when the outside temperature is too warm for ventilation, the building envelope is closed and excess heat gains are stored in the building's mass. Second, at night when the outside temperature is lower, outdoor air is allowed to ventilate through the building to remove the stored heat from the mass. The mass is thus cooled, so that it can absorb excess heat again the next day.

In night ventilation schemes, the area of the mass that can be incorporated into a structure is a major limitation on the cooling potential. The ratio of mass surface area to floor area is usually between 1:1 and 1:3; it is difficult to develop more mass surface area within the building.

The* Night-Cooled Mass Potentials Climate Zones Map *shows the months that are cool enough at night for night ventilation of mass to provide cooling (Iwersen, 1992). Find the zone for the building's climate from the map and then refer to the that zone's row in the table* Night-Cooled Mass Potential by Climate Zone. *Use the SLD columns for skin-load–dominated buildings with balance points above 60° F (15.6° C). Use the ILD column for internal-load–dominated buildings with a balance point below 60° F (15.6° C).

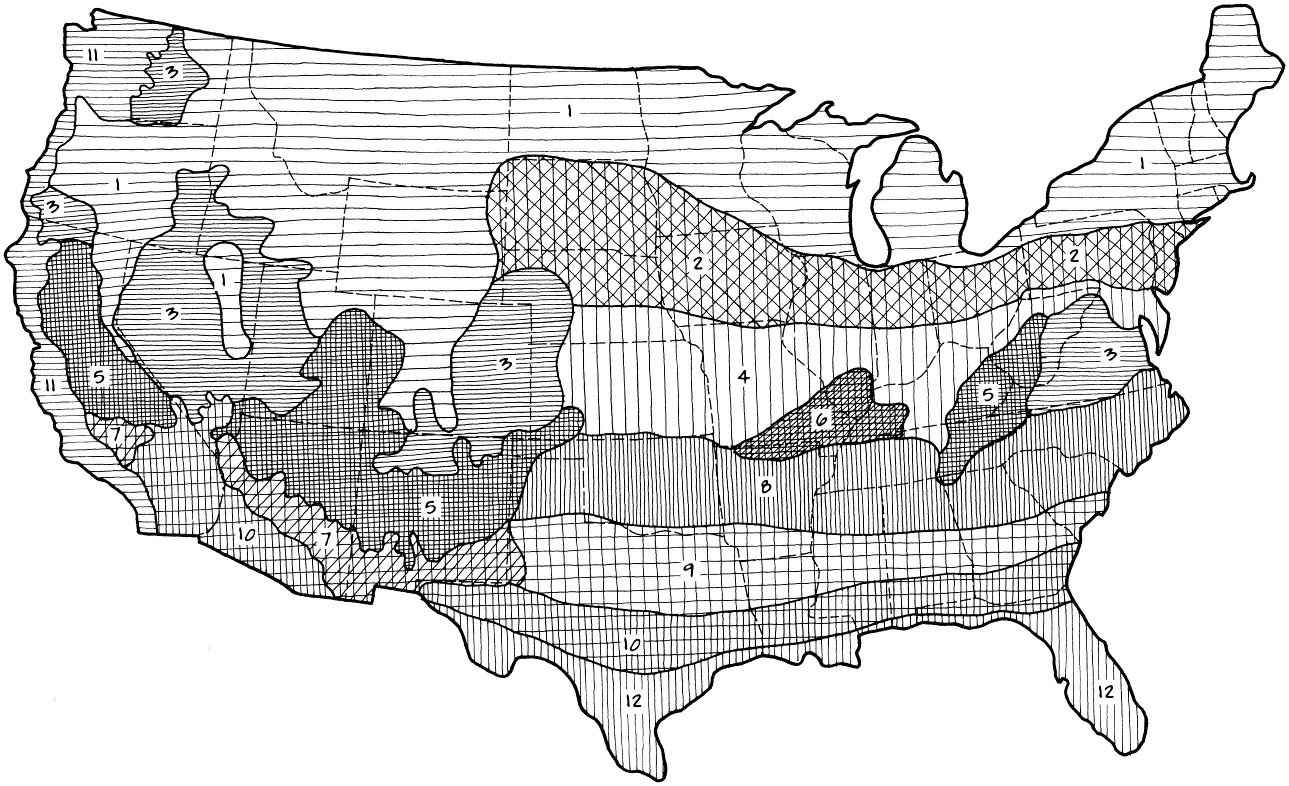
The ability to cool with outside air at night depends on having a low enough minimum temperature. Since the low mass temperature will be about 5° F (3° C) above the minimum outdoor air temperature, estimate the potential for night ventilation for a given month by adding 5° F to the minimum temperature. If this low mass temperature is below 72° F (22° C), then there is good potential for night–cooled mass.

Use the table as a rough guide. Night–cooled mass is still possible with low mass temperatures above 72° F (22° C), but higher rates of night ventilation and more mass are required.

	SLD Buildings		ILD Buildings	All Buildings
Zone	**Night–Cooled Mass Possible**	**Cooling Unnecessary**	**Night–Cooled Mass Possible**	**Too Hot for Night–Cooled Mass**
1	July & Aug	Sep to Jun	ALL	NONE
2	Jun to Aug	Sept to May	ALL	NONE
3	Jun to Sep	Oct to May	ALL	NONE
4	June & Sep	Oct to May	Sep to May	Jul & Aug
5	May to Sep	Oct to Apr	ALL	NONE
6	May & Jun; Aug & Sep	Oct to Apr	Aug to Jun	Jul
7	Apr to Jun; Aug & Sep	Nov to Mar	Sep to Jun	Jul & Aug
8	May & Sep	Oct to Apr	Sep to May	Jun to Aug
9	May; Sep & Oct	Nov to Apr	Sep to May	Jun to Aug
10	Apr & May; Oct	Nov to Mar	Oct to May	Jun to Sep
11	ALL	ALL	ALL	NONE
12	NONE	NONE	NONE	ALL

Night-Cooled Mass Potential by Climate Zone
based on low mass temp < 72° F (22° C)

The thermal storage capacity of mass depends on the amount of exposed area, its thickness and the density and specific heat of the material. See MASS ARRANGEMENT for recommendations on location and other design implications. See NIGHT–COOLED MASS in *SWL Electronic* for more details on sizing of the mass and for building examples.



Night-Cooled Mass Potentials Climate Zone Map
helps to assess the potential for night-cooled mass

From SIDELIGHT ROOM DEPTH

57 The *DAYLIGHT UNIFORMITY RULE* helps determine room proportions to maintain a minimum level of illumination and an even distribution of light. [daylighting]

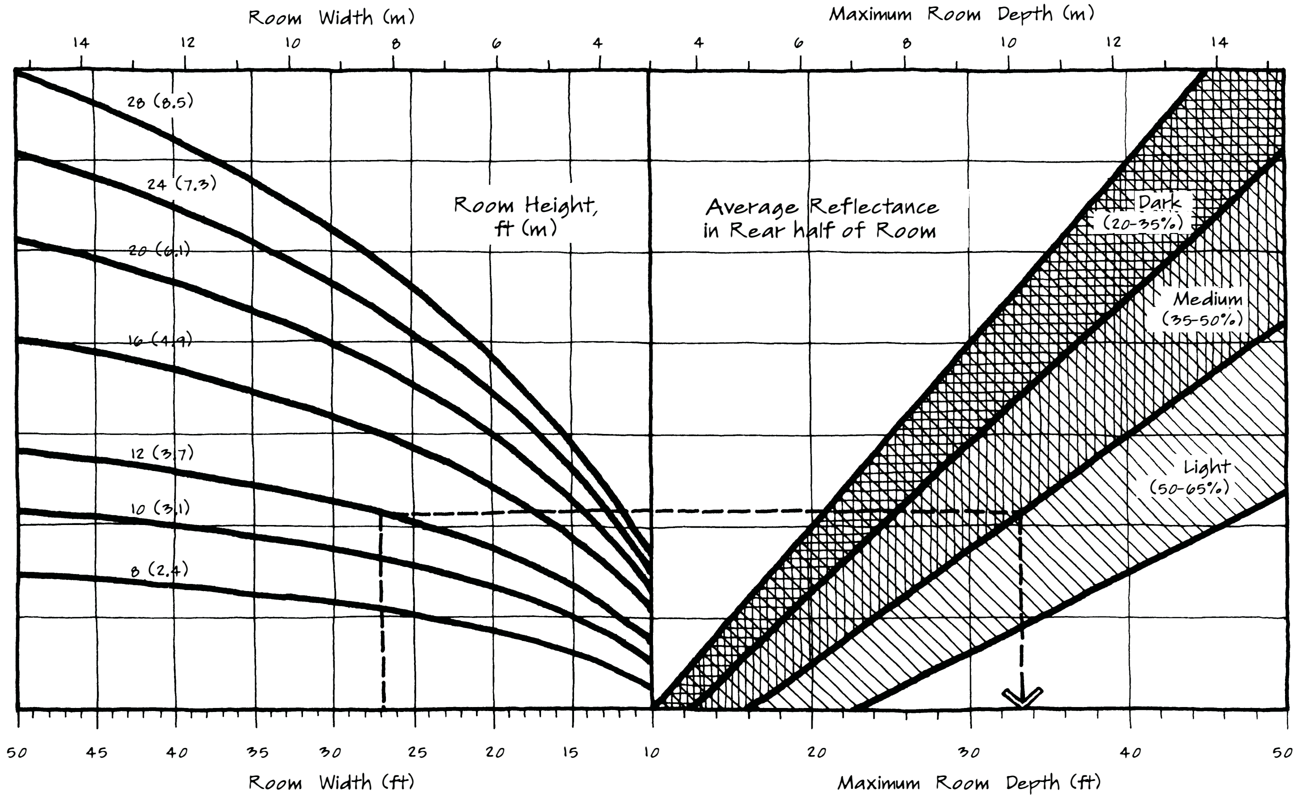
In a sidelighted room the illumination is high near the window and falls off rapidly farther away from the window wall. The deeper the room, the greater the contrast between the area near the window and the wall farthest from the window. Under overcast conditions, assuming nearly continuous windows, when the room depth is greater than 2.5 times the height of the window's head, the ratio between the brightest and darkest part of the room will exceed 5:1 (Flynn and Segil, 1970, p. 111). Excessive gradients tend to make the lighting seem uneven; and if the eye is adapted to the lightest parts of the room, especially the window, then the darker parts of the room will seem darker than they actually are (Hopkinson et al., 1966, p. 306).

Therefore, in most cases, under overcast skies, set room depth in the direction perpendicular to the window wall at less than 2.5 times the height of the window head.

If specific room characteristics are known, the graph for **Estimating Maximum Room Depth for Daylight Uniformity** can be used. If the room depth exceeds the maximum recommendation from the graph, the rear half of the room will look dark and supplementary electric lighting will be necessary most of the time (developed from a model in Littlefair, 1996, p. 33).

To find the maximum room depth, enter the graph on the left–side horizontal axis with the room width. Move vertically to intersect the curve for the room's ceiling height, then right to the right side of the graph and over to the diagonal zone for the average reflectance in the back half of the room. Finally, move vertically to read the maximum allowable room depth on one of the horizontal scales.

The average reflectance is a weighted average of all surfaces in the back half of the room. Remember that floors and furnishings tend to be dark and glazing has low reflectance, so even with light–colored walls and ceiling, the average reflectance of most rooms does not exceed 50%. For more on surface reflectance, see DAYLIGHT REFLECTING SURFACES.



Estimating Maximum Room Depth for Daylight Uniformity

From SKIN THICKNESS

74 *INSULATION RECOMMENDATIONS* insure that heat flow through the envelope is small enough that passive strategies will be effective. [heating and cooling]

There are three basic strategies for placing thermal insulation. First, the insulation may be contained within the skin cavity; second, the insulation can be applied to the surface of the skin; and in the third strategy, the insulation and structure are integrated, with no framing. At moderate, thin insulation levels, when insulation is placed within the hollow between the framing members, the overall thickness of the wall may be less than with masonry walls, which must have the insulation on their surface.

When the insulation is placed on the surface of the wall, such as on the surface of an exterior masonry wall, one side of the skin material can be left exposed, and the structure does not need to be enlarged to accommodate thicker layers of insulation. Two strategies can also be combined, with some insulation placed on the skin's

	ROOFS		WALLS				EXPOSED FLOORS			BASEMENT/SLAB			
Zone	**Attic, Wood** (2) **in** (*R*) hi–R	**Cathedral /Compact** (2) **in** (*R*)	**Mass** (1) **in** (*R*)	**Metal Frame** (3) **in** (*R*)	**Wood Frame** (2,3) **in** (*R*)	**High–Perform** (5) **In** Assembly *R*	**Mass** (1) **in** (*R*)	**Metal Frame** (2) **in** (*R*)	**Wood Frame** (2,3) **in** (*R*)	**Walls Below Grade** (1) **in** (*R*)	**Crawl Space Wall** **in** (*R*)	**Slab Unheated** (4) **in** (*R*)	**Slab Heated** (4) **in** (*R*)
R–1	**12”** (30–49) 40	**7–12”** (22–38) 35	**1.5”** (8)	**5”** (15+5)	**4–5”** (13–15)	**4”** 10	**1”** (4)	**6”** (19)	**4”** (13) 10	**0–1”** (NR) 5	**2.5”** (13)	**0–1”** (4) NR	**1.5”** **+ 1” under** (8 + 5)
R–2	**12”** (30–60) 50	**7–13”** (22–38) 40	**2.5”** (12)	**5”** (15+5)	**6–7”** (15–21)	**7”** 15	**1.5”** (6)	**8”** (25)	**4–7”** (13) 20	**1–2”** (5–11) 10	**2.5”** (13)	**1”** (4) 5	**1.5”** **+ 1” under** (8 + 5)
R–3	**16”** (30–60) 50	**7–15”** (22–38) 45	**3”** (16)	**6”** (15+10)	**6–7”** (15–21)	**8”** 20	**1.5”** (6)	**8”** (25)	**6–8”** (19–25) 20	**2”** (8–11) 10	**5”** (25)	**1.5”** **+1” under** (8) 7.5 +5	**1.5”** **+ 1” under** (8 + 5)
R–4	**16”** (30–60) 60	**7–15”** (22–38) 45	**3”** (16)	**6”** (15+10)	**6–7”** (15–21)	**8”** 25	**2”** (10)	**8”** (25)	**8–10”** (25) 30	**2–3”** (10–11) 15	**5”** (25)	**1.5–2.5”** **+ 1.5” under** (12) 7.5 +7.5	**2”** **+ 1.5” under** (10 + 7.5)
R–5	**16”** (30–60) 65	**7–17”** (22–38) 50	**3”** (16)	**6”** (15+10)	**6–8”** (15–21 + 2.5–6)	**9–10”** (30	**2.5”** (13)	**8”** (25)	**8–10”** (25–30) 30	**2–3”** (11–12) 15	**5”** (25)	**2–2.5”** **+ 1.5 under** (12) 10 + 7.5	**3”** **+ 1.5” under** (15 + 7.5)
R–6	**16”** (49–60) 75	**7–20”** (22–38) 60	**3”** (16)	**6”** (15+10)	**6–8”** (15–21 + 2.5–6)	**10–12”** 35	**3”** (15)	**8”** (25)	**8–14”** (25–30) 40	**3–4”** (12–15) 20	**5”** (25)	**2–2.5”** **+ 2” under** (12) 10 + 10	**3”** **+ 2” under** (15 + 10)
R–7	**16”** (49–60) 90	**10–22”** (30–60) 65	**4”** (20)	**6”** (15+10)	**8”** (15–21 + 5–6)	**11–14”** 40	**4”** (20)	**8”** (25)	**8–15”** (25–30) 45	**3–5”** (12–15) 25	**5”** (25)	**2.5–3”** **+ 3” under** (12) 15 + 15	**4”** **+ 3” under** (20 + 15)
R–8	**16”** (49–60) 100	**10–25”** (30–60) 75	**4”** (20)	**6”** (15+10)	**8”** (15–21 + 5–6)	**12–17”** 50	**4”** (20)	**8”** (25)	**8–17”** (25–30) 50	**3–7”** (12–15) 35	**5”** (25)	**2.5–4”** **+ 4” under** (12) 20 + 20	**4”** **+ 4” under** (20 + 20)

NOTES Thicknesses assume *R*–5 (*RSI* 0.88) rigid insulation and *R*–3 (0.05) batt insulation. *R*–value range is from ORNL (2008) and represent *R*–values of the insulation only.
(1) *R*–values and thicknesses are for *rigid, continuous insulation/sheathing outside the framing* or mass structure.
(2) *R*–values and thicknesses are for *batt insulation between the framing*, and in the case of attics also above joists.
(3) *R*–values and thicknesses are for *a combination* of batt insulation between framing and rigid insulation outside the framing to reduce thermal bridging.
(4) Slab–on–grade insulation is for a given thickness on *outside edge* of the slab, extending full depth of slab or stem wall. 'Under' means rigid insulation *under the slab.*
(5) Hi–performance wall recommendations (following parentheses) from Straube (2011), other assembly configurations possible.

Low-Rise Residential Recommended Minimum Insulation (IP Units)

surface and some between the framing members. In frame structures, a continuous layer of insulation reduces thermal bridging, especially in metal frame construction.

Recommended insulation levels for low–rise residential buildings can be determined by finding the site's climate zone on one of the three maps (United States, Alaska, or Canada) in Appendix F and then referring to the* Low–Rise Residential Recommended Minimum Insulation *table. Hawaii and the Caribbean are considered Zone 1 (developed using ORNL, 2008).

Where a range of recommendations is given, use the low end recommendation for residences heated with natural gas, a middle value for fuel oil and LP gas, and the high end for electric heat. Greater insulation levels may be required above Zone 8. Recommendations are based on life–cycle cost analyses, including assumptions about mechanical system efficiencies, economic return and local fuel and construction costs.

In **nonresidential buildings**, winter heat losses are partially or totally offset by internal gains, so they tend to need less heating than residential buildings and may sometimes need more cooling than heating. Therefore, insulation standards for nonresidential buildings are usually lower than those for residential buildings.

Recommended insulation levels for nonresidential buildings can be determined by finding the site's climate zone on one of the three* maps *(United States, Alaska, or Canada) in Appendix F and then referring to the* Nonresidential Recommended Minimum Insulation *table (developed using ASHRAE, 2009a).

Zone	ROOFS Above Roof Deck (1) in (*R*)	ROOFS Attic/ Other (2) in (*R*)	WALLS Mass (1) in (*R*)	WALLS Metal Frame (3) in (*R*)	WALLS Wood Frame 3) in (*R*)	FLOORS Mass (1) in (*R*)	FLOORS Metal Frame (2,3) in (*R*)	FLOORS Wood Frame (2,3) in (*R*)	BASEMENT / SLAB Walls Below Grade (1) in (*R*)	BASEMENT / SLAB Slab Unheated (4) in (*R*)	BASEMENT / SLAB Slab Heated (4) in (*R*)	DOORS U (*R*)
1	**4”** (20 c)	**12”** (38)	**1”** (6)	**5”** (13+5)	**5”** (13+4)	**1”** (4)	**6”** (19)	**6”** (19)	**0”** (NR)	**0”** (NR)	**1.5” + 1” under** (8 @ 12” +5)	**0.6** (2)
2	**5”** (25 c)	**16”** (49)	**1.5”** (8)	**5”** (13+5)	**5”** (13+4)	**1.5”** (6)	**10”** (30)	**10”** (30)	**0”** (NR)	**0”** (NR)	**1.5” + 1” under** (8 @ 12” +5)	**0.6** (2)
3	**5”** (25 c)	**16”** (49)	**2”** (10)	**5”** (13+5)	**5”** (13+4)	**1.5”** (6)	**10”** (30)	**10”** (30)	**0”** (NR)	**0”** (NR)	**1.5” + 1” under** (8 @ 12” +5)	**0.6** (2)
4	**5”** (25 c)	**16”** (49)	**2”** (11)	**6”** (13+10)	**5”** (13+4)	**2”** (10)	**12”** (38)	**12”** (30+8)	**1.5”** (8)	**2”** (10 @ 24”)	**2” + 1” under** (10 @ 24” +5)	**0.6** (2)
5	**5”** (25 c)	**16”** (49)	**2.5”** (13)	**6”** (13+10)	**6”** (13+8)	**2.5”** (13)	**12”** (38)	**12”** (30+8)	**2”** (10)	**2”** (10 @ 24”)	**3” + 1” under** (15 @ 36” +5)	**0.4** (2.5)
6	**6”** (30 c)	**16”** (49)	**3”** (15)	**6”** (13+10)	**6”** (13+10)	**3”** (15)	**12”** (38)	**12”** (30+8)	**2”** (10)	**3”** (15 @ 24”)	**3” + 1” under** (15 @ 36” +5)	**0.4** (2.5)
7	**7”** (35 c)	**16”** (49)	**4”** (20)	**6”** (13+10)	**6”** (13+10)	**4”** (20)	12” (38)	**12”** (30+8)	**2”** (10)	**2” + 1” under** (10 @ 24” +5)	**4” + 1” under** (20 @ 36” +5)	**0.4** (2.5)
8	**7”** (35 c)	**20”** (60)	**4”** (20)	**6”** (13+10)	**6”** (13+10)	**4”** (20)	15” (38+13)	**12”** (30+8)	**2”** (10)	**2” + 1” under** (10 @ 24” +5)	**4” + 1” under** (20 @ 36” +5)	**0.4** (2.5)

NOTES Thicknesses assume *R*–5 rigid insulation and *R*–3 batt insulation.
(1) *R*–values and thicknesses are for rigid, continuous insulation/sheathing outside the framing or mass structure.
(2) *R*–values and thicknesses are for batt insulation between the framing.
(3) *R*–values and thicknesses are for a combination of batt insulation between framing and an additional layer of rigid insulation outside the framing to reduce thermal bridging
(4) Slab–on–grade insulation is for a given thickness on the outside edge of the slab, extending a specified depth below grade (i.e., 3” insulation extending @ 24” down).
“Under” refers to rigid insulation under the slab.
c = continuous outside structure

Nonresidential Recommended Minimum Insulation (IP Units)

75 The *SIZING DIRECT THERMAL STORAGE* nomograph helps fit thermal storage area, type and thickness to the building's passive solar target. [heating]

Thermal storage can be in the form of masonry, water or phase change materials. Its size depends on the amount of heat that needs to be stored, based on the building's solar savings fraction (SSF) as found in SOLAR APERTURES. After location, the other important variables are the material, thickness and surface area, with surface area being the most significant.

For a given SSF, the storage size depends on location relative to the SOLAR APERTURES. *Direct mass* is in the same zone as the collection aperture so that the mass can exchange radiation with surfaces struck by the sun. It is the most effective type. *Indirect mass* is not in the room that collects heat, such as when warmed air is distributed to mass in adjacent rooms. Heat transfer for indirect mass is by convection and requires significantly more area and volume than does direct mass.

Nomographs for direct mass, indirect mass and phase change materials are given in THERMAL MASS. The tool for **Sizing Direct Thermal Mass for Direct Gain Rooms and Sunspaces** is reproduced here.

In* DIRECT GAIN ROOMS*, the masonry mass thickness should be 4–6 in (100–150 mm) thick. For direct mass the surface area should be 3–6 ft^2 of mass per ft^2 of south–facing (N in SH) glazing (3–6 m^2/m^2). This ratio works for any units of area used, and we refer to it as the ratio of *Area of mass: Area of solar glazing,* or A_m/A_g.

To keep interior temperature swings less than 10° F (5.6° C), set the A_m/A_g ratio at 6–8 (Balcomb and Wray, 1987, p. 2–7). ***If water is the storage medium, use 3.5–6.5 gal/ft^2 of solar collection glazing (145–265 L/m^2)*** (Balcomb et al., 1980, p. 26). The greater amount of mass area within this range the better the performance, especially in buildings in which a large percentage of the heat is supplied by solar energy (high SSF).

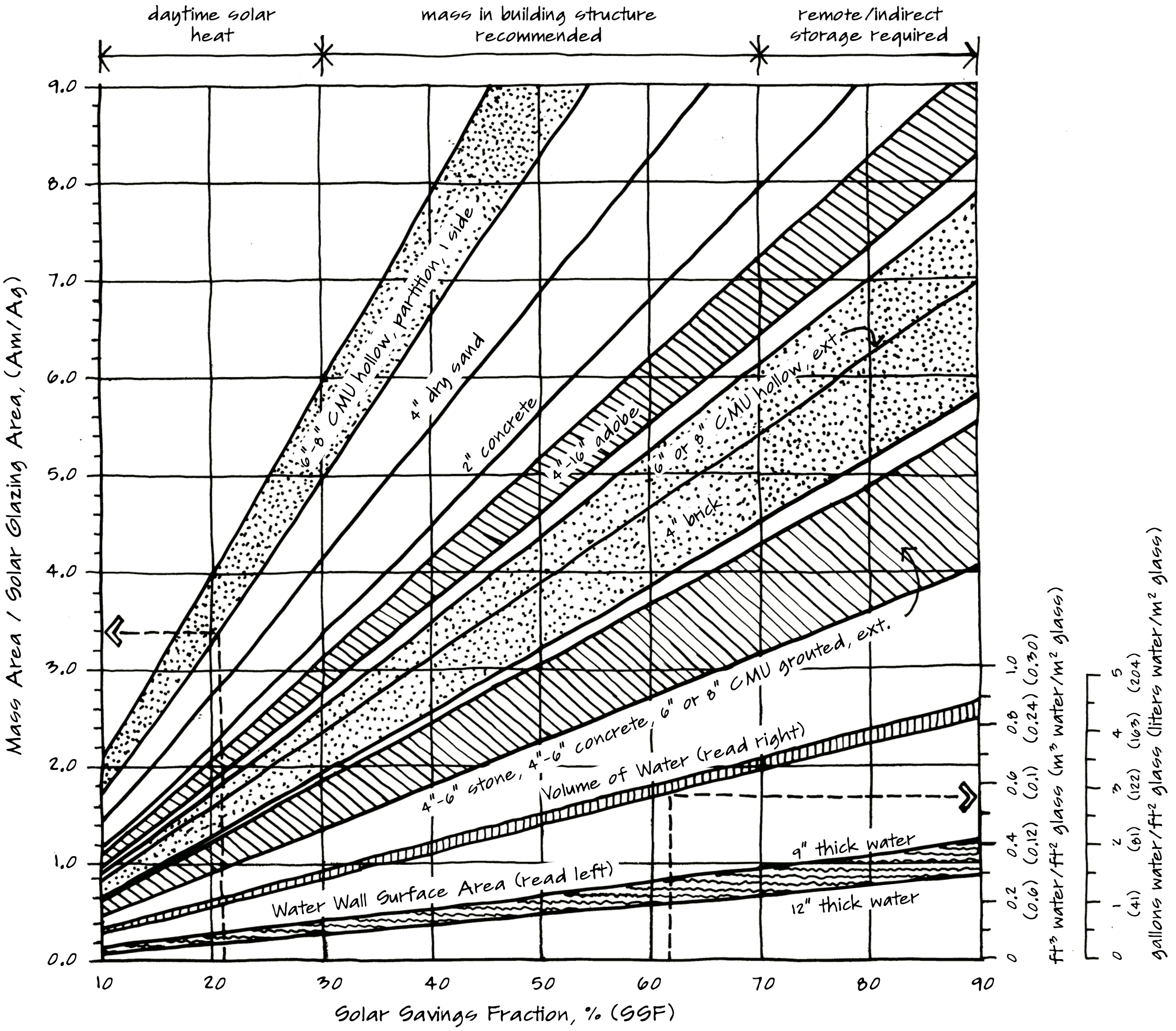
For indirect mass not in the sun–collecting room (or any remote mass), the surface area should be 2–3 times that of directly coupled mass. If the* direct mass *is in the range of 3–6 times the area of solar collection, then a comparable* indirect mass *would have an A_m/A_g ratio of 9–18. See the nomograph in THERMAL MASS.

Higher solar savings fractions require more thermal storage. SSF can be estimated in SOLAR APERTURES. When the SSF is less than 30%, solar heat mostly offsets daytime heat losses and little thermal storage is required. Between 30 and 70% SSF, more mass provides for storage into the night. An SSF beyond 70% is difficult to achieve in most climates without daytime overheating, thus remote multi-day storage is usually required [see ROCK BEDS].

Both the selection of materials and their thickness affect the heat storage capacity. In general, heavyweight materials store heat and lightweight materials insulate. The best materials can store high levels of heat (have high volumetric heat capacity) and can readily move heat from a material's surface to its interior and back again to heat a room (high thermal conductivity). For masonry, density is the key factor. However, water is about four times more effective at storing heat than masonry.

For masonry materials, use a relatively thin mass, generally 4–6" spread over a large area. Thickness beyond 6 in (152 mm) does not increase storage on a daily cycle.

To size* direct mass *for passive solar heating, enter the graph **Sizing Direct Thermal Mass for Direct Gain Rooms and Sunspaces** on the horizontal axis with the estimated solar savings fraction for the design. Move vertically to intersect the diagonal line for the mass type and thickness, and then horizontally to read the recommended ratio of mass area to solar glazing area (A_m/A_g). Multiply this value by the area of solar aperture to yield the minimum required mass area.



Sizing Direct Thermal Mass for Direct-Gain Rooms and Sunspaces

Direct Mass is located in rooms that collect sun.

84 *PASSIVE SOLAR GLAZING AREA* recommendations match glazing size to predicted solar savings fraction. [heating]

The solar savings fraction (SSF) is the percentage of annual energy saved by using solar energy for space heating, compared to heating a nonsolar building with similar thermal characteristics (Balcomb et al., 1983, p. 5). The **Passive Solar Glazing Area Design Recommendations** table gives estimated SSF for buildings in representative U.S. and Canadian cities.

Consult the maps of climate zones in CLIMATE DATA BY LATITUDE/CITY to find the city most representative of the building site, or see SOLAR RADIATION. The variables are south–facing (N in SH) collection area (A_g) as a fraction of floor area (A_f) and whether or not high–performance glazing (or MOVABLE INSULATION) is used. The design recommendation takes the general form of:

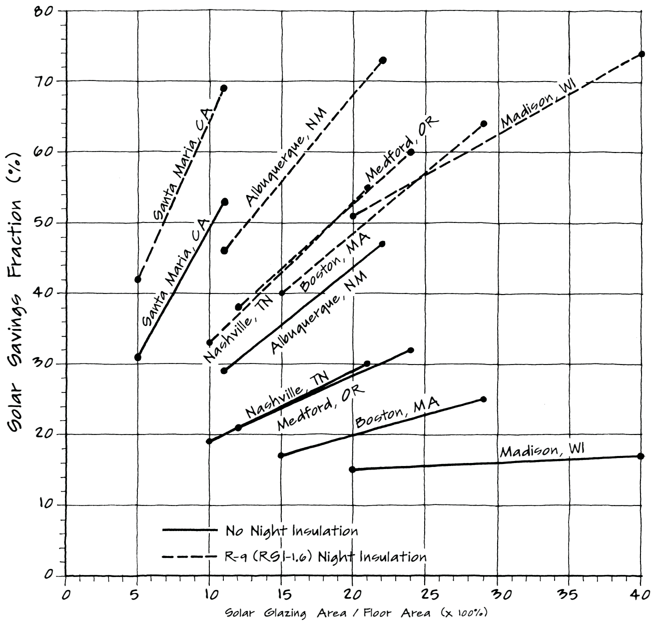
A solar collection area of (low A_g /A_f)% to (high A_g /A_f)% of the floor area can be expected to reduce the annual heating load of a building in (location) by (low SSF)% to (high SSF)%, or if* R–*9 (*RSI–*1.6) night insulation is used, by (Low SSF)% to (High SSF)% [Balcomb et al, 1980, pp. 20–23].

For example, a solar collection area of 15 to 29% of the floor area can be expected to reduce the annual heating load of a building in St. Louis, Missouri, by 21 to 33%, or if high–performance glazing (or *R*–9 night insulation) is used, by 41 to 65%.

Exceeding the high end of the recommendations may result in clear day winter overheating. Upper SSF is based on a limit of 75 °F (24 °C) interior maximum temperature on an average January clear day without night insulation.

If a high SSF is desired, more THERMAL MASS must be used to dampen extreme interior thermal swings. If additional mass cannot be stored in the building's structure, accessory storage in a ROCK BED may be appropriate.

The recommendations assume that buildings are well insulated with low infiltration rates. See TOTAL HEAT GAINS AND LOSSES and details in SOLAR APERTURES. Internal heat



Sizing Glazing for Passive Solar Heating
Plot values from table. Solar glazing should be +/- 30 degrees from south (north in Southern Hemisphere)

sources are assumed to warm the building by 5 °F (3 °C), representing a skin–load–dominated building such as a residence or light commercial building with low internal loads. Buildings with high internal loads from lights, people and equipment, generating an internal temperature rise greater than 5 °F (3 °C), such as office buildings, will have higher SSF performance than those given.

Performance does not significantly depend on the type of passive solar system used [DIRECT GAIN ROOMS, THERMAL STORAGE WALL, or SUNSPACES], except in the case of direct gain from south windows without night insulation, which will be lower than the SSF values indicated. Performance is significantly improved by the use of high–performance glazing and/or night insulation, especially in colder

USA CITIES	A_{glass}/A_{floor} ratio of solar glazing area to floor area		Approximate SSF: *R*–2 windows with No Night Insulation		Approximate SSF: H–P Windows OR *R*–2 windows with *R*–9 (*RSI*–1.6) Night Insulation	
	Low	High	Low	High	Low	High
AR, Little Rock	0.10	0.19	23	38	37	62
AZ, Phoenix	0.06	0.12	37	60	48	75
AZ, Winslow	0.12	0.24	30	47	48	74
CA, Fresno	0.09	0.17	29	46	41	65
CA, Los Angeles	0.05	0.09	36	58	44	72
CA, Santa Maria	0.05	0.11	31	53	42	69
CO, Eagle	0.14	0.29	25	35	53	77
CT, Hartford	0.17	.35	14	19	40	64
DC, Washington	0.12	0.23	18	28	37	61
FL, Jacksonville	0.05	0.09	27	47	35	62
FL, Miami	0.01	0.02	27	48	31	54
ID, Boise	0.14	0.28	27	38	48	71
IN, Indianapolis	0.14	0.28	15	21	37	60
IA, Sioux City	0.23	0.46	20	24	53	76
KS, Dodge City	0.12	0.23	27	42	46	73
LA, New Orleans	0.05	0.11	27	46	35	61
ME, Caribou	0.25	0.50	NR	NR	53	74
MN, Minneapolis	0.25	0.50	NR	NR	55	76
MS, Jackson	0.08	0.15	24	40	34	59
MO, St. Louis	0.15	0.29	21	33	41	65
MT, Billings	0.16	0.32	24	31	53	76
MT, Cut Bank	0.24	0.49	22	23	62	81
NE, North Platte	0.17	0.34	25	36	50	76
NV, Ely	0.12	0.23	27	41	50	77
NV, Las Vegas	0.09	0.18	35	56	48	75
NM, Tucumcari	0.10	0.20	30	48	45	73
NY, Buffalo	0.19	0.37	NR	NR	36	57
OR, Medford	12	24	21	32	38	60
OR, Salem	12	24	21	32	37	59
PA, Philadelphia	15	29	19	29	38	62
SC, Charleston	07	14	25	41	34	59
TN, Knoxville	09	18	20	33	33	56
TX, Brownsville	03	06	27	46	32	56
TX, Fort Worth	09	17	26	44	38	64
TX, Houston	06	11	25	43	34	59
TX, Midland	09	18	32	52	44	72
CANADA						
AB, Edmonton	25	50	NR	NR	54	72
AB, Suffield	25	50	28	30	67	85
BC, Nanaimo	13	26	26	35	45	66
BC, Vancouver	13	26	20	28	40	60
MB, Winnipeg	25	50	NR	NR	54	74
NS, Dartmouth	14	28	17	24	45	70
ON, Moosonee	25	50	NR	NR	48	67
ON, Ottawa	25	50	NR	NR	59	80
ON, Toronto	18	36	17	23	44	68
QC, Normandin	25	50.	NR	NR	54	74

Passive Solar Glazing Area Design Recommendations

climates. Increased performance with night insulation is a nonlinear function [see MOVABLE INSULATION].

***Interpolation and limited extrapolation between the recommended values are allowed. Graphic interpolation is simple if the SSF recommendations for the building's climate are first plotted on the graph* Sizing Glazing for Passive Solar Heating.**

For more details and a larger graph, see SOLAR APERTURES.

85 Use the graphs for *SIZING WINDOWS FOR DAYLIGHTING* to match daylight aperture size to the room's floor area and its target design daylight factor. [daylighting]

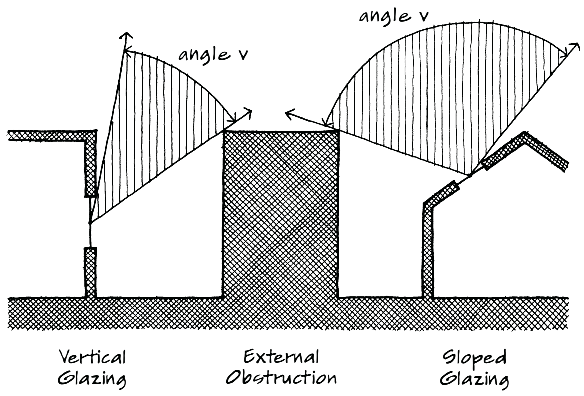
The **Sizing Windows for Daylighting** graph may be used to determine the glazing area needed to achieve a certain average daylight factor for a given floor area or to determine the average daylight factor for a combination of given floor and glazing areas.

To find the required size of a vertical unobstructed daylight aperture, begin on the upper graph on the vertical axis with the room's floor area, move horizontally to the diagonal for the DESIGN DAYLIGHT FACTOR ***From the intersection, move horizontally to read the required glazing area on the horizontal scale.***

For sloped or obstructed glazing, continue to the lower graph, dropping along the line of unobstructed vertical glazing area to the diagonal for the **Sky View Angle (v) from Glazing**, ***(see diagram). From the intersection, move horizontally to read the revised glazing area.***

Obstructions outside the glazing, such as fences, trees and other buildings, block the aperture's view of the sky and reduce the amount of light that falls on the glazing. The sky view angle *(v)* is the angle subtended, in the vertical plane perpendicular to the window, by sky visible from the center of the aperture. See the diagrams of **Sky View Angle from Glazing** (CIBSE, 1987; Littlefair, 1991, pp. 58–59).

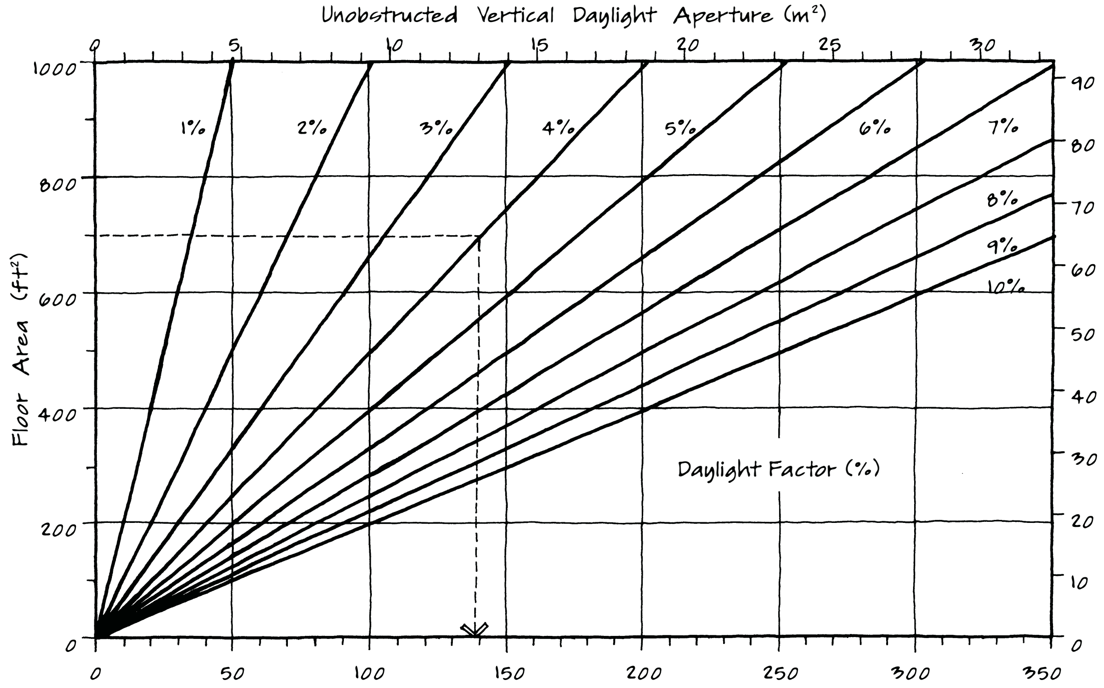
The graph assumes a 60% transmissivity for clear double glazing plus frame effects, a maintenance factor of 80%, an average room reflectance of 40% and a fairly large room, about the size of a classroom. It was developed using a model from Littlefair (1988). If other glazing and frame types with poorer visible light transmission are used (WINDOW AND GLASS TYPES), the glazing area will need to be increased proportionally. Because room size and proportions affect the pattern of internal reflections, light in small rooms is reflected more times before reaching the work plane than light in large rooms. ***For small rooms, such as bedrooms and private offices, increase the glazing size from the graph by up to 60%. For very large rooms, such as a gymnasium, reduce the glazing size by up to 30%.***

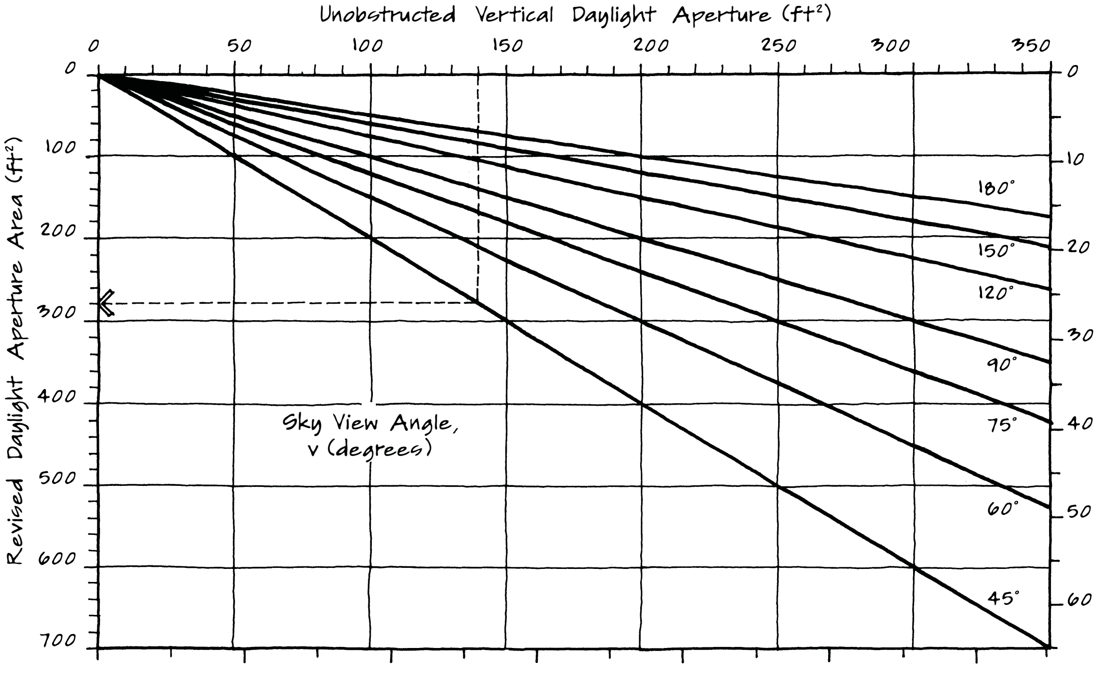


Sky View Angle (v) from Glazing

For sidelighting, the daylight factors apply to a floor zone with a maximum depth into the room of 2.5 times the height of the window wall (DAYLIGHT ROOM DEPTH). For toplighting, the floor area associated with the glazing can be estimated by projecting 45° lines from the opening to the floor. If more than one opening type is used for the same area, the daylight factors may be added.

Related: If the design daylight factor is not known, see the table in DAYLIGHT APERTURES or the quick calculation method in the DESIGN DAYLIGHT FACTOR analysis technique.


Unobstructed Vertical Daylight Aperture (m²)
0
5
10
15
20
25
30
1000
800
600
400
200
0
Floor Area (ft²)
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
Daylight Factor (%)
90
80
70
60
50
40
30
20
10
0
Floor Area (m²)
0
50
100
150
200
250
300
350
Unobstructed Vertical Daylight Aperture (ft²)


0
50
100
150
200
250
300
350
0
100
200
300
400
500
600
700
Revised Daylight Aperture Area (ft²)
Sky View Angle,
v (degrees)
180°
150°
120°
90°
75°
60°
45°
0
10
20
30
40
50
60
Revised Daylight Aperture Area (m²)

From VENTILATION APERTURES

86 The tools for *SIZING CROSS– AND STACK–VENTILATION* openings help define architectural characteristics that meet the building's cooling load. [cooling and ventilation]

The rate at which air flows through CROSS–VENTILATION ROOMS, carrying away heat with it, is a function of the area of the inlets and outlets, the wind speed, and the direction of the wind relative to the openings. The amount of heat removed by a given rate of air flow depends on the temperature difference between inside and outside the building. The maximum rate of ventilation occurs when the area of the inlets and outlets is large and the wind is relatively perpendicular to the window openings [ROOMS FACING THE SUN AND WIND].

The graph* Sizing Openings for Cross–Ventilation *helps size apertures required to remove heat from a building, as a percentage of floor area, assuming a temperature difference of 3° F (1.7° C) between inside and out. Enter the graph on the vertical axis with the design wind speed, and move horizontally until the curve for the building's heat gain rate is intersected. Then drop down to the horizontal axis to read the size of the inlet (and outlet) as a percentage of the floor area (developed based on a formula in ASHRAE, 2009c).

See WIND ROSE and WIND SQUARE for wind analysis to determine the design wind speed and TOTAL HEAT GAINS AND LOSSES for estimating the heat gains that need to be removed.

Remember to adjust the airport wind speed for local terrain conditions and speeds below average. A reduction factor of 0.75 should cover most "less than average" conditions.

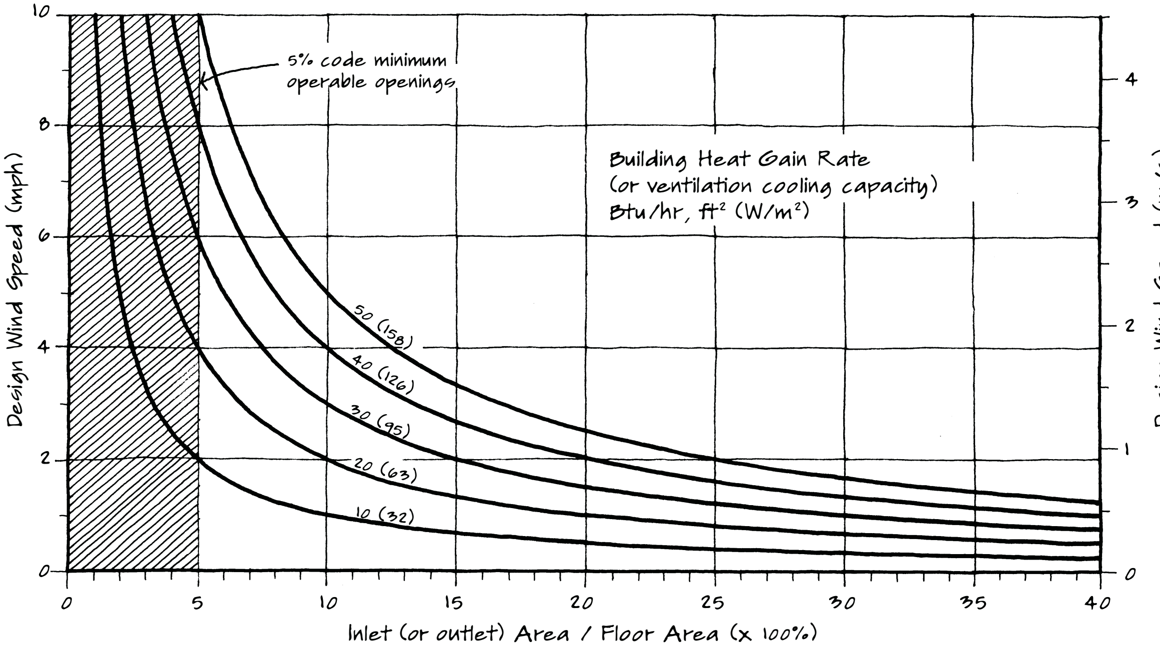
Design Wind Speed = Airport Average Speed x terrain factor x 0.75.

If the temperature difference between inside and out is less than 3 °F (1.7 °C), the openings need to be proportionally larger, and if the temperature difference is greater, the openings may be smaller. The graph assumes a wind incidence angle of 0–40°. See VENTILATION APERTURES for details of how to handle these variations.

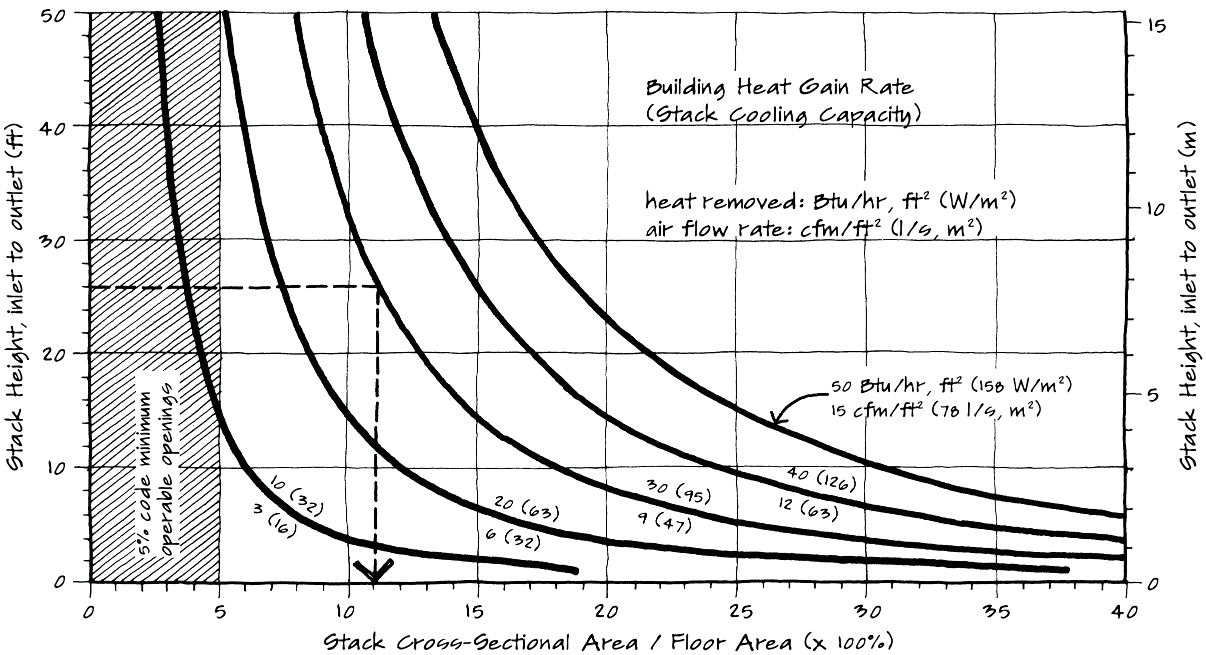
In STACK–VENTILATION ROOMS, warm air rises, exits though openings at the top of the room, and is replaced by cooler air entering low in the room. The rate at which the air moves through the room, carrying heat away with it, is a function of the vertical distance between the inlets and outlets, their size, and the difference between the outside temperature and the average inside temperature over the height of the room.

The graph* Sizing Stack–Ventilation *can be used to determine the height of the stack or room and the area of the stack cross section, given the ventilation rate (in cfm or L/s) or the heat gain to be removed (in Btu/hr, ft^2 or W/m^2). Enter the graph on the vertical axis with the height of the stack, measured from center of inlets to center of outlets. Move horizontally to the curve for the building's rate of heat gain* [TOTAL HEAT GAINS AND LOSSES]. *From the intersection, drop to the horizontal axis to find the stack area as a percentage of the floor area to be cooled. The stack area must be equaled or exceeded by the area of outlets and also by the area of inlets: the smallest area of constraint on air movement will govern the rate of flow (developed based on formula in ASHRAE, 2009c).

Approximate the building's rate of heat gain using TOTAL HEAT GAINS AND LOSSES. This graph assumes a temperature difference of 3° F (1.7° C) between inside and outside. For a temperature difference greater than 3° F (1.7° C), such as for night ventilation of mass, the stack area can be reduced. See VENTILATION APERTURES for details of how to handle these variations.



Sizing Openings for Cross-Ventilation



Note: Stack inets and outlets must be as large as stack cross section.

Sizing Stack-Ventilation

106 *GLAZING RECOMMENDATIONS* help select windows for daylighting, winter solar gain and summer heat rejection. [heating, cooling and daylighting]

Several types of energy flows occur through windows: 1) conductive and radiative flows through the window assembly; 2) solar radiant heat gain; and 3) infiltration gains and losses through air leakage.

Conduction transfers through the window are controlled by the window's *U*–factor, which indicates the rate of heat flow through a material. Lower *U*–factors (or higher *R*–values) mean better insulation. Glass has a much lower resistance to heat than most other building materials. In skin-load–dominated (SLD) buildings, windows can dominate the building's heating or cooling loads. Therefore, window *U*–factors should generally decrease as the severity of the outdoor climate increases. See WINDOW AND GLASS TYPES for recommendations by climate zone.

The table of* Generalized Recommendations for Glazing + Window Selection *gives suggestions by glazing orientation, climate type (cooling dominated, mixed, or heating dominated) and whether the building is internal-load–dominated (ILD) or skin-load–dominated (SLD). SHGC and *U*–factors in the table refer to the total window, including glass and frame.

Windows admit daylight at different levels based on their *visible transmittance* (VT), an optical property measuring the fraction of visible light striking the glazing that is passed through, expressed as a ratio between 0 and 1 (O'Connor et al, 1997, p. 4.1). It can be applied to both the glazing alone and the window as a whole, including its frame and mullions. A high VT maximizes daylight. ***In daylighted buildings select clear glass, with a VT of 0.70 or more for the glass, which translates to VT = 0.50 or above for the total window.*** Low VT glazings do not provide enough light for most daylighting situations, unless illuminance targets are low, or very large glazing areas are provided.

Windows also admit solar heat, which can be a benefit or a liability, depending on the building's needs for heating or cooling at a given time. A window's *solar heat gain coefficient* (*SHGC*) and *shading coefficient* (*SC*) are indicators of the window's transmittance of solar heat gain. SHGC is the fraction of incident radiation transmitted by the glazing or window. SC is the fraction of heat transmitted by glazing, in comparison to clear single glass. SC ≈ 1.15 x SHGC (O'Connor et al, 1997, p. 4.1).

In passively solar heated buildings, select a high (0.40–0.60) SHGC for south–facing (N in SH) windows to capture as much heat as possible. Equator–facing windows in lLD buildings can have high SHGCs also, so long as the potential for overheating is controlled by appropriate window sizing or thermal storage. Shade this glass with EXTERNAL SHADES during the summer.

In SLD buildings, select lower SHGCs for east and west windows, which do not provide significant winter gains and are harder to shade in summer, than for equator–facing windows.

Pole–facing windows can actually admit significant heat gain in summer if unshaded and provided with a full sky view because all light, including diffuse sky light, carries heat with it. ***Use a low SHGC for polar orientations in buildings with significant cooling loads.***

ILD buildings, particularly those in hot climates that require cooling most of the year, can use a low SHGC on all orientations.

Note that the values in the table are for glass with window frames. Recommended values for glazing alone differ. See text details in WINDOW AND GLASS TYPES.

Finally, windows can be selected to balance the need for admitting daylight with the need for either admitting or blocking solar heat. The *light–to–solar–gain ratio* (LSG) is an indicator of the spectral selectivity of the glazing and the "coolness" of the light. See details and nomograph in WINDOW AND GLASS TYPES.

Glazing Orientation

		Polar-Facing	Equator-Facing	East or West-Facing
Heating Dominated	SLD	* SHGC unimportant ← (low U)	* maximize SHGC for winter gain; 0.40-0.60, use thermal storage * reduce glare with lower VT in direct gain buildings * low U = 0.15-0.35 * external shade in summer	* SHGC < 0.55 → (low U) * shade in summer
	ILD	* SHGC = 0.40-0.60 ← (U) * shade in summer, if high cooling loads	* SHGC = 0.40-0.55; higher if heat required * U < 0.40-0.60 * external shade in summer	→ (U)
Heating & Cooling	SLD	* SHGC < 0.55, or < 0.40 for cooling ← (U)	* maximize SHGC for winter gain; 0.40-0.60 * U = 0.30-0.40 * external shade in summer	* SHGC < 0.55, or < 0.40 for cooling → (U) → (external shade in summer)
	ILD	* SHGC = 0.30-0.50; or < 0.40 for cooling ← (U) * shade in summer	* SHGC = 0.30-0.50; higher if heat required * U < 0.50-0.70 * external shade 3 seasons	* SHGC = 0.30-0.50; or < 0.40 for cooling → (U) → (external shade 3 seasons)
Cooling Dominated	SLD	← (SHGC) ← (U) * shade in summer	* SHGC < 0.40 for cooling * U < 0.55 * external shade 3 seasons	→ (SHGC) → (U) → (external shade 3 seasons)
	ILD	← (SHGC) ← (U) * shade 3 seasons	* SHGC = 0.30-0.40 * U < 0.40-0.70 * external shade all year	→ (SHGC) → (U) → (external shade all year)

Generalized Recommendations for Glazing + Window Selection at Temperate Latitudes

Part VI
FAVORITE DESIGN STRATEGIES
condensed

Since the second edition of *Sun, Wind & Light* was published, the authors have used it for many years in teaching design to architecture students and in consulting with professional architects. Based on experience, some favorite design strategies have been selected, ones that come up repeatedly in practice. Buildings in extreme heating or cooling climates may not use a few of these, but in the portions of North American where most people live, the climate is some combination of heating and cooling.

What appears in the pages that follow are condensed versions for quick reference of the full format strategies that appear in ⌁ *SWL Electronic*. This smaller format of this printed edition contains the essence of the strategy in one or two pages. Strategies included here are those that affect form and organization to a significant degree and those that commonly come up in the fundamental bundles.

These design strategies focus on the nature of the problem and its design solutions. Sizing tools and performance graphs have not been included here; they can be found in the extended strategies in ⌁ *SWL Electronic* or, in a few cases, in Part V "Favorite Design Tools" in *SWL Printed*. In ⌁ *SWL Electronic*, you can find the extended version with greater detail, often with some variations and with more built examples.

OCCUPANCY

A14 *ENERGY PROGRAMMING* groups together spaces with similar heating, cooling, ventilation or lighting requirements to increase the efficiency of passive and active strategies. [heating, cooling and daylighting]

Conventional programming defines a building's spaces: what they are used for, how big they are, their characteristics and their relationships to one another, such as adjacency. Energy programming adds drivers of energy use and occupancy to the conventional program's analysis.

Energy programming is intended to discover and develop strategies that take advantage of interactions among climate and use patterns, which can reduce total and peak energy use, first cost and operating costs and make it easier to achieve net-zero or peak-zero, net-positive. Spaces that have similar heating, cooling and lighting needs, along with similar occupant schedules, can employ the same energy-efficient design strategies. If these spaces are in the same spatial zone, these strategies can be more efficiently and economically used. The cost of adding energy conserving features to a building increases dramatically as the design process progresses. Therefore, it is important to identify energy-efficient design strategies as early in the design process as possible.

Two occupancy characteristics are important in determining building energy use: 1) the occupancy period (see LOAD-RESPONSIVE SCHEDULING), and 2) the thermal, visual and ventilation requirements for each space (see ADAPTIVE COMFORT CRITERIA and DESIGN DAYLIGHT FACTOR). The spatial organization of buildings can be explored using these two pieces of information when applied in the strategies DAYLIGHT ZONES, COOLING ZONES and HEATING ZONES.

Energy zones are identified by their dominant needs or characteristics. ***Use the table* Design Criteria for Energy Zones *to determine the energy zone type for each space based on its combination of ambient and task lighting levels, allowable temperature ranges, internal gain rates and occupant density levels.***

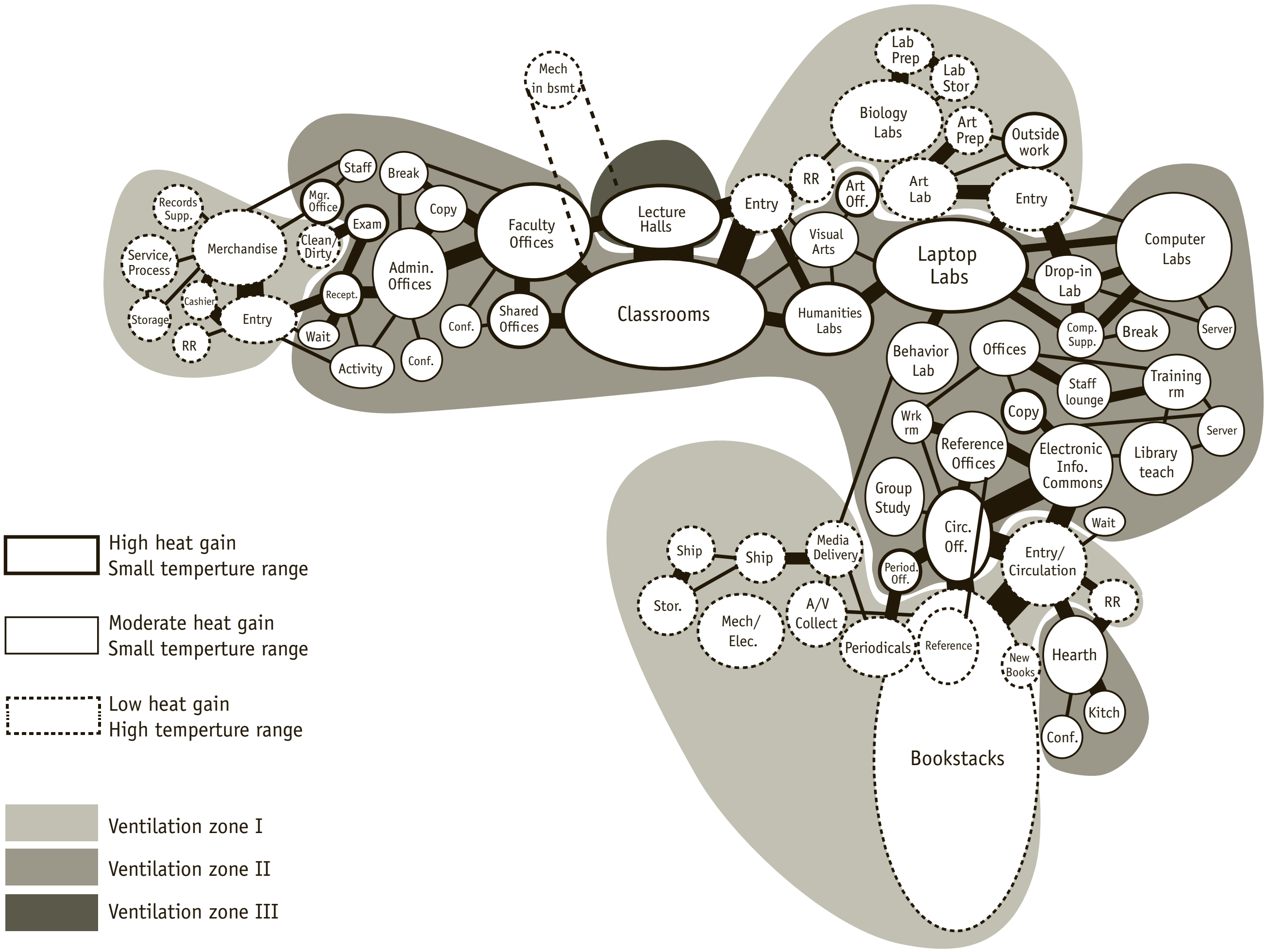
There are three light level groups: 1) high ambient and task, 2) low ambient and high task and 3) low ambient and task [see ELECTRIC LIGHTING ZONES]. The allowable temperature range can be large or small, and internal gain rates [ELECTRIC LIGHTING HEAT GAIN and EQUIPMENT HEAT GAIN] and occupant density levels [see OCCUPANCY HEAT GAIN] can be either high or low. While the table shows all possible combinations of criteria, only a few combinations are typically present in most buildings.

Zones with low ambient lighting levels can use daylighting, and some zones can have both ambient and TASK LIGHTING met with daylighting. Zones with a large allowable temperature range can be cooled with NIGHT-COOLED MASS and with natural ventilation, as CROSS-VENTILATION ROOMS or STACK-VENTILATION ROOMS. Where internal gains are high, efficient use of outside air for cooling during cooling months [AIR-AIR HEAT EXCHANGERS, AIR FLOW WINDOWS] and a high *R*-value envelope [SKIN THICKNESS] with low solar gains [EXTERNAL SHADING, INTERNAL AND IN-BETWEEN SHADING] is called for, while zones with low internal gains can use NIGHT-COOLED MASS and an optimized RESPONSIVE ENVELOPE. Zones that have a high occupant density will have a large fresh air ventilation load, and therefore heat recovery from ventilation air is recommended. Low occupant density zones will benefit most from cross- or stack-ventilation during the day.

After determining the energy zone types for each space, group them into a few spatial zones. Construct an* Energy Programming Bubble Diagram *that groups spaces with similar requirements together and shows important functional connections, such as communication or physical movement of people. If more than one topic (heating, cooling, lighting or ventilation) is prioritized, construct bubble diagrams for each topic and compare the results to identify potential synergies and conflicts.

LIGHT LEVELS	high ambient / high task								low ambient / high task								low ambient / low task							
ALLOWABLE TEMPERATURE RANGE	large				small				large				small				large				small			
INTERNAL GAINS	high		low		high		low		high		low		high		low		high		low		high		low	
OCCUPANT DENSITY	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low	high	low
ZONE TYPE	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X

Design Criteria for Energy Zones



Energy Programming Bubble Diagram

A24 The *BIOCLIMATIC CHART* identifies potential passive solar heating and cooling strategies appropriate to the building's climate.

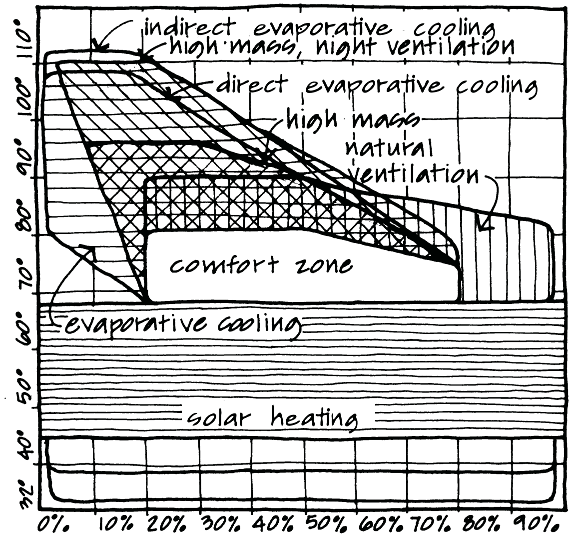
The **Bioclimatic Chart With Design Strategy Zones** is subdivided into zones that define passive solar heating and cooling strategies, based on the work of Milne and Givoni (in Watson, 1979, pp. 96–113) and later work by Givoni (1998, pp. 22–45). The zones crossed by the lines plotted indicate strategies that may be appropriate for that climate. In most temperate climates, there will be a seasonal change from one strategy to another. Some months lend themselves to several different strategies. In most cases, to reduce cost, select a few strategies that are compatible with each other and with other design issues.

On the* Bioclimatic Chart With Design Strategy Zones*, plot two points: first, the average minimum temperature for one month paired with the maximum relative humidity; second, the maximum temperature paired with the minimum relative humidity. Connect these points with a straight line, and then repeat the process for each month of the year. Each line represents the change in temperature and relative humidity over an average day.

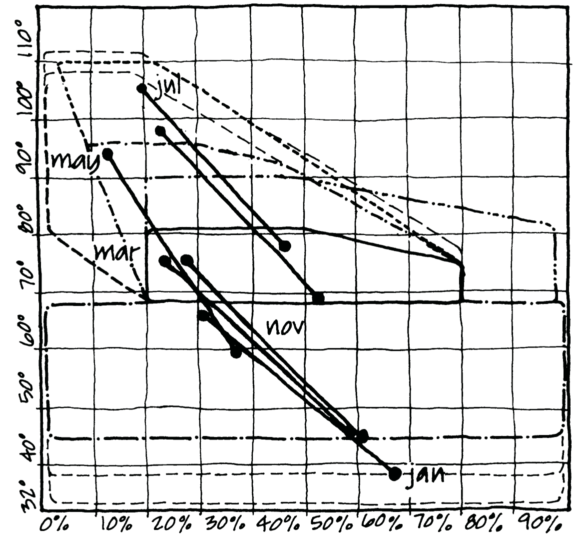
The design strategies suggested by this version of the bioclimatic chart are appropriate only for residences and those other buildings with small internal heat gains. A residential rate of heat gain is assumed to be about 20 kBtu/day per person (21,100 kJ/day per person).

Passive solar heating is usually an appropriate strategy for months when the plotted lines fall below the comfort zone. The solar heating zone is based on certain assumptions about glazing areas and insulation levels. It may be extended to lower temperatures depending on building design, radiation levels and the desired solar savings fraction.

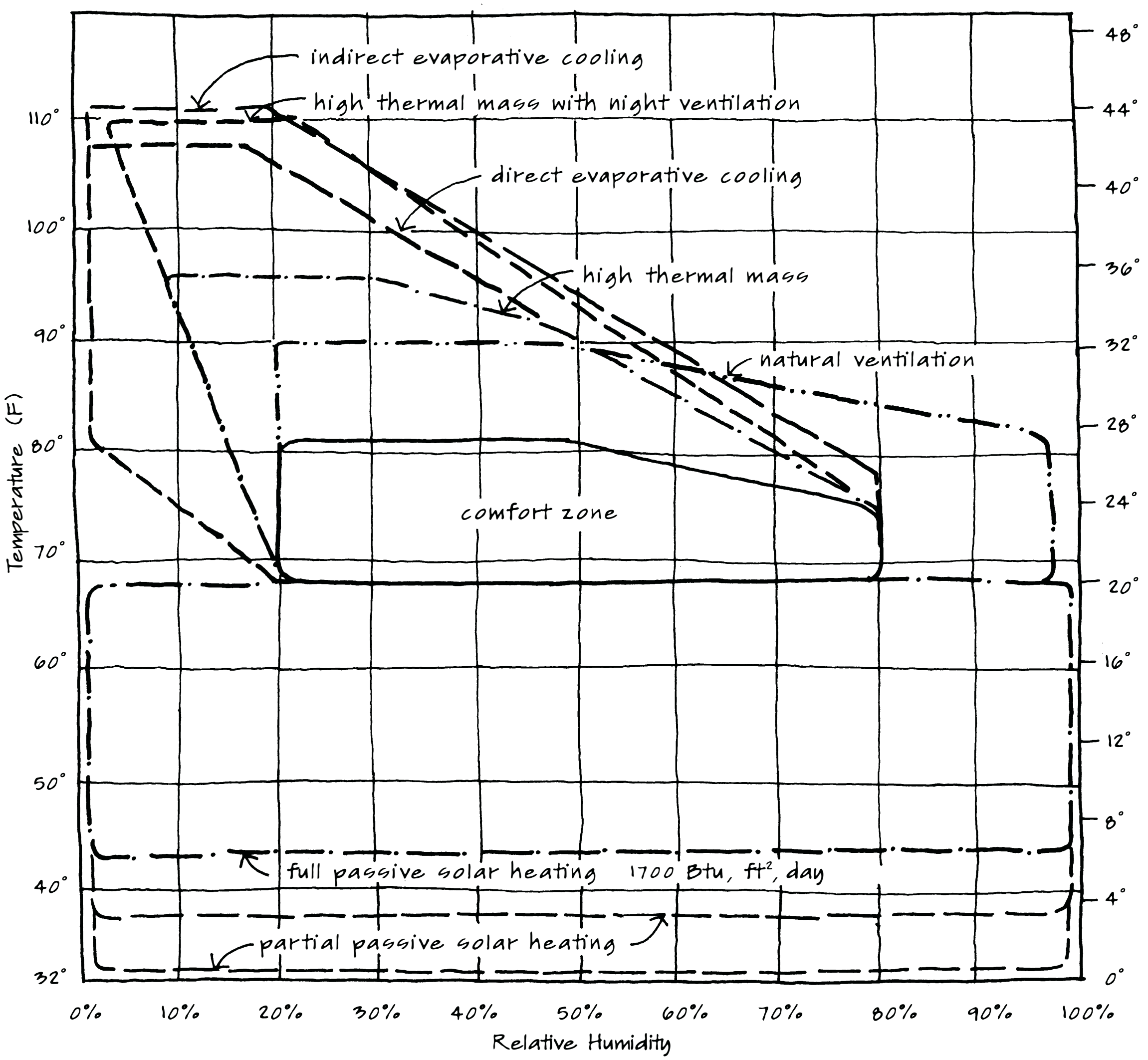
There are five cooling strategies represented by the five somewhat overlapping zones above the comfort zone: 1) natural ventilation, which depends solely on air movement to cool occupants; 2) large THERMAL MASS, which depends



Bioclimatic Chart-Design Strategy Zones



Bioclimatic Chart - Phoenix



Bioclimatic Chart With Design Strategy Zones (for skin-load-dominated buildings)

on the building's materials to store heat during the day and reradiate it at night; 3) large thermal mass combined with night ventilation [NIGHT-COOLED MASS], which relies on mass heat storage during the day and ventilation at night to cool the mass; 4) direct evaporative cooling raises the humidity and lowers the temperature of the indoor space; and 5) indirect evaporative cooling, such as the cooling of the outside of a roof or wall by evaporating water on its surface, which lowers the temperature of a building element, so it becomes a heat sink for the adjacent space (Givoni, 1994, p. 147). To assess the appropriateness of earth-sheltering strategies in the building's climate, see EARTH CONTACT.

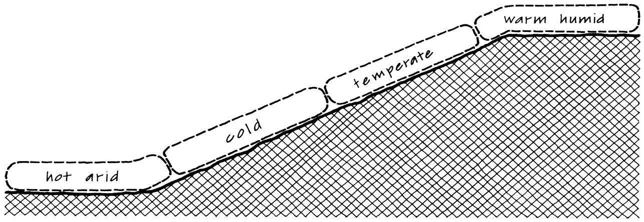
The **Bioclimatic Chart for Phoenix** indicates that high mass with night ventilation [NIGHT-COOLED MASS] and evaporative cooling [EVAPORATIVE COOLING TOWERS] are good strategies for cooling, and heating can be done effectively by the sun.

STREETS, OPEN SPACES, & BUILDINGS: Orientation and Location

3 *TOPOGRAPHIC MICROCLIMATES* can be used to locate building groups. [heating and cooling]

On a large scale, topography, solar radiation and wind combine to produce microclimates that accentuate certain characteristics of an area's macroclimate. These microclimates make some locations within the topography more desirable than others, depending on the macroclimate and season. Building group location can thus enhance comfort and productivity, change the length of heating or cooling seasons, and reduce energy used for heating and cooling.

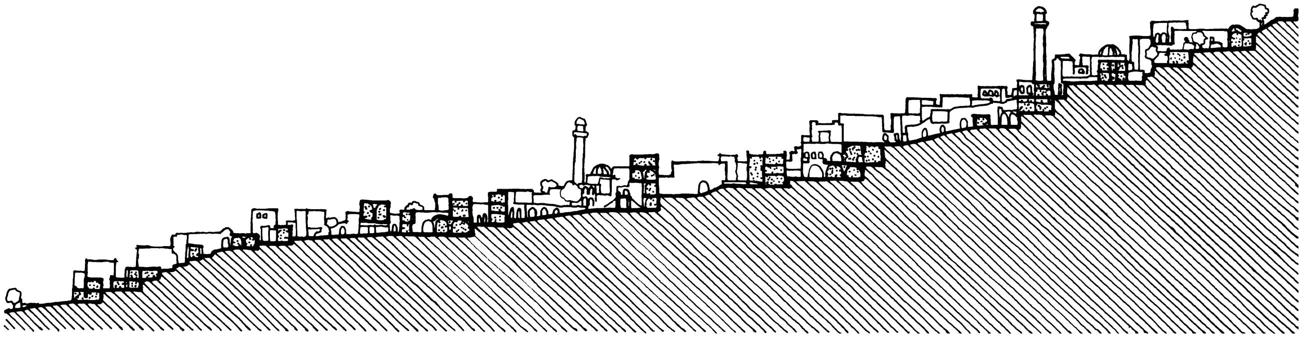
The **City of Mardin** in southeastern Turkey, is located in a hot-arid climate with mild but cool winters, is sited on a 20–25° slope above a steeper rise that abuts the plain below. Streets are organized to follow topography, giving the whole city a southeasterly orientation that reduces afternoon solar heat gain. Densely packed buildings give self-shading on east and west orientations, while allowing good winter solar access to south facades. On summer nights, differences in air density create a downhill flow of cool air that pools in low areas, between buildings and behind walls. Such cool pools are often used for outdoor sleeping. Calculations indicate that building groups in this region located on a 20% south-facing slope require approximately 50% less heat to maintain the same indoor temperatures than a similar settlement on a flat plain (Turan, 1983).



Slope Location Based on Climate

As the diagrammatic section of* Slope Locations Based on Climate *shows, the most favorable microclimate location for each region is:

- Cold: *Low on a south-facing slope (N in SH)* to increase solar radiation; low enough to give wind protection but high enough to avoid cold air collection at the bottom of the valley.
- Temperate: *In the middle to upper part of the slope* with access to both sun and wind but protected from high winds.
- Hot-Arid: *At the bottom of the slope* for exposure to cold air flow at night and *on east orientations* for decreased solar exposure in the afternoons.
- Hot-Humid: *At the top of the slope* for exposure to wind and *on east orientations* for decreased solar exposure in the afternoons.



Cross-Section, City of Mardin, Turkey

STREETS & BUILDINGS:
Dispersed and Compact Organizations

7 *LOOSE URBAN PATTERNS* maximize cooling breezes in hot climates, while *DENSE URBAN PATTERNS* minimize winter winds in heating climates. [heating and cooling]

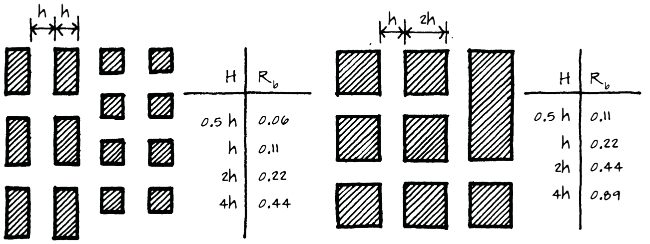
Air movement in streets can be either an asset or a liability, depending on season and climate. Wind is desirable in streets of hot climates to cool people and remove excess heat from the streets; it also becomes a potential resource to cool buildings by cross-ventilation. This is important all the time in humid climates and mostly at night in arid climates. On the other hand, wind reduces pedestrian comfort in cool seasons and increases infiltration heat losses of buildings.

To reduce wind flows in streets, windbreaks can be used to block undesirable cold winter winds or hot, dusty desert winds [WINDBREAKS]. Buildings spaced closer together will also reduce flows in the streets. For regular organizations of buildings in an urban pattern, taller buildings on narrow streets yield the most wind protection, while shorter buildings on wider streets promote more air movement. In cool climates, major streets oriented perpendicular to winter winds and street networks with discontinuous organization and many T-intersections will slow and block wind flow in streets.

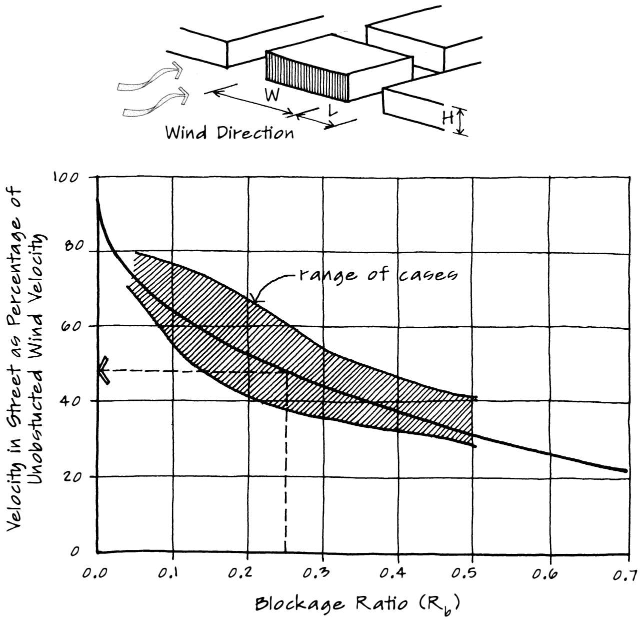
When major streets are parallel to winds, the primary factors affecting street wind velocity are the width of streets and the frontal area (height and width) of windward building faces. The graph **Predicting Wind Velocity in Streets** shows wind speed in the streets as a function of the blockage ratio of a given building group organization (Wu, 1994). Blockage ratio *(R_b)* is defined, with variables given in the diagram, as: $R_b = (W \times H) \div (W + L)^2$.

Find the blockage ratio using the formula or from the calculated ratios in* Blockage Ratios for Buildings/Streets Organizations. *The graph predicts average wind speed in streets as a fraction of prevailing unobstructed speed. High fractions are desirable for the cooling season and low fractions for the heating season.

See details, assumptions and more examples in LOOSE OR DENSE URBAN PATTERNS. The graph assumes regular building layout, buildings that fill the block, forming a continuous street wall on the windward side, and wind perpendicular to the block face and parallel to the major streets.

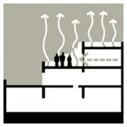


Blockage Ratios for Buildings/Streets Organizations



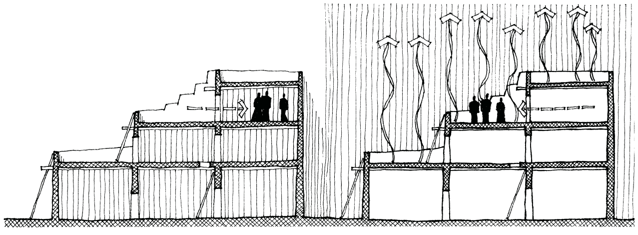
Predicting Wind Velocity in Streets

ROOMS & COURTYARDS: Zoned Organizations

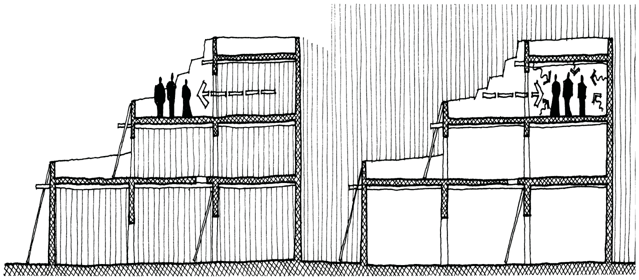


24 ***MIGRATION:*** **Rooms and courts can be zoned so that activities can take place in cooler areas during warm periods and warmer areas during cool periods of the day or season. [heating and cooling]**

This strategy combines migration—moving from one place to another to maintain thermal comfort—with providing a variety of zones, each of which is comfortable under a different set of climatic conditions. Because each zone is tuned to a limited set of conditions, its design can be simpler. Design criteria can be selected that do no more than simply moderate climatic extremes; they may take advantage of the beneficial relationship between some materials' thermal characteristics and certain climate patterns, such as thermal lag and large diurnal temperature swings; or they may exploit the compatibility of certain climate conditions with existing social patterns, like moving from a living to a sleeping area.



Pueblo Acoma, Warm Day (left); Night (right)



Pueblo Acoma, Cool Day (left); Night (right)

Pueblo Acoma, near Albuquerque, New Mexico, is a two-zone residence in which the time of day that each zone is used changes dramatically from season to season. In cool seasons, the outside terraces are used during the day and the interior spaces at night. In the warm season, the reverse is true: The outside terraces are used at night and the shaded cool interiors during the day (Knowles, 2006; Nabokov, 1986).

One zone, the exterior south-facing terrace, is wind-protected and sunny during the day, an advantage when the air is cool and a disadvantage when it is warm. It radiates heat to the sky at night, an advantage when it's warm and a disadvantage when it's cool. The second zone, the interior room, follows the outside climate less closely than the terrace. The heat storage characteristics of the massive construction cause the interior temperature to lag several hours behind the exterior temperature. In the cool seasons the mass absorbs the sun's heat during the day and releases it to the interior at night. In warm seasons, the mass is cooled at night by the air and by radiation to the sky, and so remains cool during the day.

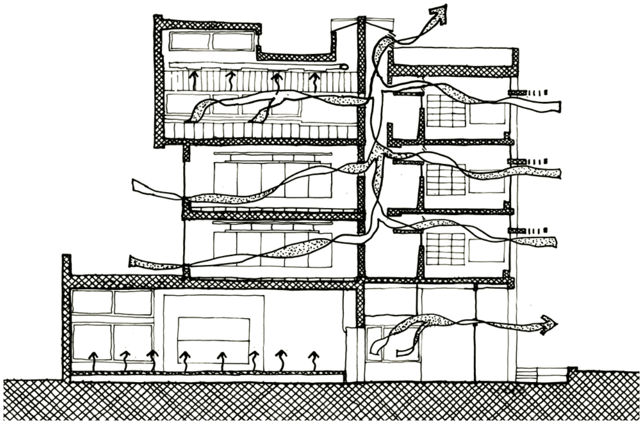
ROOMS & COURTYARDS: Zoned Organizations

26 Rooms can be grouped into *COOLING ZONES* based on similar cooling requirements, facilitating the use of the same cooling strategies at the same time. [cooling and ventilation]

Many buildings house a range of activities with ranging cooling needs. When a building is treated as a single thermal zone during the cooling season, it cannot adapt to these varying demands. Multiple cooling zones allow each zone to be designed to meet different criteria for temperature, humidity and ventilation. In conventional commercial HVAC systems, each zone has its own thermostat and varying amounts or temperature of cooling are supplied as needed. In a passively cooled building, cooling zones allow different cooling strategies to be employed at different times. Cooling zones are the spatial prerequisite for most MIXED MODE BUILDINGS.

The table **Thermal Criteria for Cooling Zones** outlines three broad options. Some uses, such as a rare books archive, require strict criteria for temperature and humidity, whereas recreational uses, which often allow for occupants to adjust their clothing, activity rates and location, can have flexible thermal criteria over a wider range of temperatures. The stricter the criteria, the harder for passive strategies to always meet criteria and the greater the need for responsive MANUAL OR AUTOMATED CONTROLS.

The **Seminar II Building** at Evergreen State College in Olympia, Washington, by Mahlum Architects, uses a variety of cooling zones (Moody, 2007; Astier, 2005; Macaulay and McLennan, 2005). Covered outdoor circulation connects five small buildings, eliminating most conditioning of circulation. Two large MIXED MODE ground floor lecture rooms are mechanically cooled and naturally ventilated. Offices and classrooms are STACK-VENTILATION ROOMS with perimeter inlets and sound-baffled outlets into a multi-story circulation space. The top floor lab is similarly stack ventilated, but with greater heat gains; it also has intermittent MECHANICAL SPACE VENTILATION to assist. Concrete structure serves as NIGHT-COOLED MASS during hot periods. Ground floor lounge CROSS-VENTILATION ROOMS use large

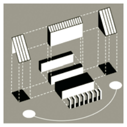


Seminar II Building at Evergreen State College, Olympia, WA, 2004, Mahlum Architects

	THERMAL CRITERIA			
	Migration	**Flexible**	**Moderate**	**Strict**
Comfort Zone	Very Broad Range 20–40° F (11.1–22.2° C)	Broad Range 10–20° F (5.6–11.1° C)	Moderate Range 5–10° F (2.8–5.6° C)	Narrow Range 2–5° F (1.1–2.8° C)
Variation Tolerance	Very High (intermediate occupancy)	High	Medium	Low
Control	Little or None	Little Manual	Moderate Smart/ Feedback	Precise Automated
Cooling Options	Passive Only	Passive Only Possible	Passive, Hybrid and/or Mixed Mode	Mixed Mode or Active Systems

Thermal Criteria for Cooling Zones

sliding doors opening to unconditioned intermittently occupied outdoor classrooms. The result is the elimination of the conventional air-conditioning system for 80% of the occupied space, and significantly reduced operating periods for the remaining mechanical cooling system.



ROOMS & COURTYARDS: Zoned Organizations

28 Rooms can be organized into *HEATING ZONES* based on their needs for heating and whether or not they can make use of internal heat sources. [heating and ventilation]

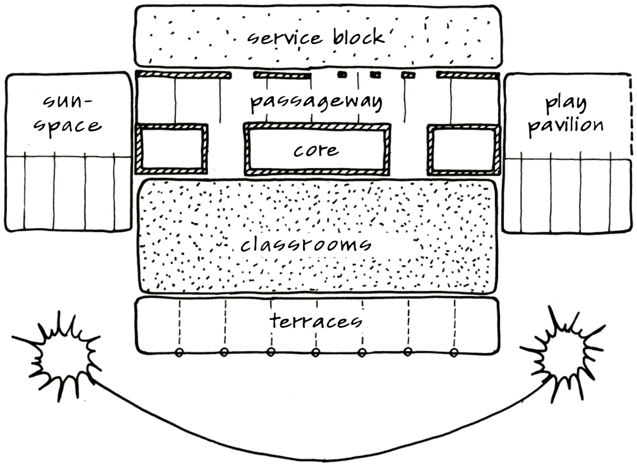
Depending on the occupant activity level, occupant clothing and the length of occupancy, temperature criteria for heating may vary significantly. Rooms can be organized into zones with similar needs for heating. Some rooms, such as a computer lab, may need cooling while, other rooms need only a little heat, and still others have a higher demand.

In general, spaces with a short occupancy period can have a very wide comfort zone. An example is an unheated staircase or corridor. BUFFER ZONES are often unconditioned while other spaces, such as a SUNSPACE or courtyard, can be occupied when they are comfortable and remain unoccupied when uncomfortable [MIGRATION]. More continuously occupied rooms also have a range of heating needs and criteria. A gymnasium, for example, can be cooler than an office with sedentary workers.

Consider these spatial implications of heating zones:

1 *Group rooms together* that have similar heating needs.
2 *Organize the occupied rooms* around outdoor or unconditioned, solar-heated circulation.
3 *Orient groups of rooms* with the greatest heating needs toward the winter sun [ROOMS FACING THE SUN AND WIND]. See kindergarten example in PASSIVE SOLAR BUILDING.
4 *Design a range of open, semi-enclosed and enclosed rooms* to create degrees of climate separation and modification. Use OUTDOOR MICROCLIMATES strategies to reduce the heated zone size.
5 *Define which zones can be heated with only passive solar strategies* and which will require active back-up heating. The passive-only rooms can be grouped together to minimize the heating distribution systems runs and equipment size.

Olivia Schimek's **Solar City Kindergarten** in Linz,



Heating Zones in the Solar City Kindergarten

Austria, is organized into clear heating zones with different temperature criteria. (Treberspurg, 2008; A + W, 2000) A south-facing outdoor zone sheltered by a LAYER OF SHADES is the most exposed, while glazed play pavilions offer semi-enclosed BUFFER ZONES. A central SUNSPACE is comfortable enough to pass through at any time. A toplit, glazed and solar heated passageway zone is not mechanically conditioned and allows for a wider range of acceptable temperatures in a space used primarily for short periods of movement. The DIRECT GAIN classrooms are located to the south, with the best access to light and heat. A north-facing service block accommodates service functions and more private spaces. Its window area is limited to that needed for daylight. The large roof slopes south, capturing sun as a PHOTOVOLTAIC ROOF and supporting THERMAL COLLECTORS and SOLAR HOT WATER collectors, along with direct gain SOLAR APERTURES. Heat is stored in the central core's concrete structure [THERMAL MASS], in a ROCK BED and in water tanks.

29 *BUFFER ZONES:* Rooms that can tolerate temperature swings can be located between protected rooms and undesired heat or cold. [heating and cooling]

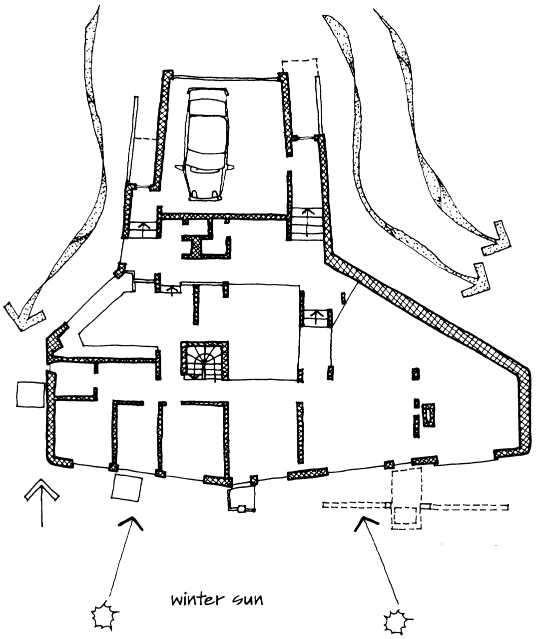
Some spaces in a building's program have less rigid temperature requirements because of the nature of their use, like storage, or the duration of their use, like circulation. Some spaces, like bedrooms, have temperature requirements only at certain times of the day. These spaces can frequently be used as thermal buffer zones between the exterior environment and spaces that need careful temperature control.

Ralph Erskine used the garage and storage areas in the **Villa Gadelius** as a buffer zone against the cold north winds in Lindingö, Sweden. The south zone of the house is extended in the east–west direction and increased in height so that the living spaces have access to the south sun (*Deustch Bauzeitung* 11/1965; Collymore, 1994).

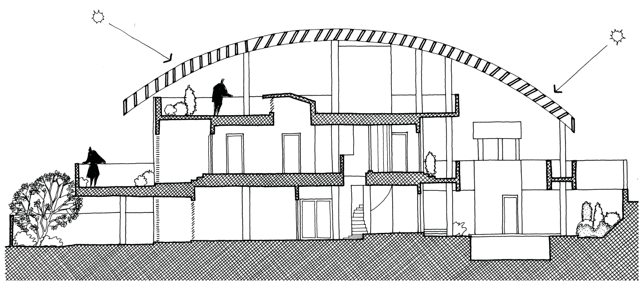
At low latitudes the sun attains a high altitude for much of the day, and the roof is the major collector of heat gain. Ken Yeang located shaded outdoor rooms on the roof of his **Roof-Roof House** in Kuala Lampur, Malaysia. The living spaces are located below an over-arching, white, louvered, concrete umbrella roof. The ground floor plan is fragmented by interwoven outdoor space, providing an option for full shade and rain shelter, while remaining open to prevailing winds (Yeang, 1987, pp. 52–55; Khan, 1995, pp. 108–109).

Large glazed rooms, if not heated or cooled mechanically, will usually have an average temperature in winter somewhere between the indoor and outdoor temperatures, thus reducing the heating load of the conditioned spaces. The buffer space will also reduce the daylight available to adjacent rooms, so windows facing a buffer must be larger than those in exterior facades. See also related strategies GLAZED STREETS, SUNSPACES, LAYER OF SHADES, ATRIUM and AIR-AIR HEAT EXCHANGERS.

If the buffer space faces equatorially, it can heat nearby spaces and its average temperature will be close to that of the interior rooms. If it faces east, west, or polar, it reduces envelope losses but will not provide net winter solar gains.



Villa Gadelius, Lindingö, Sweden, Ralph Erskine



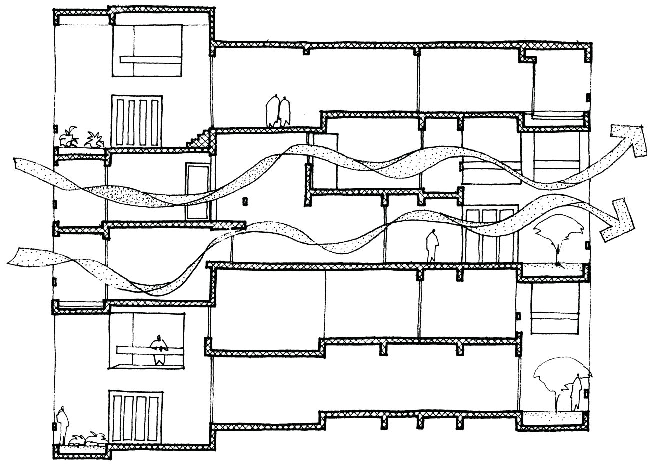
Roof-Roof House in Malaysia, Ken Yeang

30 *PERMEABLE BUILDINGS* can combine open plans and sections for cross-ventilation, stack-ventilation or both. [cooling and ventilation]

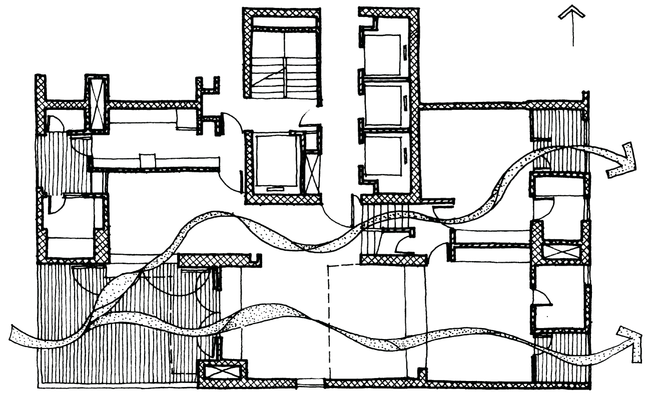
Cross-ventilation is a particularly valuable means of cooling during warm periods because it not only removes heat from the space but also increases the sensation of cooling by increasing people's rate of evaporation [CROSS-VENTILATION ROOMS]. However, in hot climates and in warm summer mixed climates at night, air movement is frequently slow, in which case stack-ventilation becomes an important supplementary strategy [STACK-VENTILATION ROOMS]. Combined strategies may also be employed for different rooms in the same building. For example, cross-ventilation might be used in windward side and upper level rooms, while stack-ventilation might be used in lee side and lower rooms that have less access to wind.

Both cross-ventilation and stack-ventilation work better in certain configurations, yet can be facilitated with a variety of different room organizations. When designing a scheme for both types of ventilation, parts of both the plan and the section must be kept open to air movement.

Charles Correa avoided the problem of wind-blocking internal corridors in the **Kanchunjunga Apartments** in Bombay, India, with the use of vertical circulation cores serving two units per floor (Khan, 1987; Correa, 1996). This allows ventilation air to move from one side of the building to another by flowing around the cores. Because air must move from the windward rooms through one or two more rooms, the plans and sections are treated in a loose, open manner, with private bedrooms on the upper levels for privacy. Double volumes provide some opportunity for stack-ventilation, while numerous level changes help create spatial definition with a minimum of internal partitions. Because the sea breezes are from the west, the main facades face east and west and are protected from storm rains and sun by a buffer zone of double-height terrace gardens. The same basic strategy of one or more vertical circulation cores serving two units of floor area works equally well for shorter buildings.



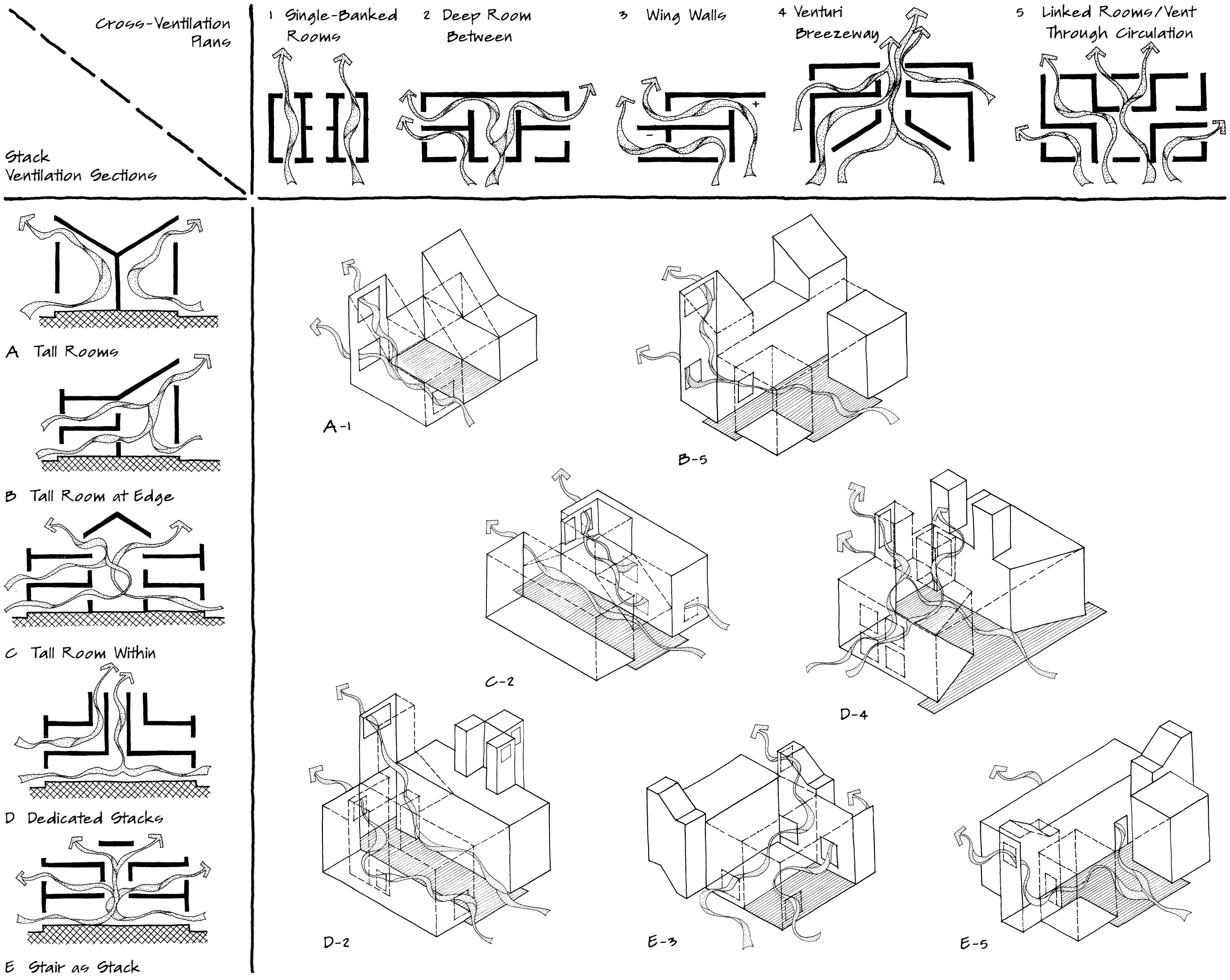
E-W Section



Lower Level Plan

Kanchunjunga Apartments, Bombay, India, C. Correa

The ideal cross-ventilated building is one room thick, thin in plan and elongated to maximize exposure to prevailing winds. In practice, this is rarely possible in all but small buildings with few site constraints. In buildings more than one room thick and in all buildings with circulation corridors, the windward rooms can block the



Room Organization Strategies That Facilitate Both Cross- and Stack-Ventilation

wind to leeward rooms. ***In the matrix* Room Organization Strategies That Facilitate Both Cross- and Stack-Ventilation**, ***the horizontal axis shows several strategies of organizing rooms for cross-ventilation that bring air to all rooms.***

Stack-ventilation is dependent on the height between inlets and outlets, and so is maximized by tall rooms and chimneys. ***The vertical axis of the matrix shows several strategies of organizing rooms for stack-ventilation. The body of the matrix shows a few of the possible diagrammatic combinations of organizations that facilitate both cross- and stack-ventilation that brings air to all rooms.***

The combined effect of stack- and cross-ventilation is due to the sum of the pressures, is nonlinear and is detailed in PERMEABLE BUILDINGS.

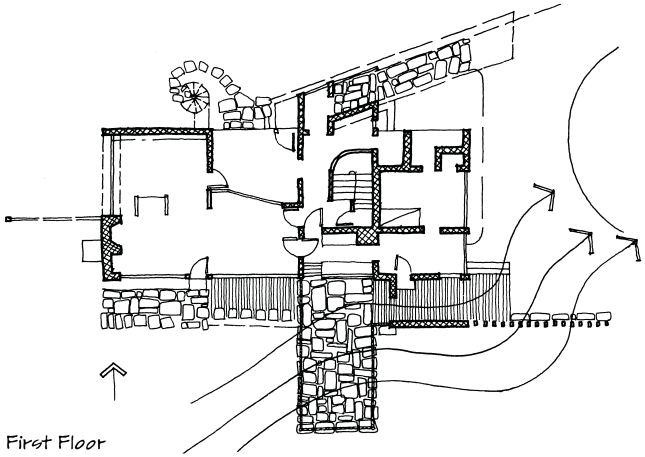
32 *LOCATING OUTDOOR ROOMS* in relation to sun and wind can extend the seasons of outdoor comfort. [heating and cooling]

Because buildings can block sun and wind, they create a series of different microclimates around them. Combinations of wind and sun directions have implications for where to locate outdoor rooms. For example, in warm–humid summers, when summer wind and sun directions are oblique to each other, the outdoor room can be located to the polar side of the building where there is more shade and the wind will blow through the space. However, when summer wind and sun directions are coincident, the outdoor room should *not* be located on the polar side of the building, because it would then not have access to wind.

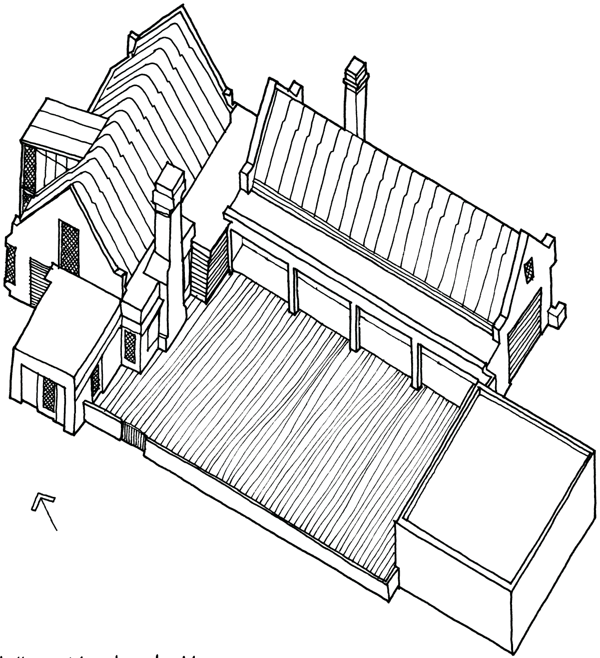
In the cool New England climate of Lincoln, Massachusetts, Walter Gropius and Marcel Breuer placed the screened porch of the **Gropius House** extending from the south side of the house where it could be swept by the southwesterly summer breezes. Although a north-side location would have provided some shade by the building, the porch would have no access to wind. The porch is shaded by an opaque roof and roll-down shades. The scheme provides a sunny south-facing second-floor roof deck, screened from winter winds by an opaque west wall (*Process Architecture,* 1980).

In heating seasons, outdoor rooms are best in the sun and protected from the wind. In cold climates, there will be little need to cool outdoor spaces and a location on the sunny equatorial side of the building is prime. When winter wind is coincident with or oblique to the sun, WINDBREAKS can be used to shelter the space.

Bernard Maybeck set the **Wallen Maybeck House** on the top of a cool, windy hill near Berkeley, California. The southwest-facing outdoor space is surrounded on two sides by the house, on a third by the garage and on the fourth by a low wall. The organization allows the occupants to keep the view while being protected from winter winds from the north-northwest (Woodbridge, 1992).



Gropius House, Lincoln, Massachusetts, Walter Gropius & Marcel Breuer



Wallen Maybeck House, Berkeley, California, Bernard Maybeck

33 An *ATRIUM BUILDING* with a glazed or unglazed light court within can provide light to surrounding interior rooms. [daylighting]

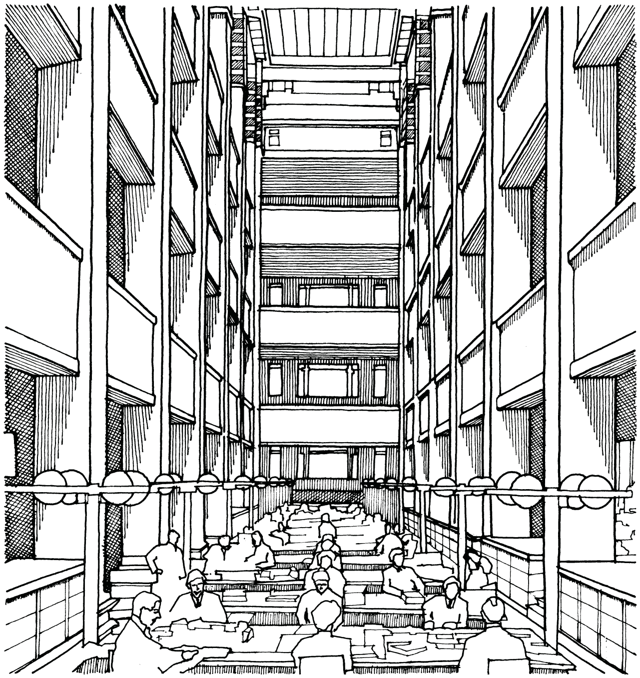
When buildings are thicker than the dimensions that can support sidelighting, unglazed light courts or glazed atria may be used to bring light into the interior. Atria are used both for lighting adjacent rooms and for providing light to plants and activities that occur in their climate-buffered space. Potentially, they have the additional advantages of increasing marketability, reducing conductive heat loss and gain in the building [BUFFER ZONES], providing winter solar heat gain as SUNSPACES, and serving as a passive STACK-VENTILATION ROOMS.

Frank Lloyd Wright designed the offices of the **Larkin Administration Building in Buffalo, New York,** around a tall toplit atrium. Openings into the atrium were unglazed, and the atrium floor was also used for office work. Wide, light-colored sills with filing storage underneath were used as LIGHT SHELVES to reflect light into the office galleries. The atrium was roofed with a double layer: a gridded horizontal ceiling covered by a gabled upper glass layer (Quinan, 1987).

Sidelighting can be usable to a depth of 2–2.5 times the head height (*H*) of exterior windows [DAYLIGHT ROOM DEPTH], thus the thickness of rooms between an atrium and the exterior wall is limited to about 5*H* for full daylight. If an internal electrically lit zone is used for circulation, services and storage, the building thickness can be increased. Building thickness affects the fraction of a building's floor area that can be daylit.

Use a thickness dimension between outside wall and atria of 6*H *to achieve 90–100% net occupied area daylighted, and use 7*H *to achieve 80–90% area daylighted (DeKay, 1992, 2010). This principle holds true for all latitudes and atrium sizes. The guideline assumes a gross to net ratio of 1.35, excluding atrium area, and a 2.5*H* maximum penetration of daylight.

Daylight levels in rooms adjacent to atria are affected by the height and width of the atria, the amount of daylight available in the building's climate, the reflectivity of interior facades, the size and position of windows facing the atrium, the atrium roofing design, the transmittance of the glazing system, and reflection strategies at the interior window wall. Just as in exterior sidelighting, room lighting is affected by room geometry, window glazing transmission and interior room reflectances. The most important of these factors in providing daylight via an atrium is the proportion of the atrium. Tall, narrow atria have less "view" of the sky than short, wide atria.



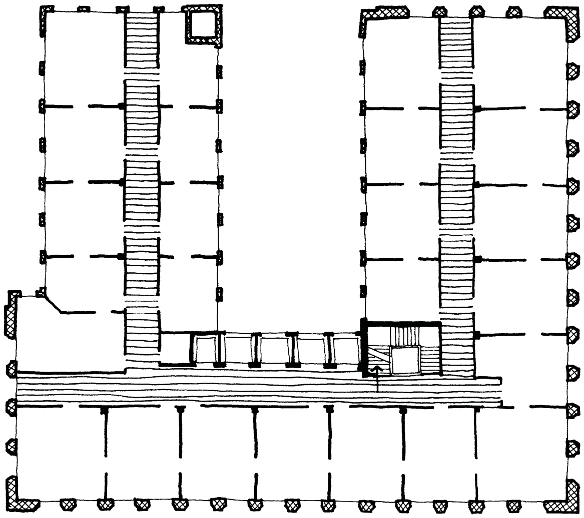
Atrium, Larkin Adminstration Building, Buffalo, New York, Frank Lloyd Wright

35 *THIN PLAN* room arrangements will have daylight available for each space. [daylighting]

The amount of light that reaches the interior of a room lit from one side is a function of the distance from the window [DAYLIGHT ROOM DEPTH], the head height of the window above the floor, the size of the window [DAYLIGHT APERTURES] and the reflectivity of the room surfaces [DAYLIGHT REFLECTING SURFACES]. As one moves away from the window wall, the proportion of the exterior daylight available inside decreases. Therefore, the thickness of the building is an important design consideration for a daylit building.

The **Science and Technology Park** in Gelsenkirchen, Germany, by Kiessel + Partner, is organized into nine thin office pavilions, with offices facing north and south, connected by a single-loaded spine with offices facing east. Thus, the large office building gives ample natural light to every unit of floor area (Rumpf, 1995).

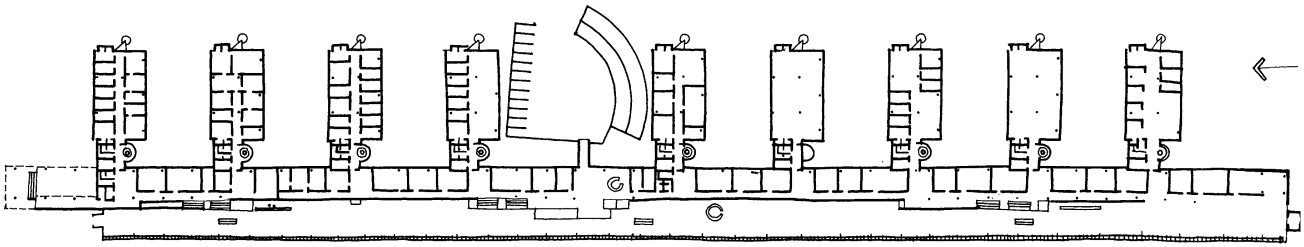
The **Wainwright Building** in St. Louis, Missouri, by Adler and Sullivan, has side-lit offices arranged on both sides of a single corridor. The building is U-shaped to fit a corner site and to provide a continuous facade for both streets. The light courts traditionally formed by O-, U- and E-shaped plans reduce the amount of light available to the windows that face them because the court walls absorb some of the light. Sullivan addressed this problem in the Wainwright Building by giving the rooms facing the court less depth than the ones facing the more open street



Wainwright Building
St. Louis, Missouri, Adler and Sullivan

(Cannon, 2011; Manieri-Elia, 1996).

Penetration of light can be enhanced by LIGHT SHELVES. When the sun is visible in the partly cloudy sky or the clear sky, light penetration into the space may be much greater than under overcast sky conditions. When sunlight reflectors are used, the width of the building may be increased, yet effectively daylighted. See details in THIN PLAN.



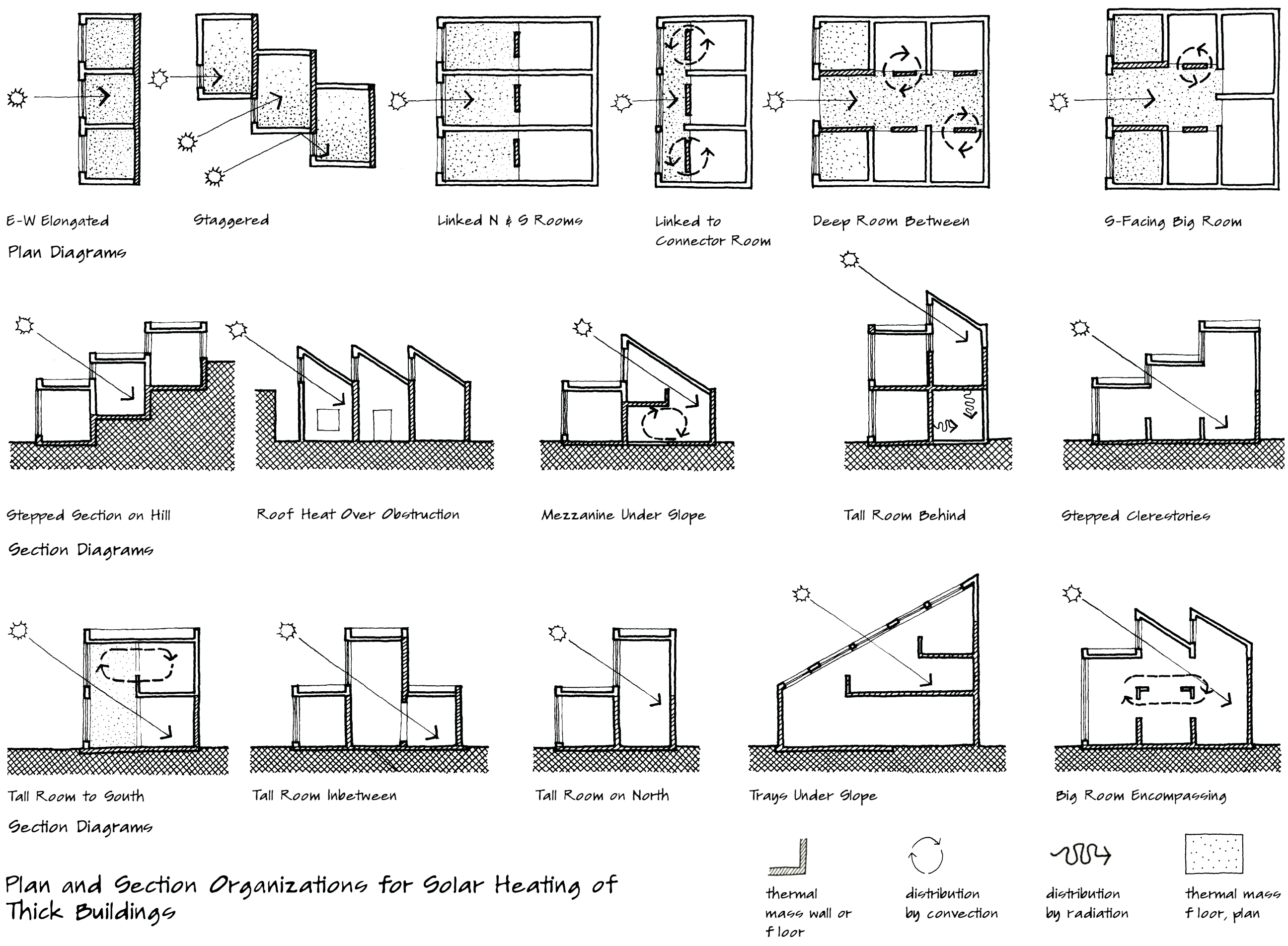
Science and Technology Park, Gelsenkirchen, Germany, Kiessel + Partner

ROOMS: Thick Organizations

37 *DEEP SUN* in thick buildings depends on effectively organized plans and sections. [heating]

While solar access to each room makes solar heating each space simple for thin, elongated organizations facing the sun [EAST–WEST PLAN], buildings of two or more rooms thick provide a challenge when solar heat is desired.

Several formal strategies to bring sun deeper into buildings are shown in **Plan and Section Organizations for Solar Heating of Thick Buildings.** For example, plans of two or more rooms deep may be staggered to get some sun to each room. Polar-side nonsolar-zone rooms without access to sun can be convectively linked to solar zone rooms. When a building must be oriented long in the north–south direction, it can be stepped in section so that more northern rooms capture heat above more southern ones.



Plan and Section Organizations for Solar Heating of Thick Buildings

ROOMS: Zoned Organizations

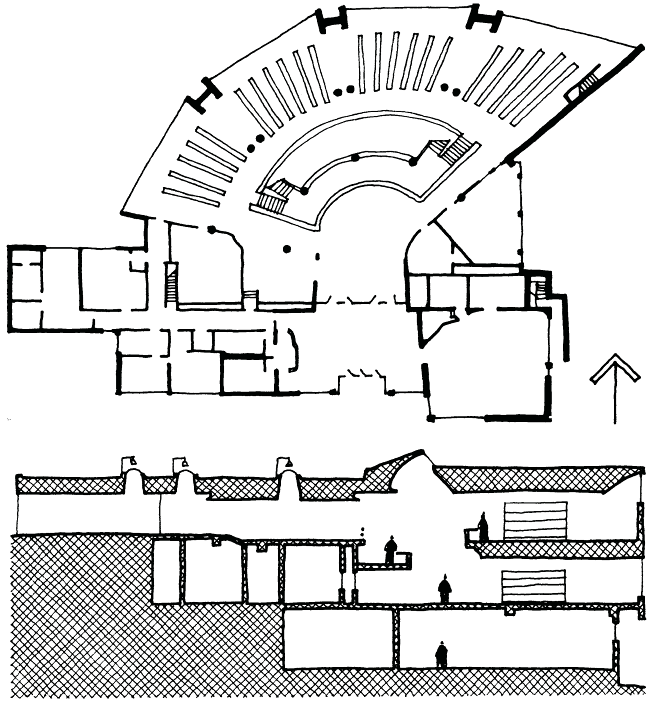
41 ***DAYLIGHT ZONES:*** **Rooms can be arranged within the building so that activities that need higher lighting levels are near the windows while activities that don't need as much light are farther from daylight sources. [daylighting]**

Many buildings have a range of activities that have varying visual tasks and therefore different illumination needs. Areas nearest the skin of the building have the greatest opportunity for daylight at the highest illumination levels. If activities are zoned so that those that need the light are placed near openings in the skin and those that don't are placed in the interior, then the amount of relatively expensive skin and glazed openings can be reduced because of a smaller skin/volume ratio. The rate of electric light use, and thus heat gains are also reduced.

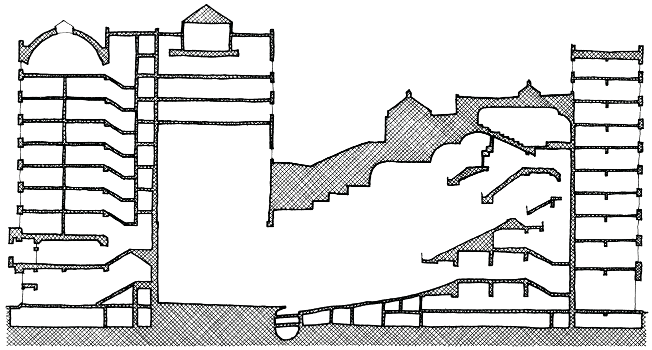
The **Mount Angel Library** in Oregon, by Alvar Aalto, divides activities into two main groups: reading, which requires high illumination levels, and book storage, which requires lower levels (Anderson et al, 2012). The reading areas are next to openings in the skin along the perimeter wall and under the skylight in the center, while the book storage occurs between the two reading areas, farthest from the pools of light (see perspective in TASK LIGHTING.

Adler and Sullivan followed a similar approach in the **Auditorium Building** in Chicago, Illinois, ringing the exterior of the building with offices that need light and putting the auditorium, which needs light control, in the darker center of the building (Siry, 2002; Perlman & Vinci, 1988; Pridmore, 2003; Canty, 1992).

In dense urban areas more is light available on upper floors than at street level [DAYLIGHT ENVELOPES]. Rooms with greater need for light can occupy upper floors, while those requiring less light can be located nearer the ground level. Some spaces, such as circulation or rest rooms, are used for short periods, and others, such as storage, have little occupancy. These may be located in areas with less access to perimeter lighting, while longer occupancy uses are located closer to daylight apertures. Overall, the principle is zoning to group rooms with similar needs together.



Library, Mount Angel Abbey, Oregon, Alvar Aalto



Auditorium Building, Chicago, Illinois, Adler & Sullivan

43 *ROOMS FACING THE SUN AND WIND* increase the effectiveness of solar heating and cross-ventilation. [heating and cooling and ventilation]

As air flows around a building, it causes higher pressure zones on the windward side and lower pressure zones on the lee side. Cross-ventilation occurs when inlets are placed in higher pressure areas and outlets in lower pressure zones (Melarango, 1982, p. 321). Maximum ventilation occurs when inlets and outlets are large [VENTILATION APERTURES] and the wind is relatively perpendicular to openings.

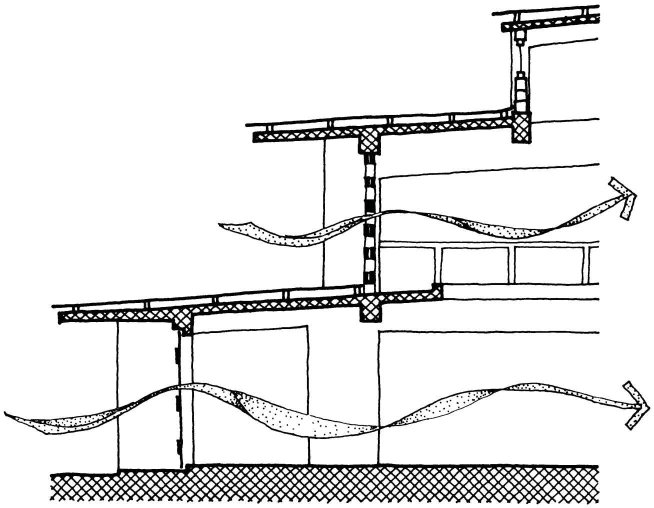
Variations in orientation up to 40° from perpendicular to the prevailing wind do not significantly reduce ventilation. (Givoni, 1976, p. 289). An orientation of 20–45° from the prevailing wind gives two sides positive pressure and two sides negative pressure. To determine wind direction, see WIND ROSE and WIND SQUARE.

A **church in the Philippines** completely opens its long sides with folding doors. All the ventilating openings are protected with deep overhangs or interior drains so that the building may be ventilated during rainstorms (Fry and Drew, 1956, p. 181).

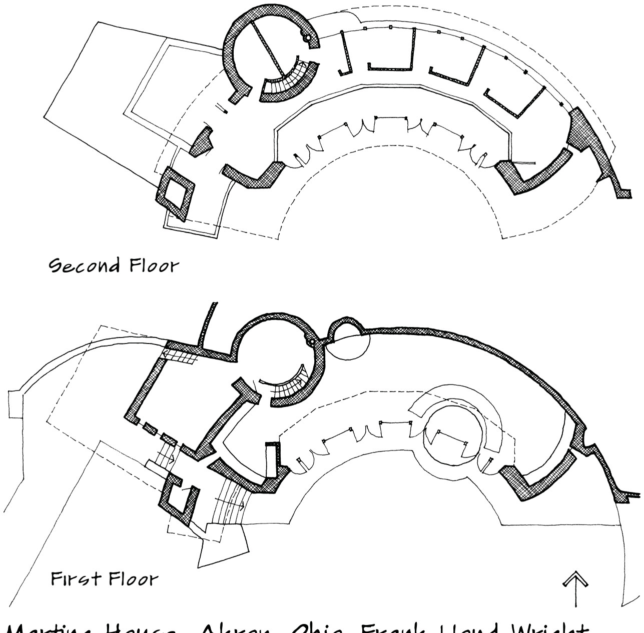
In the winter most radiation falls on the equator-facing facade between about 10 AM and 2 PM. Additionally, the amount of radiation reflected from the glazing increases as the angle of incidence is more acute. Buildings with large solar glazing and low night glazing *R*-values are more sensitive to orientation. Sunspaces are about half as sensitive to orientation as other solar heating systems.

If the solar collection glazing is within 30° east or west of equatorial, the decrease in performance will be less than 10% of the optimum. Performance decreases with the glazing declination from equatorial (Balcomb et al., 1984, p. 2.10).

Frank Lloyd Wright used this flexibility in orientation to bend the rooms in the **Marting House** in Akron, Ohio, in an arc to form a south-facing outside terrace (Architectural Forum, 1/1948).



Church in the Philippines



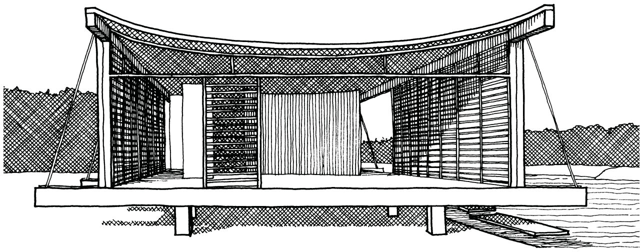
Marting House, Akron, Ohio, Frank Lloyd Wright

44 Air flow through *CROSS-VENTILATION ROOMS* is increased by open plans and uninterrupted pathways between windward inlets and leeward outlets. [cooling and ventilation]

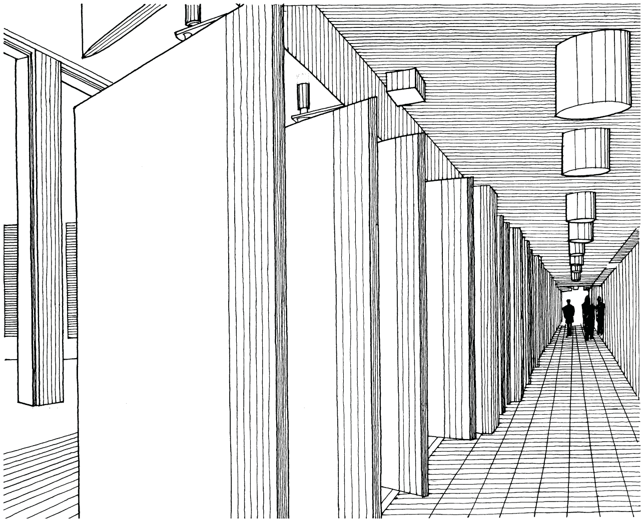
The rate at which air flows through a room, carrying away heat with it, is a function of the area of the inlets and outlets, the wind speed, the direction of the wind relative to the openings, and having a relatively unobstructed pathway for the air to flow within the room. The amount of heat removed by a given rate of air flow depends on the temperature difference between inside and outside the building. As air flows around a building, it causes higher pressure zones on the windward side and lower pressure zones in the lee of the building. The most effective cross-ventilation occurs when the inlets are placed in the higher pressure area and the outlets in the lower pressure zones.

The maximum ventilating area may be achieved, as in Paul Rudolph's **Cacoon House** in Sarasota, Florida, by treating almost the entire house as a single room and opening its opposite walls completely with operable louvers (Fry and Drew, 1956, p. 75).

Effective ventilation may be achieved when the wind does not come from a direction perpendicular to the window (Givoni, 1976, p. 289; Chandra et al., 1986, p. 66). ***Variations in orientation up to 40° from perpendicular to the prevailing wind do not significantly reduce ventilation*** [ROOMS FACING THE SUN AND WIND]. When openings cannot be oriented to the prevailing breeze and if rooms have windows in only one wall, landscaping or wing walls can alter the positive and negative pressure zones around the building and induce wind flow through windows parallel to the prevailing wind directions (R. H. Reed, 1953, p. 56; Robinette, 1977, p. 29). If located correctly, vertical fin projections create a positive pressure at one window and a negative pressure at another. Outward opening casement windows can create a similar effect. The effect of wing walls is limited to windows on the windward side of a building and has no effect on leeward openings. The **Rectorate of the Academy of the Antilles and Guiana** in Fort-de-France, Martinique, by Hauvette and Nouel uses on the windward side of the building wide vertical aileron fins that are constantly adjusted in response to variations in wind direction. The fins also help with shading the openings, which are sheltered from rain by a large projection of the upper floor (Hauvett and Contal, 1997; Jones, 1998).



Cacoon House, Sarasota, Florida, Paul Rudolph



Interior View of Alierons, Academy of the Antilles and Guiana, Christiane Hauvette & Jérôme Nouel

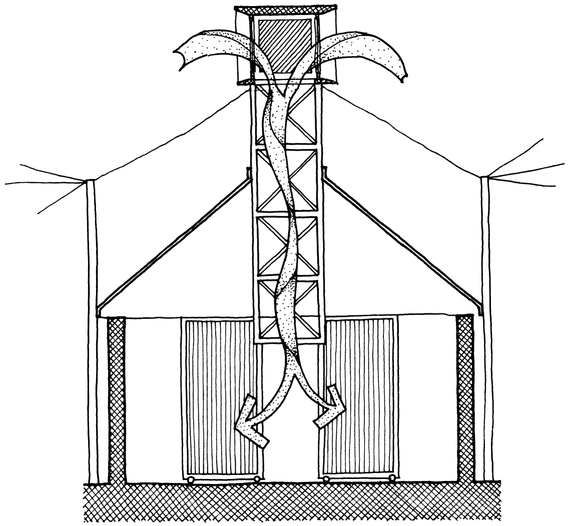
46 *EVAPORATIVE COOLING TOWERS* can supply cool air to rooms without the use of fans or wind. [cooling and ventilation]

In climates where evaporative cooling is effective, downdraft evaporative cooling towers (cool towers) can be used to supply cool air to rooms without the use of fans or the need for wind. If designed with outlets at the top, they can also be used for stack-ventilation during periods when the outside air is cooler than the indoor air.

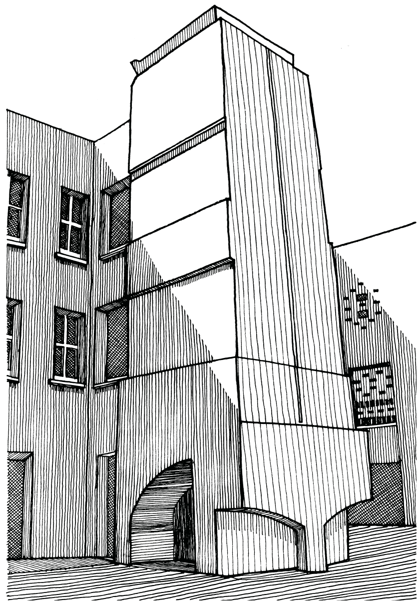
The cool tower provides cool air by taking in hot, dry outdoor air through high inlets covered with a wetted evaporative pad. The trickle flow in the pad is fed by a small electric water pump, which may be photovoltaic powered. As the air passes through the pad, it picks up moisture, raising its humidity, and lowering its temperature. The cooler, denser air then falls by gravity down the tower shaft, creating a positive pressure that pushes air through the occupied space and typically, out of operable windows or doors the building perimeter. A negative pressure is created at inlets, drawing in more outside air through the pads.

Since cool towers supply air at a single point at the bottom of the tower, rooms can be bunched around two or more sides of the tower. For air to flow through the building, there must be an open path from the supply tower through adjacent rooms to outlet windows. Small buildings may be served by a single tower, but in larger buildings with multiple towers, each tower will cool one zone of the building. Exiting air can also be used to temper adjacent courtyards, such as in the courtyards of the **Residence Halls at the University of Arizona** in Tuscon, by Moule and Polyzoides (Steele, 1997, pp. 85–99).

Pliny Fisk's **Laredo Blueprint Demonstration Farm,** in Laredo, Texas, uses downdraft evaporative cooling towers to cool sheds that house offices, classrooms, and packing areas. Air from the cooling tower drops into one shed from above, cools the space below, passes into an adjacent shed and exits out a stack-ventilation chimney (Tilley, 1991).



Section Through Evaporative Tower, Laredo Demonstration Blueprint Farm



Courtyard, University of Arizona Residence Hall, Moule and Polyzoides

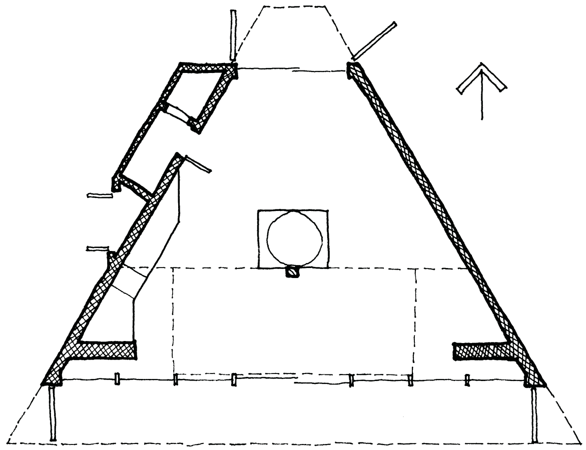
48 *DIRECT GAIN ROOMS* are open to collect the sun through windows and can store heat within a space. [heating]

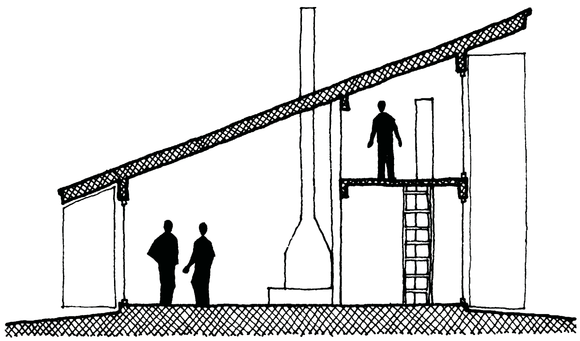
The proportion of the annual heating load that can be supplied by the sun results from a balance between the amount of solar radiation collected, the building's rate of heat loss, and the amount of heat that can be stored in thermal mass during the day for use at night. Collectible radiation is a function of the amount of equator-facing glazing [see SOLAR APERTURES] and the climate's available radiation; the amount of heat loss is a function of the insulating qualities of the building skin [SKIN THICKNESS] and the severity of the climate.

Direct gain solar buildings collect radiation in ROOMS FACING THE SUN AND WIND to heat the air and THERMAL MASS. The MASS SURFACE ABSORPTANCE characteristics help absorb the heat, which keeps the air temperature from rising too high during the day, and gives its stored heat back to the space at night as the space cools (Mazria, 1979, p. 28). At night, high-performance WINDOW AND GLASS TYPES and/or MOVABLE INSULATION help keep the collected heat in. As the amounts of sun-collecting glazing and thermal mass increase, greater demands are placed on the shape, orientation and materials of rooms.

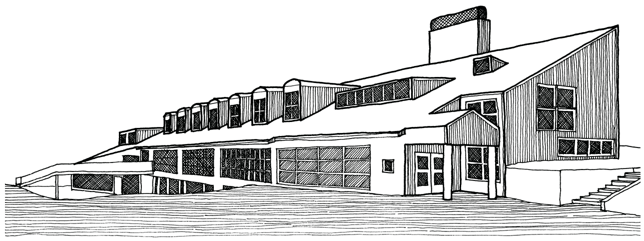
The **Shelton Solar Cabin** in Hazel Valley, Arkansas, by James Lambeth, is a diagrammatic expression of these demands. The south exposure is enlarged in plan and section and filled with glass, while the remaining exposures are reduced in size, almost windowless, and well insulated. The concrete floor is used for thermal storage (Lambeth and Delap, 1977, p. 56).

The **Milford Reservation Environmental Center** in Milford, Pennsylvania, by Kelbaugh and Lee, uses a section similar to Lambeth's but at a larger scale and with its largest wall facing north rather than south. This gave the architects the opportunity to puncture the roof with dormers, thereby increasing the south-facing glazing area and allowing sunlight to penetrate to the north edge of the building (*Progressive Architecture,* 4/1980; 4/1981).





Shelton Solar Cabin, Hazel Valley, Arkansas, James Lambeth



Milford Reservation Environmental Center, Milford, Pennsylvania, Kelbaugh and Lee

49 *SUNSPACES* can be used to collect the sun's heat, store it centrally and distribute it to other rooms. [heating]

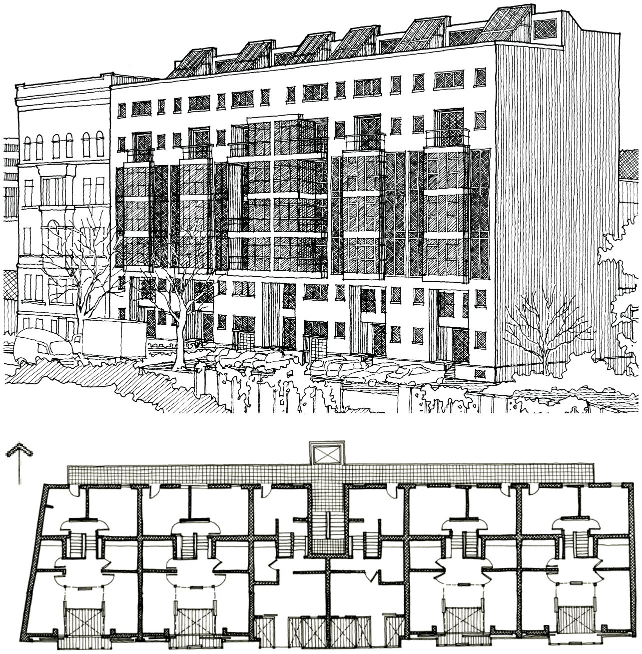
A sunspace, unlike direct gain and trombe wall systems, adds a room to the building. Since the purpose of the sunspace is to provide heat to the rest of the building, it experiences large diurnal temperature swings and is therefore not always comfortable. In sunny periods it will be too warm, and at night it will be too cold. It is usually assumed that the sunspace can get as hot as 95° F (35° C) and as cool as 45° F (7° C). More THERMAL MASS will reduce the temperature swings in the sunspace and store more of the heat collected.

The sunspace may be attached to the main space, sharing one common wall, or be encompassed by the building, sharing three common walls. Enclosed sunspaces are more efficient than attached sunspaces because they lose heat at night through only one exposed wall. Heat is usually transferred to the main space through a common masonry thermal storage wall and by convection through openings in the common wall. The common wall may also be an insulated wall with all the mass located in the sunspace and the heat transfer completely dependent on either CONVECTIVE LOOPS or the aid of fans. To get enough thermal storage, sunspaces with insulated common walls usually need additional mass, either in the form of water or a rock bed under the sunspace floor. See MASS ARRANGEMENT.

Insulated masonry end walls with INSULATION OUTSIDE of attached sunspaces will improve both performance and thermal comfort in the sunspace, as compared to glazed end walls, which have a lower *R*-value and collect little winter heat. Like all passive solar approaches, sunspaces require good shading and ventilation in summer to prevent excessive heat gain.

Sunspace performance can be dramatically improved in many climates by the use of night insulation [MOVABLE INSULATION] or high-performance WINDOW AND GLASS TYPES.

The **Solarhaus Lützowstrasse** in Berlin, Germany, by the Institute for Building, Environment and Solar Research (IBUS: Institut für Bau-, Umwelt-, Solarforschung), uses one- and two-story semi-enclosed sunspaces for levels 3–6. Moveable sliding insulation panels insulate these at night. Attached sunspaces, with blown-in polystyrene-bead night insulation between the glazing layers, heat penthouse split level units. North-facing bedrooms are one-half level lower to promote better sun and light penetration from the south [see section in THERMAL COLLECTOR WALLS AND ROOFS] (*A + W*, 12/1991; Kok and Holtz, 1990, pp. 33–42).



South Facade, Solarhaus Lützowstrasse, Berlin, Germany, IBUS

See SUNSPACES for more specific guidelines.

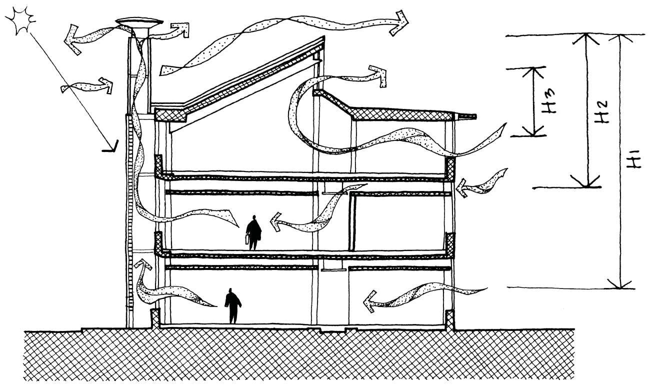
53 *STACK-VENTILATION ROOMS* is increased by open sections and unrestricted pathways between the low inlets and high outlets. [cooling and ventilation]

When the wind is blowing and the outside temperature is below the inside temperature, CROSS-VENTILATION ROOMS can be an effective cooling strategy. However, wind is not always available at certain times such as at night, or winds may be very calm in some climates, or site or urban conditions may block a building's access to wind. In such conditions, stack-ventilation, which does not require wind to move the air through a building, can provide a similar cooling effect. It also has the advantage of orientation independence.

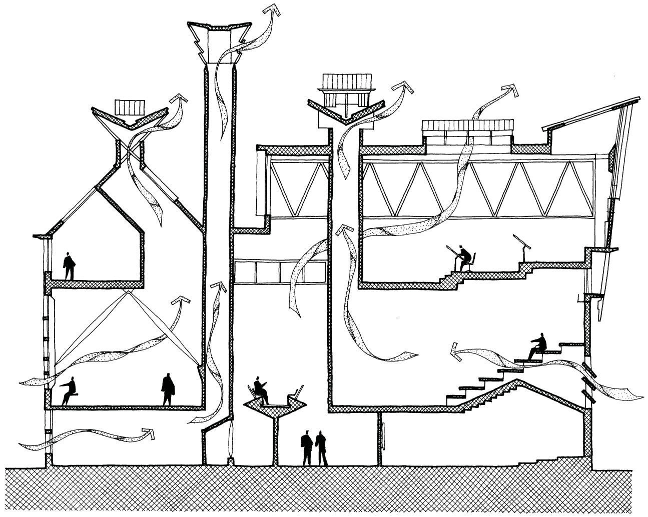
In a room cooled by stack-ventilation, warm air rises, exits though openings at the top of the room and is replaced by cooler air entering low in the room. Several strategies may be used to enhance this ventilation system; all deal with the design of a building's section.

The effective height of the room can be increased by a stack chimney at the top, as it is in the **Building Research Establishment Office Building** in Garston, England, by the firm of Feilden-Clegg. Five stacks, which serve the lower two floors, are located on the south side of the building and extend the distance between inlets and outlets by two stories. Their south face is glazed to further heat the outgoing air and increase the temperature difference with the incoming air. Fans in the stacks assist ventilation when natural flow is insufficient (Allen, 1997; Jones, 1998, pp. 178–181). Outlet performance is enhanced by placing it in a negative pressure zone created by wind flowing over the building, as in the BRE building's top floor, which is stack cooled by clerestory windows on the leeward side.

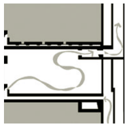
The **Queen's Building of the deMonfort University Engineering School** in Leicester, England, by Short + Ford architects, addresses acoustic isolation by ventilating separate acoustic zones with individual stacks. In the auditorium, sound-baffled inlets are located in the wall beneath the seats. Air enters the room from registers under the seats and exits through two dedicated stacks with outlets above roof level, allowing daylight and ventilation to be controlled separately (Davies, 1995; Thomas, 1996, pp. 171–188).



BRE Office, Typical Section, Garston, England, Feilden-Clegg, architects



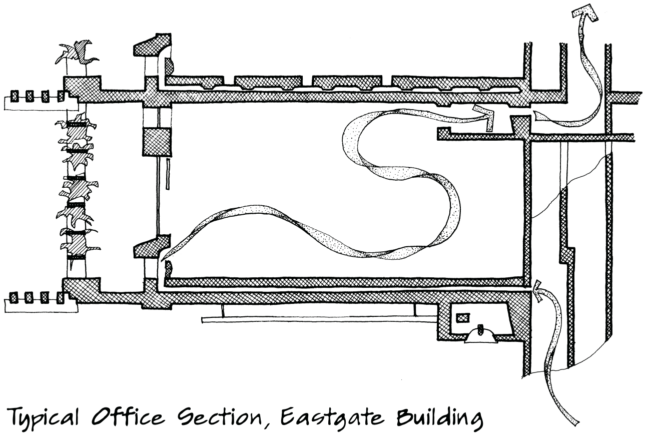
Queen's Building, deMonfort University, Leicester, England, Short + Ford, architects



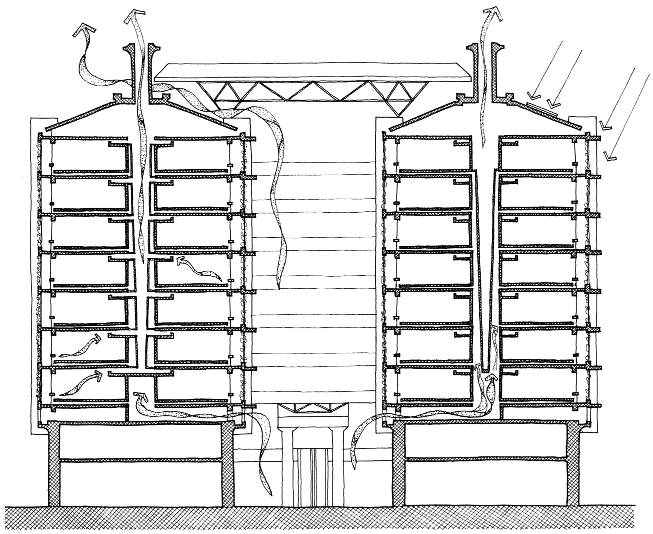
54 *NIGHT-COOLED MASS:* Thermal mass can be used to absorb heat from a room during the day and then be cooled at night with ventilation. [cooling]

Cooling a building using nighttime ventilation of the thermal mass depends on a twofold process. First, during the day, when the outside temperature is too warm for ventilation, the building envelope is closed and excess heat gains are stored in the building's mass. Second, at night, when the outside temperature is lower, outdoor air is allowed to ventilate through the building to remove the stored heat from the mass. The mass is thus cooled so that it can absorb excess heat again the next day. For this to work, there must be enough mass in the building to absorb the heat gains, and the mass must be distributed over enough surface area so that it will absorb the heat quickly and keep the interior air temperature comfortably low. The openings must be large enough to allow enough cool outside air to flow past the mass to remove the heat accumulated during the day and carry it outside the building.

Pearce Partnership, with Ove Arup engineers, designed the high-mass, night-ventilated **Eastgate Building in Harare,** for Harare, Zimbabwe's tropical high-altitude climate. Only the lower two shopping floors are mechanically conditioned. For the narrow office blocks above, air is drawn in with the aid of large fans from a central atrium and up through 32 vertical supply ducts. It is then distributed horizontally through a plenum under the floor, where the air can cool the mass. The major mass is in the ceiling, which is vaulted to increase the exposed surface area. Air enters rooms low near the windows and moves diagonally back to the interior, where it is collected at high bulkheads and discharged through stack towers to outlets above the roof level. During the day, the flow is reduced to a rate sufficient for fresh air supply, and the massive structure can absorb heat from internal and envelope gains. At night, air flow increases to seven air changes per hour (Slessor, 1996).



Typical Office Section, Eastgate Building



Section, Eastgate Building, Harare, Zimbabwe
Pearce Partnership, architects, and Ove Arup, engineers

WALLS, ROOFS & FLOORS: Orientation, Location and Material

60 ***MASS ARRANGEMENT* can be optimized for solar heating, passive cooling, or both; and thermal mass can be located in rooms where sun is collected in adjacent rooms or outside of rooms, remotely. [heating and cooling]**

Thermal mass refers to materials within the insulated envelope that can store heat when coupled to the indoor air. Buildings with high levels of thermal mass can store excess daytime solar heat gains that can be used for heating a space on winter nights or can be flushed with cool night air in summer.

Heavyweight materials store heat and lightweight materials insulate. Because these two types of materials have different construction logics and they impact so strongly and differently how people experience a space, their size and the relationship between them is a primary consideration in preliminary design. This is especially true of a building using passive heating or cooling. The THERMAL MASS strategy gives guidance on sizing mass for solar heating, while the NIGHT-COOLED MASS, ROOF PONDS and EARTH CONTACT strategies give sizing procedures for passive cooling applications.

For heating, when masonry is used for THERMAL MASS, its area can be about as large as the conditioned floor area, and for NIGHT-COOLED MASS, up to twice the size of the floor area, so deciding where to locate the thermal mass is a significant design choice. The placement of thermal mass in floor, wall or ceiling locations affects the rate that heat flows in and out of the mass because the heat transfer coefficients for convective exchanges between the room air and the mass vary for different surface orientations.

***The following guidelines for mass arrangement apply for* both a PASSIVE SOLAR BUILDING *and a* PASSIVELY COOLED BUILDING:**

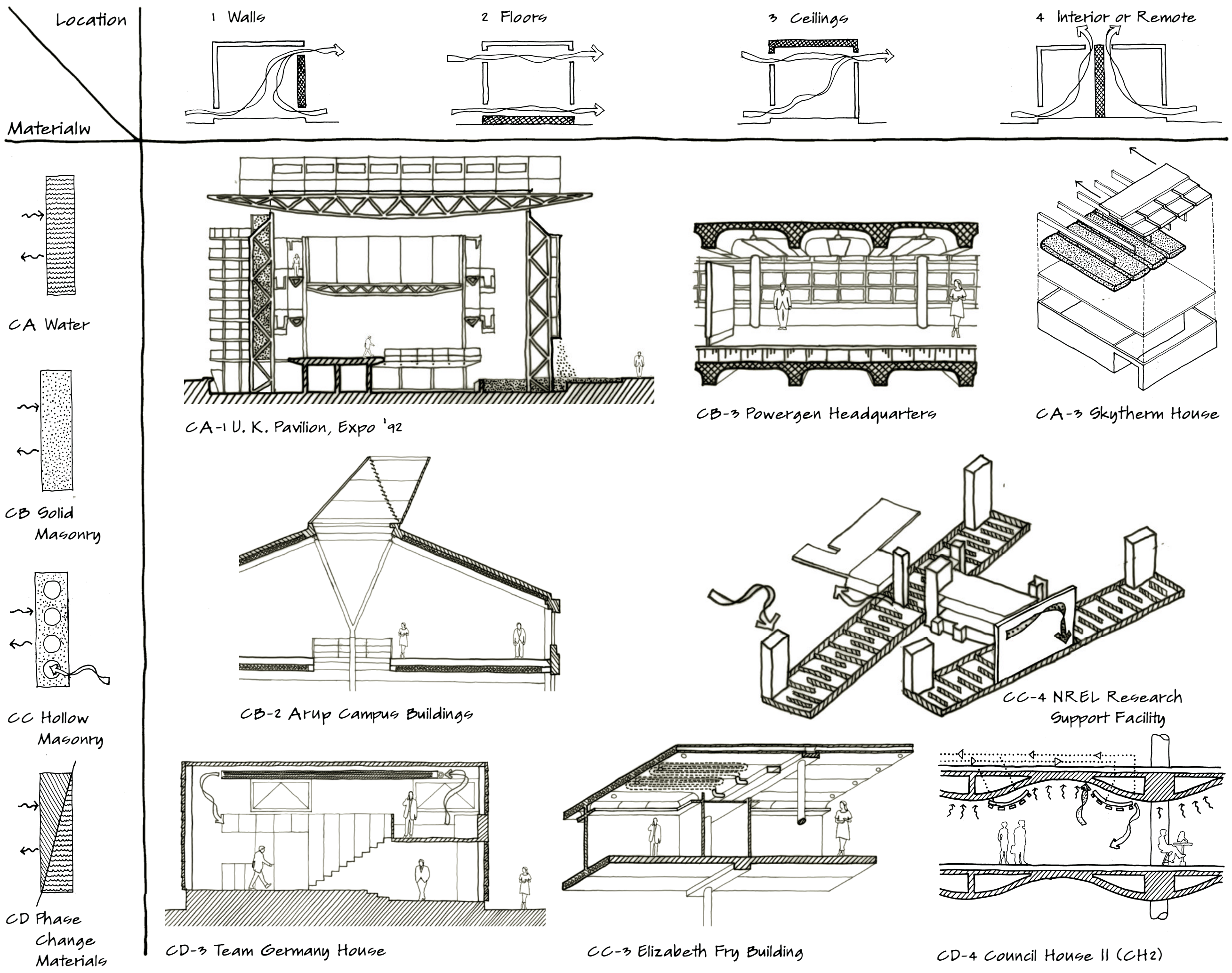
- *Expose structural mass to the interior room air,* so it can exchange heat with the air.
- *Place* INSULATION OUTSIDE *to protect mass located in the envelope* from losing its heat to the outdoors.
- *Locate thermal mass out of the summer sun,* and make certain it is fully shaded.

***Use the following design guidelines for the arrangement of mass for a* PASSIVELY COOLED BUILDING:**

- *Place mass where people can see it,* such that their bodies can radiate (cool) to it and the mass will lower the mean radiant temperature (MRT) of the space.
- *Place a significant portion of the mass in the ceiling,* so that heat exchange will be maximized.
- *Use ceiling fans* to increase heat exchange with mass on ceilings and walls.
- *Locate mass in the ceiling and secondarily on walls,* which are better than the floor. Select a VENTILATION OPENINGS ARRANGEMENT that will bring flowing night air into direct contact with the mass.

***Use the following design guidelines for the arrangement of mass for a* PASSIVE SOLAR BUILDING:**

- *In* DIRECT GAIN ROOMS and SUNSPACES, *mass can be located in the floors, walls, or ceilings, or as water* in containers within the space.
- *Whenever possible, locate mass within the sun-collecting room* (direct or solar mass) so it is radiantly coupled. This works up to four times better than remote mass or mass in another room.
- *Distribute dense masonry storage materials over as large an area as practical.*
- *Limit passive solar floors in sizing calculations to the area in direct sun* for some portion of the day between 10 AM and 2 PM sun time.
- *The volume of water, not the shape of the containers, is important* when water is used as thermal mass.
- *Optimum performance in direct gain rooms is achieved with thermal storage on vertical surfaces,* as Balcomb's studies (1984) show.



Mass Arrangements for Passive Cooling by Location and Type

The matrix **Mass Arrangements for Passive Cooling by Location and Type** organizes location alternatives by material type and location in the room. For example: In location CA-1, the **U. K. Pavilion, Expo '92,** Seville, Spain, 1992, by Nicholas Grimshaw & Partners. The pavilion's west wall is constructed of stacked steel freight containers lined with a membrane and filled with water. They act as thermal storage to moderate the extreme daily temperature range by absorbing internal heat and solar gains during the day and cooling by night (Davies, 1992; Haryott, 1992). Detailed explanations of options indicated in the matrix are given in MASS ARRANGEMENT.

MASS ARRANGEMENT includes an additional matrix, **Mass Arrangements for Passive Solar Heating by Location and Type**, which organizes mass location alternatives by material type and location in the room.

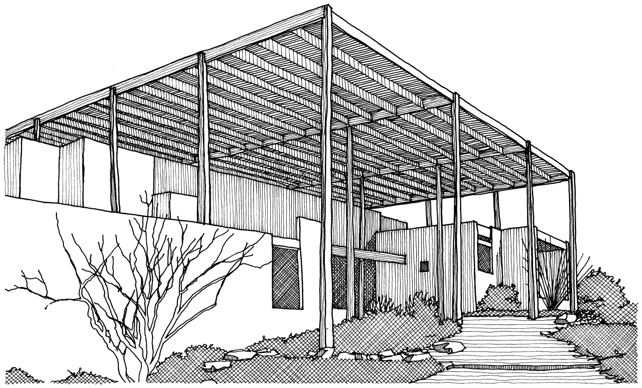
63 A *LAYER OF SHADES* overhead protects the courtyard and building from the high sun, while a layer of vertical shades can protect from low sun. [cooling]

During the summer at temperate latitudes, or year-round at tropical latitudes, the sun is high enough in the sky for much of the day that horizontal overhead shading devices are more effective at shading outdoor space than vertical ones and more effective than shade from a building's massing. However, in the morning or afternoon, shading elements in the vertical plane are more effective at blocking low-angle sun.

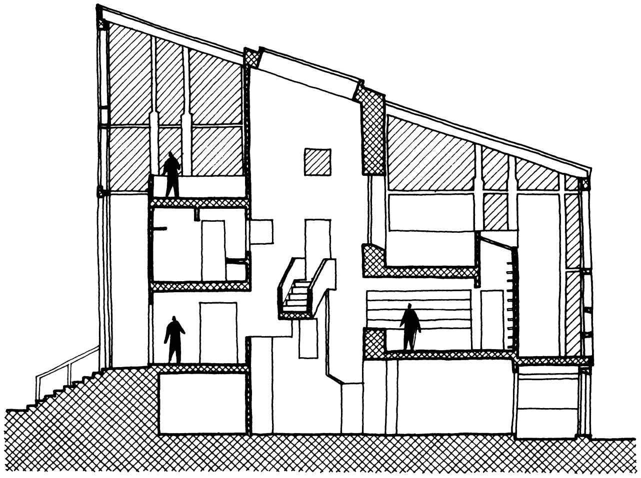
The shading devices may be opaque or louvered, as they are in a **Tucson, Arizona, house** by Judith Chafee, where the shades partially cover the building as well as outside areas (Watson & Labs, 1983, p. 15).

In hot climates, the overheated period in summer often begins near sunrise and extends into the evening. In some buildings, such as residences, the building is occupied more during the early morning and late afternoon than during the middle of the day. Thus, shading for outdoor rooms may be desirable when the sun is very low. To shade low sun by overhead shades would require very long extensions beyond the courtyard. William Turnbull of MLTW addressed this issue in the **Zimmerman House** in Fairfax County, Virginia, by creating a house within an encompassing layer of shades. A vertical redwood lattice envelope pierced by large view-framing windows gives shade from low-angle sun to porches around the inner house and roof terraces above. The outer roof is glazed with translucent plastic and fully vented below to prevent heat buildup (*GA Houses,* 1976, pp. 98–103; *Architectural Review,* 6/1976, p. 381).

Shades can be movable so that the sun can be let in when it is cold and screened when it is hot. Fixed shades have the potential disadvantage of shading equally for months on either side of the summer solstice. In climates with cool springs, say March and April in much of the United States, it is desirable to admit the sun, but in



House in Tucson, Arizona, Judith Chafee



Zimmerman House, Fairfax County, Virginia, William Turnbull/MLTW

August and September, when it is hot and sun positions are identical, shade is needed.

See also SHADING CALENDAR.

69 ***VENTILATION OPENINGS ARRANGEMENT* can be optimized to increase the rate of cross-ventilation in a room and to move air across occupants to increase their rate of cooling. [cooling and ventilation]**

In addition to removing hot air from a room, ventilation can also affect occupant cooling if the air is moving fast enough by increasing the rate of evaporation from their skin. When the outside ambient air temperature is above the comfort zone, design vents for occupant cooling as well as for heat removal.

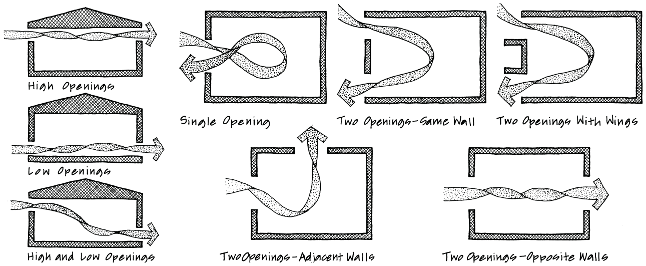
Use the* BIOCLIMATIC CHART *to determine the wind speed that will create comfort. Interior air velocity in a room can be estimated by modifying the design wind speed by the percentages in* Average Interior Air Velocity as a Percentage of the Exterior Wind Velocity. *Choose the size and arrangement of windows that best approximates the proposed room design.

The table is based on the work of Melaragno (1982) and assumes that the window height is one-third of the wall height. The average interior air velocity is a function of the exterior free wind velocity, the angle at which the wind strikes the inlet, and the location and size of the opening. For openings two-thirds of the wall width, rooms that have only one opening in one wall have average velocities of 13–17% of the outside air velocity, depending on the wind direction. For two openings placed in the same wall, average velocities are higher, about 22% of the outside air velocity, because one opening acts as an inlet and the other as an outlet. If perpendicular wings are added to the wall between the openings, this average velocity can be increased to 35% when the wind blows obliquely to the wall [see CROSS-VENTILATION ROOMS].

When openings are located in two walls, the average interior velocity is much higher, 35–65% of outside air velocity, because one opening will always be in a higher pressure zone than the other. The volume of air flow, and thus the heat removed, is greatly influenced by the size of the openings [VENTILATION APERTURES].

window height as a fraction of wall height	**1/3**	**1/3**	**1/3**
window width as a fraction of wall width	**1/3**	**2/3**	**3/3**
single opening	12–14%	13–17%	16–23%
two openings in the same wall	—	22%	23%
two openings in adjacent walls	37–45%	37–45%	40–51%
two openings in opposite walls	35–42%	37–51%	47–65%

Average Interior Air Velocity as a Percentage of the Exterior Wind Velocity
range = wind 45° to perpendicular to opening



The location of the openings and interior partitions in both plan and section influence the route of the air flow through the room. Although openings in opposite walls create rapid movement, openings in adjacent walls and wind directions oblique to the window encourage both turbulence and air mixing, and thus a more even velocity distribution and cooling effect throughout the room. Locate openings so that air moves past the occupants to be cooled. If the openings are all near the ceiling or all near the floor, the maximum velocity won't occur in the occupied zone, usually 1–6 ft (0.3–1.8 m) above the floor.

78 Orient *PHOTOVOLTAIC WALLS AND ROOFS* to collect sun, and make them large enough to meet the building's electric load. [power]

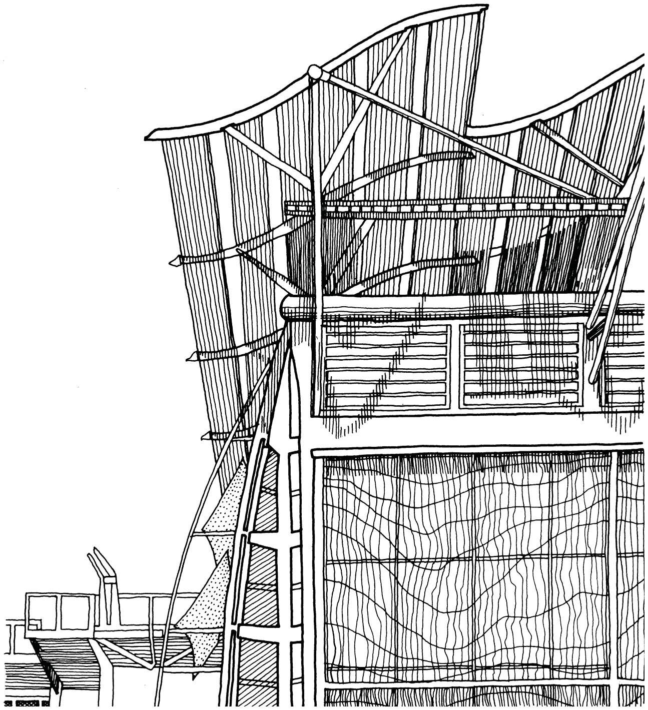
Photovoltaic cells (PVs) convert sunlight to direct current (DC) electricity. Like any solar collection surface, photovoltaics collect more sun when oriented properly. A true equator-facing orientation maximizes yield. ***Orient solar collection surfaces within 30° of south (N in SH).*** At higher latitudes, winter yield will be significantly reduced for non-south orientation (non-N in SH). At tropical latitudes, because the sun is high, tilt can be more important than orientation [see ROOMS FACING THE SUN AND WIND].

Maximize production with* Recommended PV Tilts *at an angle above horizontal as follows: winter, latitude plus 15°; summer, latitude minus 15°; annual production, equal to the site's latitude. For PV sizing, see details in **PHOTOVOLTAIC WALLS AND ROOFS.**

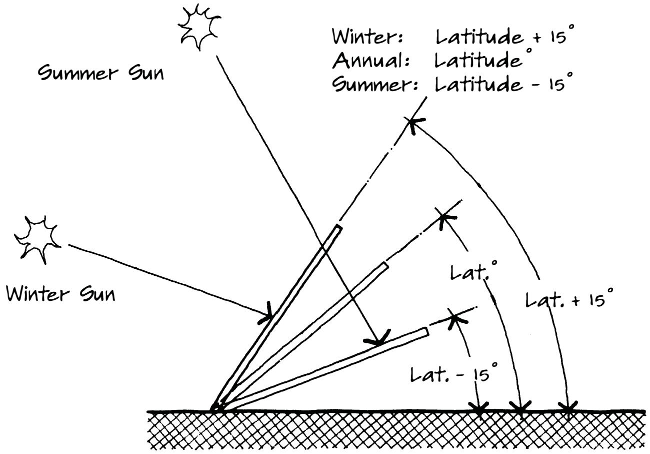
Collectors may be mounted on flat or sloping roofs, or on south-facing walls. Vertical mounting will *reduce* output substantially, especially at lower latitudes and in summer, when the sun is at a higher altitude angle. PV arrays may be integrated with the building's design in various ways. They may be 1) mounted on racks and attached to the building's structure; 2) affixed to short standoff mounts above the weather envelope; 3) integrally mounted to the structure, with PVs serving as the building skin; or 4) integrated as a part of other materials, such as roofing tiles, spandrel panels, shading devices, or glazing.

Roof design strategies that support photovoltaics include 1) roof ridges oriented east–west; 2) larger roofs sloped toward the equator, with smaller roofs sloped to the pole; and 3) chimneys, plumbing vents and other roof penetrations located on polar-oriented roofs.

Photovoltaics can perform a second function as architectural shading. PVs mounted on frames above the roof were used by Nicholas Grimshaw & Partners to power the lighting and evaporative wall water pumps while shading the roof and skylights of the **U. K. Pavilion at Expo '92** in Seville, Spain (Davies, 1992; Haryott, 1992).



U. K. Pavillion, Expo '92, Seville, Spain, Nicholas Grimschaw & Partners



Recommended PV Tilts

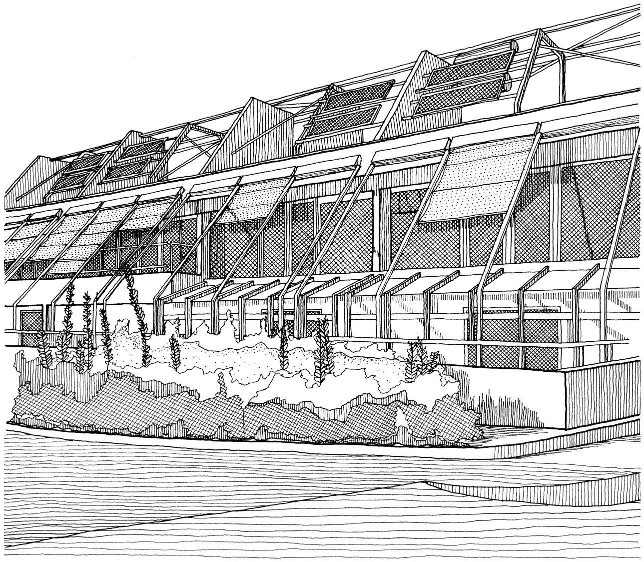
79 *SOLAR HOT WATER* systems require roofs that are large enough as well as sloped and oriented to collect sun. [power]

Heating water is one of the simplest and most cost effective uses of solar energy. Always invest in the sun to heat water before considering photovoltaics. Solar hot water systems have many benefits, including substantial reduction of fuel consumption, reduced pollution and attractive economics. In a solar hot water system, water, or in cool climates, a nonfreezing solution, is circulated through a solar collector, most often with the aid of a pump, but purely passive systems are also available.

The water is heated by the sun as it passes through the collector and is then circulated to a storage tank. In the case of a nonfreezing solution, the warmed solution heats water from storage by means of a heat exchanger. From storage (or the heat exchanger), the fluid is circulated back to the collector. Usually, an auxiliary hot water heater provides heat when the solar resource is insufficient, such as in midwinter or under unusual high use periods.

In the **Solar Village 3** neighborhood in Athens, Greece, Alexandros N. Tombazis and Associates used solar water collectors mounted on racks to provide heated water while also shading roof terraces of multistory housing (Cofaigh et al., 1996, pp. 147–154; *Architecture in Greece,* 1986, pp. 196–199). Collectors are tilted, facing south. The complex uses both active and passive solar heating and cooling systems in a variety of types. Heated water is for domestic use and in some cases, for some of the space heating requirements. Banks of collectors alternate with open rails to give both a shady and a sunny side to the roof terraces, expanding options for seasonal use and views.

The size of a building's collectors are based on the amount of energy that can be collected at the building site, the temperature of incoming water, the temperature of hot water provided and the rate of water use in the building. See sizing details in SOLAR HOT WATER.



Solar Village 3, Athens, Greece,
Alexandros N. Tombazis & Associates

Face collectors toward the equator whenever possible. Deviations from a true south (N in SH) orientation result in less heat being collected from the sun, especially at high latitudes in winter. However, on an annual basis, performance at Alaskan latitudes decreases less than 10% for orientations up to 50° from south (Siefert, 2010).

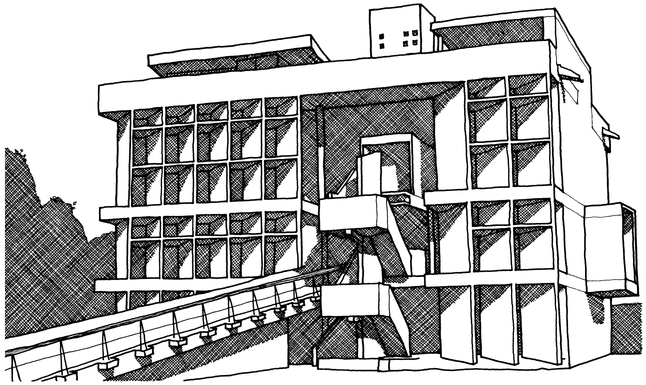
***Tilt recommendations are the same as for PVs. See diagram of collector tilts in* PHOTOVOLTAIC ROOFS AND WALLS.** For temperate, overcast-dominated sky conditions, a tilt lower than the latitude° is recommended, since under overcast conditions, the top of the sky dome is three times brighter than the horizon. At high latitudes, such as Alaska, winter radiation is very low, so annual performance is maximized by a tilt of latitude° minus 10–20° (Siefert, 2010).

91 An *EXTERNAL SHADING* layer outside the window can shade the glazing and reduce solar heat gain. [cooling]

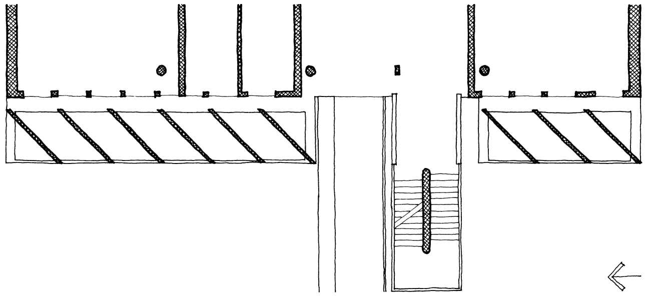
Exterior shading devices can be either horizontal, vertical, or a combination of horizontal and vertical called "egg crates." *Horizontal shades* provide effective shading on the equatorial facade when the sun altitude is high. The depth of the device determines the length of the shadow on the window wall. The sun is higher in the summer than in the winter, so horizontal shades can be proportioned to shade in the summer but admit sun in the winter to help heat the building. Because the summer sun's movement is symmetrical around Jun 21 (Dec 21 in the Southern Hemisphere), equator-facing horizontal shades that shade the glazing in hot months (August and September; February and March in SH) will also shade in cooler months (March and April; September and October in SH) when the sun might be welcome. This problem can be solved by making the shades *seasonally adjustable*, like canvas awnings. *Deciduous vines* make effective shades since they are bare in the cool spring but have dense foliage throughout the hot summer and early fall. To determine periods for fixed and moveable shades, see SHADING CALENDAR.

Vertical shades are effective when the sun is low and the broad side of the vertical elements faces the sun. Vertical shades perpendicular to the window are most effective on the polar side, where no horizontal element is needed, except at tropical latitudes where the sun is much higher.

Egg crates combine the advantages of both horizontal and vertical shades and are particularly effective on facades that do not face the equator. On the west facade of the **Millowners' Association Building,** in Ahmedabad, India, by Le Corbusier, the horizontal elements shade in the early afternoon when the sun is high and the angled vertical elements shade in the late afternoon when the sun is low and in the west (Futagawa, 1975). Note also how the brise soleil is held away from the glass to allow air circulation to remove any heat captured.



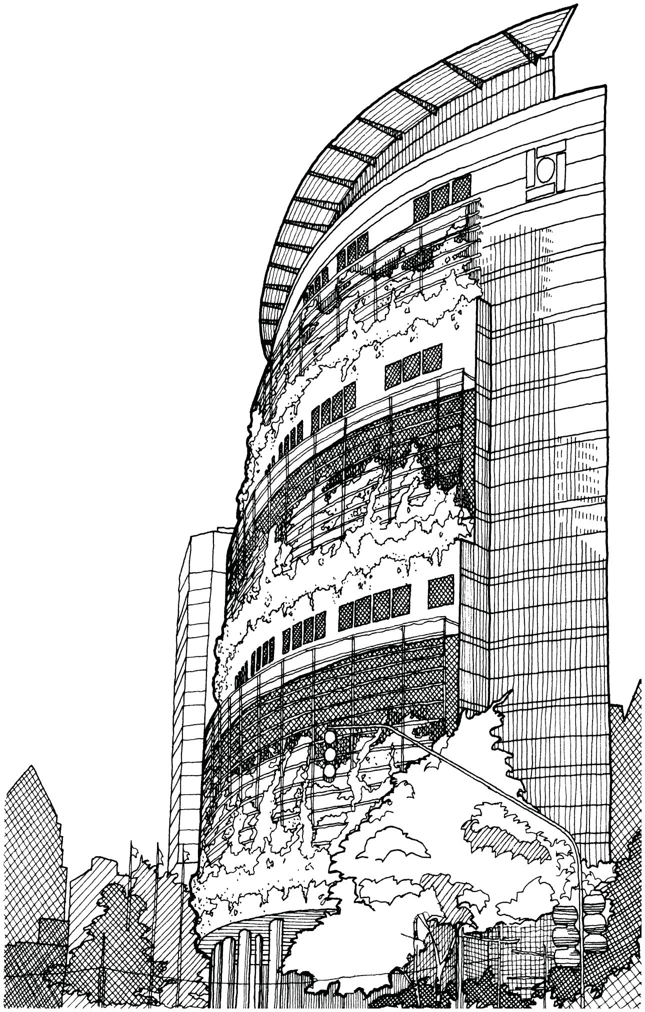
Millowner's Association Building, West Facade



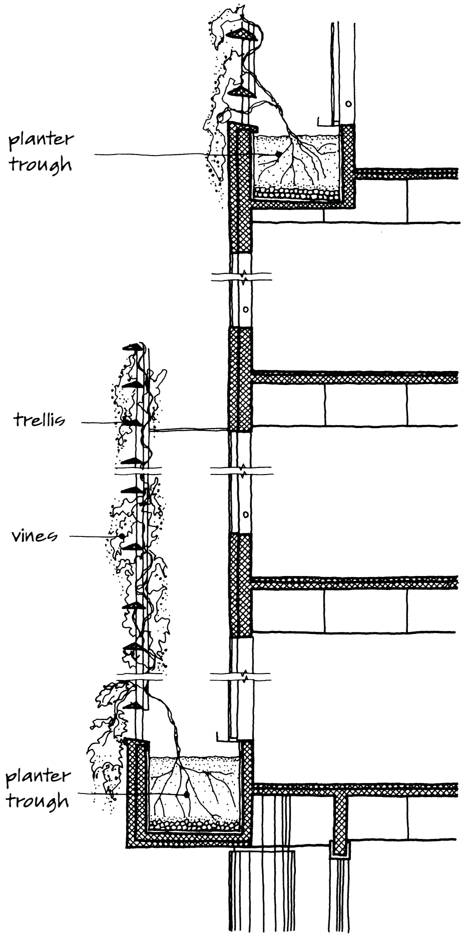
Millowner's Association Building, Ahmedabad, India, Le Corbusier

Shading devices can vary in size without changing their shading characteristics, as long as the *ratio* between the depth and the spacing of the elements remains constant.

Vegetation placed between the sun and building's surfaces reduces a building's heat gain in three ways: by reducing radiation transmitted though windows, by reducing the solar load on opaque surfaces and by lowering via evapotranspiration the outdoor air temperature near building surfaces. Architects Enrique Browne & Borja Huidobro used a *vertical screen* of vines grown on a planting trellis



Consorcio-Vida Offices, Santiago, Chile, Enrique Browne & Borja Huidobro



Section through West Elevation, Consorcio-Vida Offices

to shield the **Consorcio-Vida Offices** in Santiago, Chile, from harsh western sun (Slessor, 1999). The trellis frames, which vary in height between two and four stories, are set 1.5 m (5 ft) outside the window wall. The vines provide a filtered animated light, blocking approximately 60% of the solar gain on the wall. The perspective shows the building four years after construction, the vines having grown to cover approximately half of the trellis. This illustrates the need to begin plantings as early as possible and have an interim shading strategy while the vegetation matures. In this scheme, shorter trellises of two stories with more planter troughs would have allowed the entire facade to be covered in the same number of years. Vines can produce a dense leaf structure faster than trees; shade plants can begin growing before the building is constructed.

Shading coefficients for various external shading elements can be found in WINDOW SOLAR GAIN. For sizing details, see the methods in EXTERNAL SHADING.

Part VII
HIGH-PERFORMANCE BUILDINGS

The meaning of high-performance building design has changed dramatically since the second edition of *Sun, Wind & Light* was published in 2001. At that time, the world held only a handful of very expensive zero-energy demonstration buildings. Most people thought that renewable energy production was too expensive to be practical except for remote off-the-grid buildings, and the Architecture 2030 movement had not yet been born. In the years since the second edition, the bar has been set continually higher. First, the EPA Energy Star® program challenged designers to create buildings that used 25% less energy than buildings typical of a type and climate zone. ASHRAE responded with a series of high-performance building design guides to help designers meet the 25% reduction goal. Architecture 2030 came on the scene and both challenged and inspired the building community to adopt more progressive high-performance targets that reduce fossil fuel use in new buildings by an additional 10% every five years, culminating in a carbon-neutral performance target in which all new buildings operate without fossil fuels. ASHRAE responded with a second set of high-performance building design guides, this time setting a 50% energy reduction target. The building design and construction community has taken up this call and enthusiastically adopted the 2030 challenge.

Extending these targets further, this *SWL* edition embraces site net-zero energy buildings, which produce as much on-site renewable energy as they consume. The frontier continues to be redefined, as the building community strives to create net-positive energy buildings,which produce more energy than they consume and export energy to the utility grid. The ultra-high-performance target in that territory is the peak-net-zero building,which produces at its peak load hour as much energy as it consumes, thus having an excess of power at all other times.

The new *SWL* high-performance buildings techniques in Part VII help the designer set energy and emissions targets and then evaluate the building design at the preliminary level to ascertain if those targets have been met. Using ENERGY TARGETS and EMISSIONS TARGETS in your pre-design, unbuilt phase is recommended to better frame the design problem and seek criteria for its success. The Synergies, Bundles and Design Strategies in *SWL* are the means to propose the 'built' phase's possible design responses. Once a scheme is developed to a preliminary stage, refer to ANNUAL ENERGY USE to find the building's Energy Demand Intensity (EDI) and consult NET-ZERO ENERGY BALANCE to size renewable power and estimate the building's Energy Production Intensity (EPI). From there, use ENERGY USE INTENSITY to find the building's net site Energy Use Intensity (EUI), which is the difference between its energy demand and its energy production:

EUI = EDI – EPI

Also, in ENERGY USE INTENSITY, the building's EUI is compared to the target EUI chosen earlier in ENERGY TARGETS. Finally, in CARBON-NEUTRAL BUILDINGS, designers can estimate the Carbon Use Intensity (CUI) for the building and compare it to the target CUI established previously in EMISSIONS TARGETS.

As with all tools in *SWL,* these are intended for preliminary design rather than for detailed evaluations at the design development or post-occupancy phases, when much more detail is known about the building. Like other *SWL* tools, these are quick and approximate and come with built-in assumptions to which the user is advised to pay careful attention.

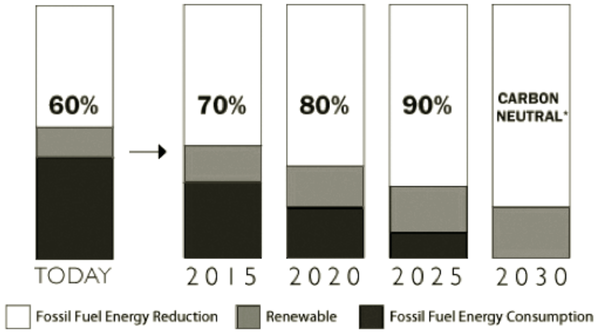
⌁ *SWL Electronic* contains the *SWL Tools* spreadsheet, which facilitates all of the calculations covered in these six techniques. Similar to the *SWL* hand estimation tools, it is designed to be relatively simple, quick and appropriate for preliminary design. Because it is a spreadsheet, the user can inquire into its logics and formulae. The text in these high-performance building techniques explains the general logic used in *SWL Tools* and explains methods for hand calculation. While the general logics are the same, the specific formulae in the spreadsheet are often more complicated, and for clarity and brevity not all of the spreadsheet features are covered in the text.

CRITERIA

P1 ***ENERGY TARGETS*** **set goals to reduce fossil fuel consumption relative to benchmarks for the building's type and climate.**

KEY POINTS

- Energy targets, measured as *energy use intensity* (EUI) allow us to make energy use comparisons between buildings on a per unit area basis.
- Energy targets are calculated as a percentage reduction from the energy use of current average buildings for the occupancy type and location.
- Select a target EUI based on one of the tables for the USA or Canada, and for residential or commercial occupancy and building type; or one can choose to design a net-zero or net-positive energy building.
- A net-zero energy building has a net site EUI = 0, while a net-positive, energy-exporting building will have a net site EUI < 0.

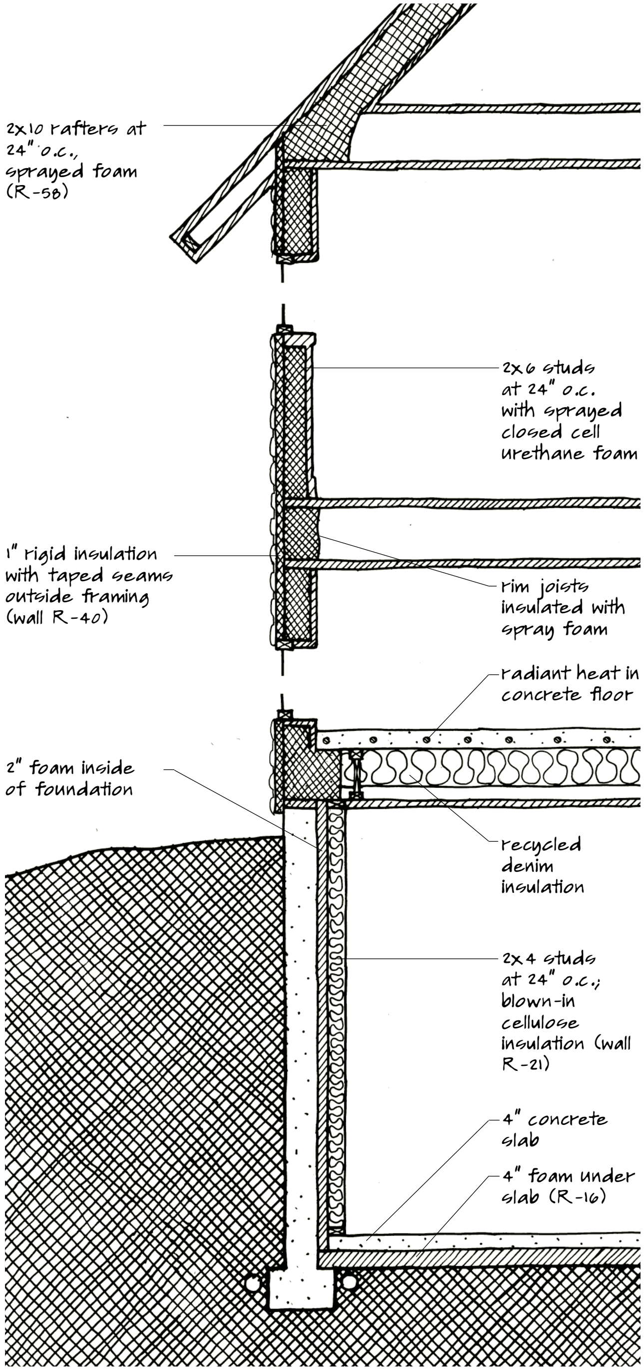


The 2030 Challenge Targets
The Architecture 2030 Challenge allows up to 20% of the overall energy reduction to come from off-site renewable energy. The carbon-neutral target uses no fossil fuel/GHG-emitting energy to operate.

Architects around the world are designing to reduce the energy use of buildings and reduce the impact of that energy use on climate change. The American Institute of Architects (AIA) and firms internationally have adopted the carbon reduction targets proposed by the group Architecture 2030 (2011). As shown in the graph, **The 2030 Challenge Targets**, the target at this writing is 60% less fossil fuel use than the median building for a particular type, with staged reductions until reaching the goal of "carbon-neutral" for all new buildings by the year 2030. Greenhouse gas (GHG) emissions attributable to buildings are a result of energy use, both on-site (direct emissions) and off-site (indirect) emissions that can be traced back to sources such as the electric power plant or natural gas fields.

The **Pill-Maraham House** in Charlotte, Vermont, by Pill-Maraham Architects, achieves a net-zero energy target by a combination of very good conservation, passive solar heating, an efficient ground source heat pump and on-site power from a wind generator (NIBS, 2012; James, 2008). The **Wall Section** drawing shows the highly insulated envelope for a cold New England climate. A typical single-family detached house in the U.S. "Northeast" region uses 46 kBtu/ft^2,yr (145 kWh/m^2, yr) of total site energy. The Pill-Maraham House uses a total of 7 kBtu/ft^2 (22 kWh/m^2, yr), a load reduction of 85%. The small remaining load is met by on-site wind-generated power.

This ENERGY TARGETS technique allows the designer to select energy targets for residential and nonresidential buildings in the United States and Canada. Because data on building energy use is not available for all building types based on climates zones or geographic regions, different tables are provided for each situation. ENERGY TARGETS uses the Energy Use Intensity (EUI) measured in kBtu/ft^2,yr (kWh/m^2,yr), which is the annual total energy use of the building, per unit of floor area.



Wall Section, Pill-Maraham House, Charlotte, Vermont, 2007, Pill-Maraham Architects

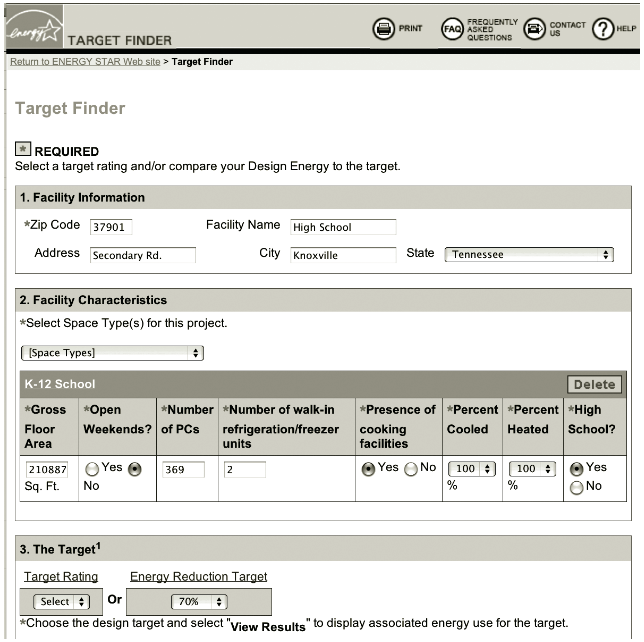
There are two steps to select the building's energy target:

STEP 1: Choose your project energy goal. Select one of three types of energy targets:

- ***A net-positive energy building target,*** where annual energy produced on-site will exceed the building's energy demand and excess energy is sold to the utility company. The target net EUI < 0.
- ***A net-zero energy building target,*** where annual energy produced on site will equal the building's energy demand. The target net EUI = 0, using *only* on-site renewable power.
- ***Choose one of the targets shown in* The 2030 Challenge Targets** graph. The target net EUI > 0 for the 2015, 2020 and 2025 goals. The carbon-neutral goal in energy terms is a form of net-zero target that allows for up to 20% purchased off-site renewable energy (RE). The target net EUI = 0, *with* off-site RE included.
- ***Input your project energy goal in the* SWL Tools *spreadsheet,*** if you are using it, on the "Energy Targets" tab.

Results for Estimated Energy Use			
Energy	**Design**	**Target**	**Median Building**
Energy Performance Rating (1-100)	N/A	100	50
Energy Reduction (%)	N/A	70	0
Source Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	45	151
Site Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	14	45
Total Annual Source Energy (kBtu)	N/A	9,569,200	31,897,333
Total Annual Site Energy (kBtu)	N/A	2,865,030	9,550,100
Total Annual Energy Cost ($)	N/A	$ 74,313	$ 247,709
Pollution Emissions			
CO2-eq Emissions (metric tons/year)	N/A	590	1,966
CO2-eq Emissions Reduction (%)	N/A	70%	0%

EPA Target Finder Results



EPA Target Finder Input Screen (EPA, 2012)

STEP 2: Find the target EUI if > 0. For targets other than net-zero or net-positive energy, use one of the following procedures.

United States, Nonresidential Buildings

***To find the EUI target for a U.S. nonresidential building, select a building type from those available in* Target Finder *and input the site zip code along with the other required information in the* EPA Target Finder Input Screen. *Set your "Energy Reduction Target" as a % reduction. Read the "Site Energy Use Intensity" value from the "Results for Estimated Energy Use" screen, as shown in* EPA Target Finder Results.**

The Commercial Building Energy Consumption Survey (CBECS) provides energy use data by building type for the United States (EIA, 2003). EPA's online "Target Finder" tool normalizes CBECS data to climate zones for 16 building types (EPA, 2012). EUI targets for Canadian nonresidential buildings can be approximated by using a city with similar heating degree days (HDD) to a U.S. city found in the same climate zone.

***EUI values have been calculated using this method and default definitions for the 16 building types found in Target Finder, as shown in the tables of* Energy Use Intensity (EUI) Targets by Building Type and Climate Zone** in the following pages.

Primary Space / Building Type	Ave. % Electric	Site EUI		
		med	70%	90%
Education	63	58	17.4	5.8
College/University (campus-level)	63	104	31.2	10.4
Food Sales	86	193	57.9	19.3
Convenience Store (w/ or w/o gas)	90	228	68.4	22.8
Food Service	59	267	80.1	26.7
Fast Food	64	418	125.4	41.8
Restaurant/Food Market	53	207	62.1	20.7
Health Care and Outpatient	72	62	18.6	6.2
Clinic/ Other Outpatient Health	76	67	20.1	6.7
Lodging	61	72	21.6	7.2
Mall (strip mall and enclosed)	71	94	28.2	9.4
Public Assembly	57	42	12.6	4.2
Entertainment/Culture	63	46	13.8	4.6
Library	59	92	27.6	9.2
Recreation	55	39	11.7	3.9
Social/Meeting	57	43	12.9	4.3
Public Order & Safety	57	82	24.6	8.2
Fire Station/Police Station	56	82	24.6	8.2
Service (vehicle repair/postal service)	63	45	13.5	4.5
Storage/Shipping/ Non-refrigerated warehouse	56	10	3.0	1.0
Retail Store (non-mall stores, vehicle dealerships)	67	53	15.9	5.3
Other (varies greatly)	56	70	21.0	7.0

Energy Use Intensity (EUI) Targets, U.S. Commercial Buildings, National Averages, kBtu/ft^2-yr

Use for occupancy types not in "EPA Target Finder" or in "Energy Use Intensity (EUI) Targets, by Building Type and Climate Zone."

Derived from Architecture 2030 (2012), based on EPA (2011) and Energy Information Administration's Commercial Building Energy Use Survey (CBECS), 2003; using the EPA's Table 1: 2003 CBECS National Average Source Energy Use and Performance Comparisons by Building Type.

Cities are representative of the climate zone and can be used to approximate EUI for other cities in the zone. Default values are given in the "Target Finder" help files for most inputs. The method modified from methods to determine building energy performance standards as described by Bryan (2009).

Tables show a "med" value for the median building in the CBECS data, representing typical practice, along with 70% and 90% reduction targets from this median value. The cities are representative of the ASHRAE climate zones. Honolulu, Hawaii, and San Juan, Puerto Rico, have been added because of the variability found in Zone 1A. Ketchikan, Alaska, has been added to the ASHRAE system, which does not include a Zone 5C. "Target Finder" does not distinguish between conditions colder than Zone 8, although much more extreme conditions than those found in Fairbanks exist in both Alaska and Canada, and therefore, buildings in Zone 8 and above on the **International Climate Zone Maps** (see "Navigation by Climate" chapter or Appendix F), will likely experience greater energy use than those in Fairbanks. Where possible, building floor areas have been taken from the DOE commercial reference buildings definitions (Torcellini et al, 2008). Two building types shown in the table, Strip Mall and Mid-Rise Apartment Building, are not found in "Target Finder." Values for EUI for these buildings are taken from the DOE commercial reference buildings for new construction (DOE, 2010).

EUI targets for *U.S. commercial buildings* not found in either "Target Finder" or in the DOE reference building models are given as U.S. national averages (not by region or climate zone) in the table **Energy Use Intensity (EUI) Targets, U.S. Commercial Buildings, National Averages.**

ASHRAE Climate Zones	City	Small Office 5,500 sf / 1story			Medium Office 53,628 sf / 3 story			Large Office 498,588 sf / 12 story			Medical Office 40,946 sf / 3 story			Primary School 73,960 sf / 1 story			Secondary School 210,887 sf / 2 story			Hospital (general medical & surgical) 241,351 sf / 5 st			Senior Care Facility 20,025 sf / 1 story			Hotel (small) 43,200 sf / 4 story		
		med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%
1A	Honolulu, HI	64	19	6	91	27	9	107	32	11	155	47	16	42	13	4	74	22	7	302	91	30	157	47	16	82	25	8
1A	San Juan, PR	53	16	5	75	23	8	88	26	9	185	56	19	27	8	3	51	15	5	172	52	17	105	32	11	56	17	6
1A	Miami, FL	63	19	6	89	27	9	105	32	11	140	42	14	49	15	5	76	23	8	266	80	27	140	42	14	73	22	7
2A	Houston, TX	61	18	6	88	26	9	103	31	10	122	37	12	59	18	6	76	23	8	256	77	26	135	41	14	72	22	7
2B	Phoenix, AZ	68	20	7	96	29	10	112	34	11	173	52	17	72	22	7	107	32	11	305	92	31	163	49	16	89	27	9
3A	Atlanta, GA	57	17	6	84	25	8	99	30	10	95	29	10	59	18	6	62	19	6	239	72	24	125	38	13	67	20	7
3B-CA	Los Angeles, CA	47	14	5	74	22	7	90	27	9	69	21	7	65	20	7	55	17	6	249	75	25	120	36	12	57	17	6
3B-other	Las Vegas, NV	65	20	7	84	25	8	108	32	11	140	42	14	74	22	7	93	28	9	289	87	29	153	46	15	84	25	8
3C	San Francisco	51	15	5	78	23	8	94	28	9	73	22	7	62	19	6	60	18	6	247	74	25	123	37	12	64	19	6
4A	Baltimore, MD	59	18	6	85	26	9	101	30	10	91	27	9	60	18	6	58	17	6	233	70	23	123	37	12	70	21	7
4B	Albuquerque, NM	61	18	6	88	26	9	104	31	10	106	32	11	74	22	7	73	22	7	266	80	27	140	42	14	79	24	8
4C	Seattle, WA	57	17	6	84	25	8	100	30	10	82	25	8	67	20	7	60	18	6	247	74	25	129	39	13	74	22	7
5A	Chicago, IL	73	22	7	104	31	10	122	37	12	113	34	11	88	26	9	79	24	8	263	79	26	152	46	15	92	28	9
5B	Boulder, CO	63	19	6	90	27	9	106	32	11	101	30	10	74	22	7	66	20	7	257	77	26	139	42	14	83	25	8
5C	Ketchican, AK	66	20	7	93	28	9	109	33	11	97	29	10	55	17	6	72	22	7	246	74	25	138	41	14	89	27	9
6A	Minneapolis, MN	77	23	8	108	32	11	126	38	13	121	36	12	89	27	9	80	24	8	263	79	26	156	47	16	97	29	10
6B	Helena, MT	65	20	7	92	28	9	108	32	11	98	29	10	72	22	7	62	19	6	250	75	25	138	41	14	86	26	9
7	Duluth, MN	78	23	8	110	33	11	108	32	11	114	34	11	85	26	9	73	22	7	254	76	25	153	46	15	101	30	10
7.5	Kenai, AK	70	21	7	97	29	10	113	34	11	105	32	11	56	17	6	73	22	7	246	74	25	141	42	14	96	29	10
8	Fairbanks, AK	76	23	8	104	31	10	120	36	12	119	36	12	69	21	7	64	19	6	247	74	25	148	44	15	107	32	11

Energy Use Intensity (EUI) Targets, by Building Type and Climate Zone, $kBtu/ft^2$-yr

na = not available in EPA "Target Finder"

Hotel (large) 12,202 sf / 6 story			Residence Hall / Dormitory 100,000 sf / 4 story			Mid-Rise Apartment 33,740 sf / 4 story			Warehouse (unrefrigerated) 52,045 sf / 1 story			Warehouse (refrigerated) 52,045 sf / 1 story			Courthouse, federal 395,000 sf.			Bank / Financial Institution 4,100 sf / 1 story branch			Supermarket / Grocery 45,000 sf / 1 story			Retail 24,962 sf / 1 story			Strip Mall 22500 sf / 1 story			House of Worship 17,000 sf / 1 story		
med	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**	**med**	**70%**	**90%**
111	33	11	102	31	10	na	na	na	27	8	3	174	52	17	107	32	11	112	34	11	384	115	38	72	22	7	na	na	na	29	9	3
74	22	7	72	22	7	na	na	na	21	6	2	139	42	14	88	26	9	92	28	9	274	82	27	63	19	6	na	na	na	21	6	2
99	30	10	92	28	9	39	12	4	23	7	2	149	45	15	105	32	11	110	33	11	280	84	28	73	22	7	56	17	6	26	8	3
98	29	10	88	26	9	39	12	4	24	7	2	127	38	13	103	31	10	108	32	11	264	79	26	73	22	7	58	17	6	25	8	3
118	35	12	118	35	12	38	11	4	30	9	3	180	54	18	112	34	11	117	35	12	410	123	41	77	23	8	57	17	6	34	10	3
92	28	9	77	23	8	38	11	4	24	7	2	94	28	9	99	30	10	104	31	10	230	69	23	71	21	7	62	19	6	20	6	2
86	26	9	58	17	6	31	9	3	24	7	2	62	19	6	90	27	9	95	29	10	229	69	23	59	18	6	44	13	4	8	2	1
113	34	11	105	32	11	36	11	4	30	9	3	147	44	15	108	32	11	113	34	11	371	111	37	75	23	8	57	17	6	30	9	3
93	28	9	67	20	7	33	10	3	27	8	3	56	17	6	94	28	9	99	30	10	245	74	25	65	20	7	53	16	5	13	4	1
95	29	10	82	25	8	42	13	4	26	8	3	80	24	8	101	30	10	106	32	11	228	68	23	75	23	8	74	22	7	22	7	2
108	32	11	94	28	9	37	11	4	31	9	3	98	29	10	104	31	10	109	33	11	322	97	32	75	23	8	64	19	6	25	8	3
102	31	10	82	25	8	38	11	4	31	9	3	58	17	6	100	30	10	105	32	11	275	83	28	73	22	7	69	21	7	20	6	2
123	37	12	112	34	11	47	14	5	42	13	4	102	31	10	122	37	12	128	38	13	257	77	26	109	33	11	85	26	9	36	11	4
112	34	11	101	30	10	41	12	4	34	10	3	78	23	8	106	32	11	111	33	11	319	96	32	79	24	8	72	22	7	27	8	3
118	35	12	113	34	11	na	na	na	38	11	4	56	17	6	109	33	11	114	34	11	320	96	32	86	26	9	na	na	na	31	9	3
128	38	13	126	38	13	54	16	5	45	14	5	102	31	10	126	38	13	132	40	13	270	81	27	115	35	12	99	30	10	41	12	4
115	35	12	107	32	11	48	14	5	36	11	4	64	19	6	108	32	11	113	34	11	318	95	32	83	25	8	89	27	9	29	9	3
132	40	13	133	40	13	59	18	6	48	14	5	78	23	8	128	38	13	133	40	13	266	80	27	120	36	12	111	33	11	43	13	4
124	37	12	130	39	13	na	na	na	41	12	4	56	17	6	113	34	11	118	35	12	340	102	34	91	27	9	na	na	na	36	11	4
135	41	14	163	49	16	76	23	8	45	14	5	57	17	6	120	36	12	125	38	13	373	112	37	99	30	10	156	47	16	44	13	4

Energy Use Intensity (EUI) Targets, by Building Type and Climate Zone, $kBtu/ft^2$-yr

na = not available in EPA "Target Finder"

Commercial Space / Building Type	Site EUI		
	med	70%	90%
ATLANTIC			
Wholesale Trade	436.1	130.8	43.6
Retail Trade	525.0	157.5	52.5
Transportation & Warehousing	319.5	95.8	31.9
Information & Cultural Industries	558.4	167.5	55.8
Offices	405.6	121.7	40.6
Educational Services	444.5	133.3	44.4
Healthcare & Social Assistance	738.9	221.7	73.9
Arts, Entertainment & Recreation	497.3	149.2	49.7
Accommodation & Food Service	719.5	215.9	72.0
Other Services	391.7	117.5	39.2
QUEBEC			
Wholesale Trade	527.8	158.3	52.8
Retail Trade	563.9	169.2	56.4
Transportation & Warehousing	452.8	135.8	45.3
Information & Cultural Industries	780.6	234.2	78.1
Offices	452.8	135.8	45.3
Educational Services	561.2	168.3	56.1
Healthcare & Social Assistance	905.6	271.7	90.6
Arts, Entertainment & Recreation	661.2	198.3	66.1
Accommodation & Food Service	894.5	268.4	89.5
Other Services	505.6	151.7	50.6
ONTARIO			
Wholesale Trade	463.9	139.2	46.4
Retail Trade	469.5	140.8	46.9
Transportation & Warehousing	394.5	118.3	39.4
Information & Cultural Industries	444.5	133.3	44.4
Offices	397.3	119.2	39.7
Educational Services	452.8	135.8	45.3
Healthcare & Social Assistance	697.3	209.2	69.7
Arts, Entertainment & Recreation	502.8	150.8	50.3
Accommodation & Food Service	666.7	200.0	66.7
Other Services	436.1	130.8	43.6

Commercial Space / Building Type	Site EUI kWh/m², yr		
	med	70%	90%
MANITOBA			
Wholesale Trade	433.4	130.0	43.3
Retail Trade	527.8	158.3	52.8
Transportation & Warehousing	394.5	118.3	39.4
Information & Cultural Industries	538.9	161.7	53.9
Offices	422.3	126.7	42.2
Educational Services	486.2	145.8	48.6
Healthcare & Social Assistance	780.6	234.2	78.1
Arts, Entertainment & Recreation	458.4	137.5	45.8
Accommodation & Food Service	794.5	238.4	79.5
Other Services	463.9	139.2	46.4
SASKATCHEWAN			
Wholesale Trade	566.7	170.0	56.7
Retail Trade	725.1	217.5	72.5
Transportation & Warehousing	497.3	149.2	49.7
Information & Cultural Industries	711.2	213.4	71.1
Offices	563.9	169.2	56.4
Educational Services	600.0	180.0	60.0
Healthcare & Social Assistance	786.2	235.9	78.6
Arts, Entertainment & Recreation	583.4	175.0	58.3
Accommodation & Food Service	827.8	248.4	82.8
Other Services	563.9	169.2	56.4
ALBERTA			
Wholesale Trade	413.9	124.2	41.4
Retail Trade	500.0	150.0	50.0
Transportation & Warehousing	369.5	110.8	36.9
Information & Cultural Industries	508.4	152.5	50.8
Offices	380.6	114.2	38.1
Educational Services	425.0	127.5	42.5
Healthcare & Social Assistance	616.7	185.0	61.7
Arts, Entertainment & Recreation	463.9	139.2	46.4
Accommodation & Food Service	725.1	217.5	72.5
Other Services	391.7	117.5	39.2

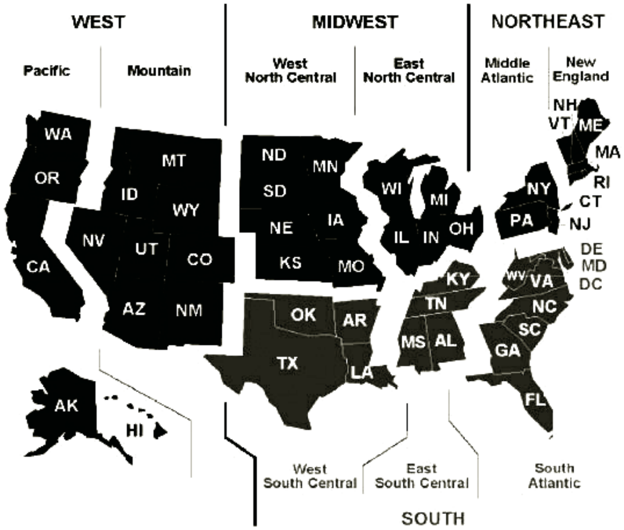
Energy Use Intensity (EUI) Targets, Canadian Commercial Buildings, Provincial Averages, kWh/m²/yr

Derived from Natural Resources Canada, Office of Energy Efficiency, Comprehensive Energy Use Database.
Multiply kWh x 277.7 to get GJ

Commercial Space / Building Type	Site EUI		
	med	70%	90%
BRITISH COLUMBIA & TERRITORIES			
Wholesale Trade	252.8	75.8	25.3
Retail Trade	297.2	89.2	29.7
Transportation & Warehousing	244.5	73.3	24.4
Information & Cultural Industries	241.7	72.5	24.2
Offices	280.6	84.2	28.1
Educational Services	294.5	88.3	29.4
Healthcare & Social Assistance	466.7	140.0	46.7
Arts, Entertainment & Recreation	358.4	107.5	35.8
Accommodation & Food Service	494.5	148.3	49.4
Other Services	308.4	92.5	30.8

Canada, Nonresidential Buildings

EUI targets for *Canadian nonresidential buildings* are given by province for 10 building types in the table **Energy Use Intensity (EUI) Targets Canadian Commercial Buildings, Provincial Averages**. Canadian designers might compare the EUI targets for their ASHRAE zone (or for an equivalent U.S. city in “Target Finder”) with those of the Canadian regional averages. The climatic factor most significant to almost all Canadian climates is heating degree days (HDD). Architecture 2030 suggests using the provincial averages simply because that is how the data is available; with this approach be alert that climate may vary significantly within a province. A similar benchmarking tool is currently being developed by Natural Resources Canada.



U.S. Census Regions
Use for EUI Residential Regional Targets

United States, Residential Buildings

EUI targets for *USA residential buildings* by geographic region for 5 categories of housing are shown in the table **Energy Use Intensity (EUI) Targets, U.S. Residential Buildings, Regional Averages.** This table is based on 2009 data. The EUI targets are based on **U.S. Census Regions**; new government analyses will likely use the more preferable climate zones for categories.

Canada, Residential Buildings

EUI targets for *Canadian residential buildings* by province for four categories of housing are shown in the table **Energy Use Intensity (EUI) Targets, Canadian Residential Buildings, Provincial Averages.** This table is based on 2009 NRC data.

Residential Space / Building Type	Site EUI		
	med	70%	90%
Northeast			
Single-Family Detached	44	13	4
Single-Family Attached	50	15	5
Multi-Family, 2 to 4 units	80	24	8
Multi-Family, 5 or more units	76	23	8
Mobile Homes	77	23	8
Midwest			
Single-Family Detached	46	14	5
Single-Family Attached	50	15	5
Multi-Family, 2 to 4 units	80	24	8
Multi-Family, 5 or more units	66	20	7
Mobile Homes	85	26	9
South			
Single-Family Detached	40	12	4
Single-Family Attached	40	12	4
Multi-Family, 2 to 4 units	51	15	5
Multi-Family, 5 or more units	43	13	4
Mobile Homes	53	16	5
West			
Single-Family Detached	42	12	4
Single-Family Attached	43	13	4
Multi-Family, 2 to 4 units	51	15	5
Multi-Family, 5 or more units	42	13	4
Mobile Homes	66	20	7

Energy Use Intensity (EUI) Targets, U.S. Residential Buildings, Regional Averages, kBtu/ft^2, yr

Derived from Energy Information Administration, Residential Energy Consumption Survey (RECS), conducted in 2009. The survey data is available on the EIA's website at www.eia.doe.gov.

Commercial Space / Building Type	Site EUI med	Site EUI 70%	Site EUI 90%
CANADA, averages			
Single Family, Detached	230.6	69.2	23.1
Single Family, Attached	200.0	60.0	20.0
Apartments	197.2	59.2	19.7
Mobile Homes	327.8	98.3	32.8
NEWFOUNDLAND			
Single Family, Detached	186.1	55.8	18.6
Single Family, Attached	191.7	57.5	19.2
Apartments	152.8	45.8	15.3
Mobile Homes	247.2	74.2	24.7
PRINCE EDWARD ISLAND			
Single Family, Detached	166.7	50.0	16.7
Single Family, Attached	152.8	45.8	15.3
Apartments	141.7	42.5	14.2
Mobile Homes	236.1	70.8	23.6
NOVA SCOTIA			
Single Family, Detached	172.2	51.7	17.2
Single Family, Attached	158.3	47.5	15.8
Apartments	152.8	45.8	15.3
Mobile Homes	261.1	78.3	26.1
NEW BRUNSWICK			
Single Family, Detached	230.6	69.2	23.1
Single Family, Attached	188.9	56.7	18.9
Apartments	166.7	50.0	16.7
Mobile Homes	325.0	97.5	32.5
QUEBEC			
Single Family, Detached	258.4	77.5	25.8
Single Family, Attached	216.7	65.0	21.7
Apartments	202.8	60.8	20.3
Mobile Homes	369.5	110.8	36.9

Commercial Space / Building Type	Site EUI med	Site EUI 70%	Site EUI 90%
ONTARIO			
Single Family, Detached	213.9	64.2	21.4
Single Family, Attached	202.8	60.8	20.3
Apartments	202.8	60.8	20.3
Mobile Homes	294.5	88.3	29.4
MANITOBA			
Single Family, Detached	261.1	78.3	26.1
Single Family, Attached	241.7	72.5	24.2
Apartments	202.8	60.8	20.3
Mobile Homes	366.7	110.0	36.7
SASKATCHEWAN			
Single Family, Detached	272.2	81.7	27.2
Single Family, Attached	225.0	67.5	22.5
Apartments	197.2	59.2	19.7
Mobile Homes	377.8	113.3	37.8
ALBERTA			
Single Family, Detached	319.5	95.8	31.9
Single Family, Attached	213.9	64.2	21.4
Apartments	250.0	75.0	25.0
Mobile Homes	416.7	125.0	41.7
BRITISH COLUMBIA			
Single Family, Detached	172.2	51.7	17.2
Single Family, Attached	161.1	48.3	16.1
Apartments	152.8	45.8	15.3
Mobile Homes	244.5	73.3	24.4
TERRITORIES			
Single Family, Detached	172.2	51.7	17.2
Single Family, Attached	169.5	50.8	16.9
Apartments	133.3	40.0	13.3
Mobile Homes	238.9	71.7	23.9

Energy Use Intensity (EUI) Targets, Canadian Residential Buildings, Provincial Averages, kWh/m²/yr
Derived from Natural Resources Canada, Office of Energy Efficiency, Comprehensive Energy Use Database.

P2 *ANNUAL ENERGY USE* can be estimated to understand the energy savings of passive strategies.

KEY POINTS

- Estimate annual *heating* energy use, accounting for passive solar and equipment efficiency.
- Estimate annual *cooling* energy use, accounting for passive cooling, shading and equipment efficiency.
- Estimate annual energy use for all other *non-space conditioning* uses, accounting for solar hot water and daylighting design.
- If appliances use electric and non-electric fuels, keep track of these separately.

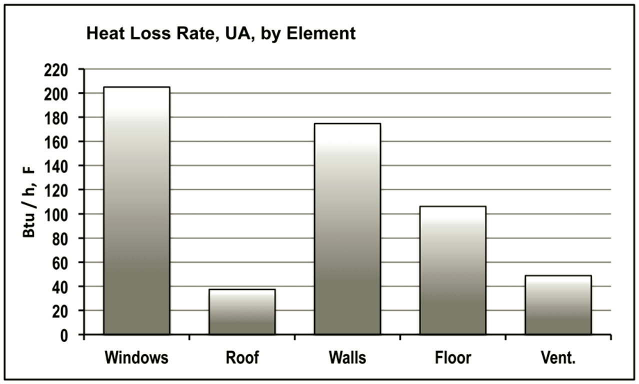
The energy used by a building over a typical year is the basis for estimating operating costs for energy, the emissions for which the building is responsible, and the renewable energy needed to achieve the building's ENERGY TARGETS and EMISSIONS TARGETS. A building's Energy Use Intensity (EUI) is equal to its Energy Demand Intensity (EDI) minus its Energy Production Intensity (EPI):

EUI = EDI – EPI

EDI is a building's annual energy demand (need for energy), due to its design, expressed on a per unit of floor area basis (kBtu/ft^2, yr or kwh/m^2, yr). EPI is the renewable energy produced on-site expressed in the same terms.

For these purposes, *annual energy use*, expressed here as EDI, is the sum of heating and cooling energy use (accounting for the contributing load reductions of passive heating, cooling and ventilation) plus the other energy loads for other non-space conditioning uses, such as hot water, refrigeration and electric lighting (accounting for the load reductions from daylighting and solar hot water).

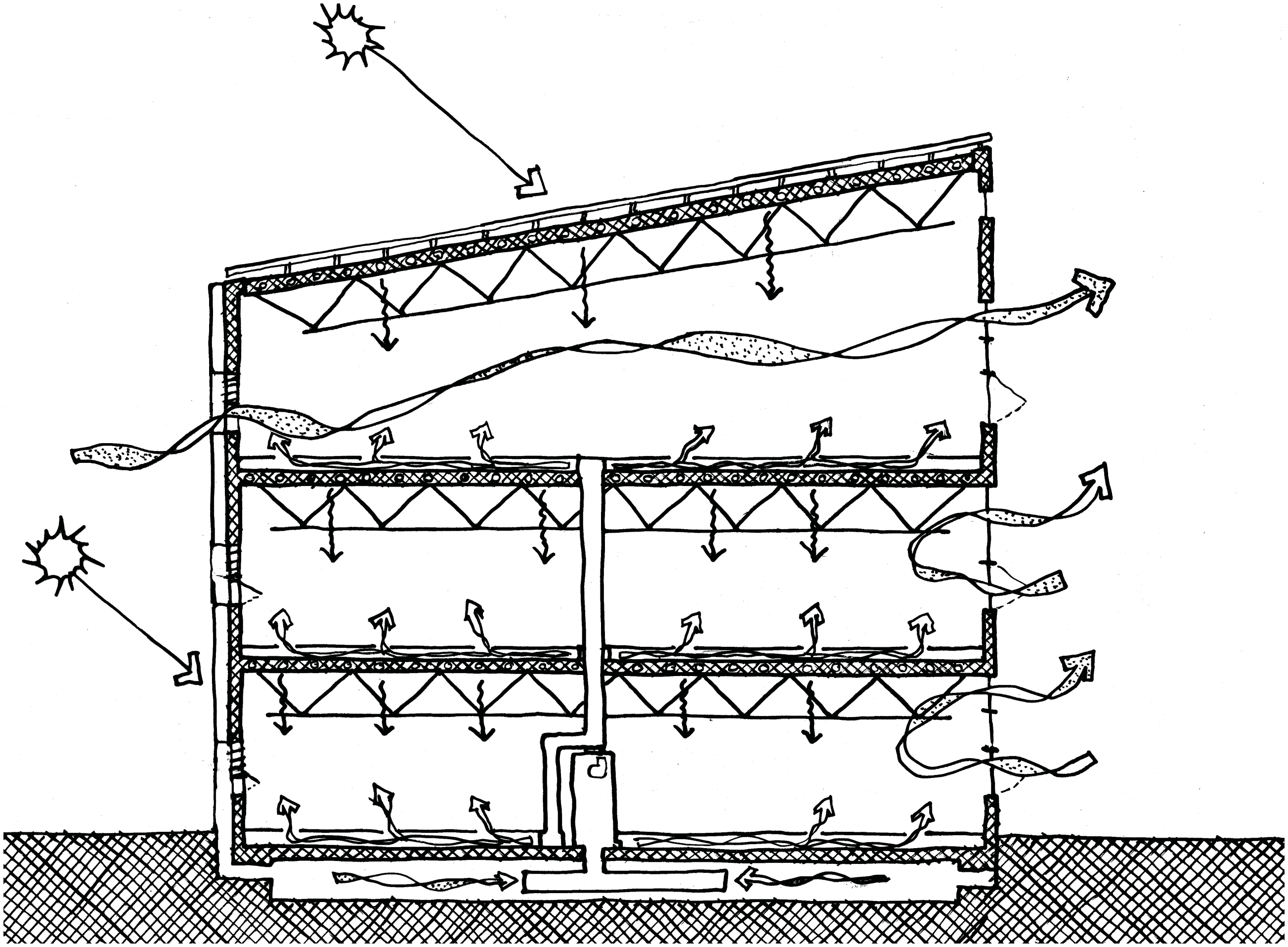
Not long ago, renewable energy supply, such as from wind generators or photovoltaics, was thought to be



Heat Loss Rate Graph
from SWL Tools Spreadsheet

impractical for space heating and cooling needs. The loads were simply too large and the renewable energy system too expensive. Since the second edition of this book, that view has changed radically. First, the cost of on-site renewable supply continues to decrease and the availability of off-site purchased renewable power, such as utility-provided wind energy, continues to increase. Second, and even more significant, research and practice have shown that net-zero energy projects that reduce loads dramatically from past conventional expectations are both practical and feasible.

The **NREL Research Support Facility** at the National Renewable Energy Laboratory in Golden, Colorado, by RNL Architects, uses numerous passive and active strategies to achieve annual energy use low enough to be met with renewable power and create a net-positive energy building (NREL, 2012). The project is a large office building with over 800 workers and a heat-generating data center. The section drawing shows some of



NREL Research Support Facility, National Renewable Energy Laboratory, Golden, Colorado, 2010, RNL, architects

the building's energy features; also see the description and drawing of the thermal labyrinth in MASS ARRANGEMENT. The south facade includes BREATHING WALLS for preheating incoming air, CROSS-VENTILATION ROOMS, EXTERNAL SHADING and NIGHT-COOLED MASS using ceiling and wall mass and the massive crawlspace labyrinth. Annual heating energy use is 8.47; cooling, 0.86; and non-space energy, 22.4 kBtu/ft^2, yr for a total energy use of 31.7 kBtu/ft^2, yr. The PHOTOVOLTAIC ROOF produces 32.9 kBtu/ft^2 annually, a net-positive energy production of 1.2 (BuildingGreen.com, 2011).

This book provides a host of resources and tools for reducing space heating loads with passive solar design, reducing space cooling loads with shading and passive cooling design, reducing electric lighting loads with daylighting design and reducing domestic hot water loads with solar hot water systems. To reach your net-zero energy goal, start with these schematic and preliminary design phase tools. We recommend using the software *Energy Scheming* or a similar tool to help refine your design as soon as you have generated a scheme using the design strategies in *SWL*. Once you have met your design

ANNUAL HEATING & COOLING LOADS (CONVENTIONAL)

City	Floor Area, ft²	Range	Int Temp Low	Int Temp High	# Occ. Hours	UAns loss	UA gain	Internal Gain
Knoxville, TN	1472	Indoor T	65	80	12	317	1101	5888

Bin Temps °F range		Temp, F Bin Ave	Temp Diff, F	UA	Skin Btu/ hr	Internal Btu/ hr	Sensible Gain/Loss	Bin Hr/ Yr	Gain/Loss Btu/ Yr	Cooling Btu/ Yr	Heating Btu/ Yr
95	99	97	17	1101	18712	2944	21656	17	368150	368150	
90	94	92	12	1101	13208	2944	16152	97	1566783	1566783	
85	89	87	7	1101	7705	2944	10649	304	3237266	3237266	
80	84	82	2	1101	2201	2944	5145	522	2685899	2685899	
75	79	77	0	1101	0	2944	2944	721	2122624	2122624	
70	74	72	0	1101	0	2944	2944	1086	3197184	3197184	
65	69	67	0	1101	0	2944	2944	985	2899840	2899840	
60	64	62	-3	317	-950	2944	1994	771	1537249	1537249	
55	59	57	-8	317	-2534	2944	410	720	295369	295369	
50	54	52	-13	317	-4117	2944	-1173	724	-849519		-849519
45	49	47	-18	317	-5701	2944	-2757	680	-1874741		-1874741
40	44	42	-23	317	-7285	2944	-4341	638	-2769287		-2769287
35	39	37	-28	317	-8868	2944	-5924	579	-3430099		-3430099
30	34	32	-33	317	-10452	2944	-7508	436	-3273393		-3273393
25	29	27	-38	317	-12035	2944	-9091	247	-2245572		-2245572
20	24	22	-43	317	-13619	2944	-10675	126	-1345049		-1345049
15	19	17	-48	317	-15203	2944	-12259	63	-772291		-772291
10	14	12	-53	317	-16786	2944	-13842	26	-359897		-359897
5	9	7	-58	317	-18370	2944	-15426	10	-154258		-154258
0	4	2	-63	317	-19953	2944	-17009	4	-68038		-68038
-5	1	-1	-66	317	-20904	2944	-17960	2	-35919		-35919
						Sensible Conventional Totals			**35088428**	**17910366**	**17178062**
							kBtu/ ft²/ yr		23.8	12.2	11.7

Annual Heating and Cooling Loads Before Savings from Passive Design from SWL Tools Spreadsheet

criteria using the *SWL Tools* spreadsheet, and even better, achieved good performance on the four analysis days in *Energy Scheming,* you are ready to estimate the building's annual energy use. Note that *Energy Scheming* does not calculate annual energy use, but the *SWL Tools* spreadsheet does, or you can use numerous other building energy analysis tools.

Using the "degree days method" you can estimate the annual heating energy use with tools provided in *SWL*, accounting for the effect on the building's Solar Savings Fraction (SSF). Estimating annual cooling energy is more complicated because the cooling load comes from both conduction through the envelope (similar to heating) and from the solar gains through windows and on walls and roofs, which are more dynamic. Annual cooling load calculations require long hand calculations, a spreadsheet tool, or a computer model. In *SWL Electronic,* you can use the *SWL Tools* spreadsheet for relatively quick analysis.

Annual energy use can be estimated in two parts: 1) Heating energy, and 2) Cooling energy.

PART ONE: Estimate Annual Heating Energy.

Although there are several steps involved, the tools in *SWL* are designed to make the process as simple as possible on the front end of the design process and to avoid the need for detailed engineering knowledge during preliminary design. Some of the results are shown in the excerpt **Annual Heating and Cooling Loads Before Savings from Passive Design**.

STEP 1: Find the rate of heat loss from techniques in **TOTAL HEAT LOSSES.** The heat loss rate is the sum of skin losses [SKIN HEAT FLOW] and losses from bringing

ANNUAL HEATING ENERGY with PASSIVE SOLAR SAVINGS *Q = (1-SSF) x Q heat / Equip Eff.*

							Ann. Space Heating Energy		
Q heat conventional kBtu / yr	SSF	Fan w/Solar kWh / yr	Q heat w/Solar kBtu / yr	Q total w/Solar kBtu/ yr	% Savings Passive	Seasonal Heat EFF. or COP	Site Heating kBtu / yr	Site EUI heat kBtu/ft^2/yr	Equiv. Electric kWh / yr
17178	63%	49	6356	6523	63	2.4	3176	**2.2**	931

Include Latent?	Humidification Load kBtu/ yr
Yes	361

ANNUAL COOLING ENERGY with PASSIVE COOLING SAVINGS *Q = Q cool / Equip Eff.*

							Ann. Space Cooling Energy		
Q cool conventional kBtu / yr	Passive Cooling Strategy (select below)	Q cool w/Passive kBtu/yr	% Savings Passive	Fan Energy, kWh / yr	Seasonal Cool EFF. or COP	Site Cooling kBtu / yr	Site EUI cool kBtu/ft^2/yr	Equiv. Electric kWh / yr
17910	Natural Vent + Ceiling Fans	5172	71	342	4.3	3530	**2.4**	1034

Include Latent?	Dehumidification Load kBtu/ yr			
Yes	1160	Total Space Conditioning Energy	**1965**	kWh/ yr

Annual Space Heating and Cooling Energy with Savings from Passive Design
from SWL Tools Spreadsheet

in outdoor air [VENTILATION OR INFILTRATION LOSSES], see **Heat Loss Rate Graph** (previous spread). For passive solar buildings keep track of losses from the south facade separately. Sum the total of non-south losses to obtain "UA non-south," written as $UA_{ns.}$ For buildings without substantial passive solar design, include losses from *all* orientations. These analysis techniques provide instructions for hand calculation methods. Alternatively, the *SWL Tools* spreadsheet is provided in the *SWL Electronic* to help with these calculations. See the "Quick Heat Loss" tab.

STEP 2: Redesign to meet the building conservation criteria. Find conservation criteria for passive solar buildings in TOTAL HEAT LOSSES. If your heat loss rate, in Btu/DD, ft^2, is greater than the criteria, redesign to reduce losses until it meets the criteria. Otherwise, estimates for the solar savings fraction in the next step will not be accurate. The heart of net-zero design is always conservation.

STEP 3: Estimate the solar savings fraction (SSF). Find the SSF from passive solar heating with tools in SOLAR APERTURES. Adjust the projected SSF% if needed for the use of MOVABLE INSULATION. The *SWL Tools* spreadsheet helps with modifying the projected SSF based on using better windows, a better skin heat loss rate than the criteria call for, or the use of MOVABLE INSULATION. See the "Passive Solar" worksheet.

***STEP 4: Estimate the building's balance point temperature with the technique in* BALANCE POINT TEMPERATURE.** The "balance point" for a building is defined as the outdoor temperature at which the heat gains balance the heat losses to maintain a desired indoor temperature. Below the balance point, heating is required. Once the rates of heat loss and heat gain are known, the balance point temperature is easily determined from the graph. To quickly estimate the need for winter heating, you need to find the winter day balance point. The BALANCE POINT analysis technique provides instructions for hand calculation. Alternatively, the *SWL Tools* spreadsheet helps with these calculations. See the "Bal Pt + Heating Energy" worksheet.

STEP 5: Select the annual heating degree days for the building's climate, using the building's balance point temperature. If the winter balance point for your building falls between the published values, you may interpolate. Heating degree days for different base temperatures can be found for the United States in NCDC (2002) and for

Canada in Environment Canada (2012). A copy of the NCDC publication is included on *SWL Electronic*. Degree days can be calculated for any base temperature for airports in most of the world from online software for the last three years or for longer periods with purchased software (BizEE, 2012).

STEP 6: Estimate the annual heating load in Btu/yr. Multiply the building's heat loss rate, UA_{ns}, (step 1) by 24 hours times the factor (1 minus SSF) (step 3) times the heating degree days (step 5) to get the annual heating load in Btu/yr:

$$Q_h = UA_{ns} \times 24h \times (1 - SSF) \times HDD_b$$

Where:

Q_h = annual heating load, Btu/yr

UA_{ns} = heat loss rate, Btu/h, F

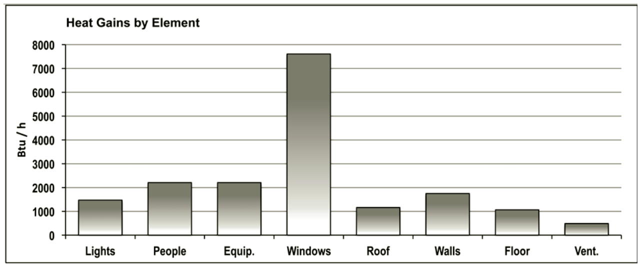
SSF = solar saving fraction expressed as 0-1.

HDD_b = heating degree days at the balance point

Alternatively, the *SWL Tools* spreadsheet is provided in *SWL Electronic* to help with these calculations. See the "Bal Pt + Heating Energy" worksheet and the excerpt **Annual Space Heating and Cooling Energy with Savings from Passive Design** (previous page). If the design is further along, and thus more detail is known about it, you may also opt for the more detailed method in *SWL Tools* for estimating heat losses as found on the "Detail Heat Loss & Gain" worksheet.

STEP 7: Convert the annual heating load to site energy based on HVAC equipment efficiency. If any heating load remains after passive solar heating is subtracted in step 6, these must be met by a back-up mechanical heating system.

The site energy required to meet the heating load can be *more* or *less* than the heating load called for by the building design, based on the efficiency of the equipment chosen. For example, an Energy Star® air-air heat pump in heating mode has a seasonal efficiency of 2.4, while an Energy Star® natural gas furnace has a rating of 0.9. Equipment efficiency values greater than 1.0 will require less energy than the estimated load; efficiencies less than 1.0 require more energy than the estimated load.



Heat Gains by Element graph
from SWL Tools Spreadsheet

To estimate the site energy required, divide the annual heating load in Btu/yr from step 6 by the equipment efficiency. Resulting units are also in Btu/yr.

$$Q_{h\ site} = Q_h \div \text{Equipment Efficiency}$$

Efficiencies depend on the specific equipment type specified. For heating equipment, seasonal efficiency is measured by annual fuel utilization efficiency (AFUE) for combustion fuel equipment, such as a gas furnace. Units are percentage (%) and represent the ratio of Btus of energy input to Btus of heating energy output. For heat pumps, use a percentage efficiency equivalent derived from the heating season performance factor (HSPF). HSPF has units of Btuh/W. Divide by 3.41 to get an efficiency in watts of energy input to Watts of heating energy output (W/W), which can be expressed as a percentage (%). If no seasonal rating is available, use the coefficient of performance (COP) rating for the equipment. Equipment efficiency values are listed on manufacturer's data sheets. A general list is given in SYMPATHETIC HVAC and in the *SWL Tools* spreadsheet.

If the method used also calculates fan energy, such as when using an all-air distribution system, remember that the equipment efficiency factors do not apply to fans. For conventional residential furnaces with air distribution, fan energy is roughly 2.5–3% of the heating load. A water-based distribution system will use less energy.

Alternatively, the *SWL Tools* spreadsheet is provided to help with these calculations. See the "Equip Eff" worksheet for a list of seasonal heating and cooling efficiencies of different HVAC options. When selected, the

equipment efficiency value is input on the "Annual H + C Energy" worksheet.

STEP 8: Convert to units of Energy Demand Intensity (EDI). Divide annual heating energy by the building floor area:

$$EDI_h = Btu/yr \div \text{Floor Area, } ft^2$$
$$= Btu/ft^2, yr$$

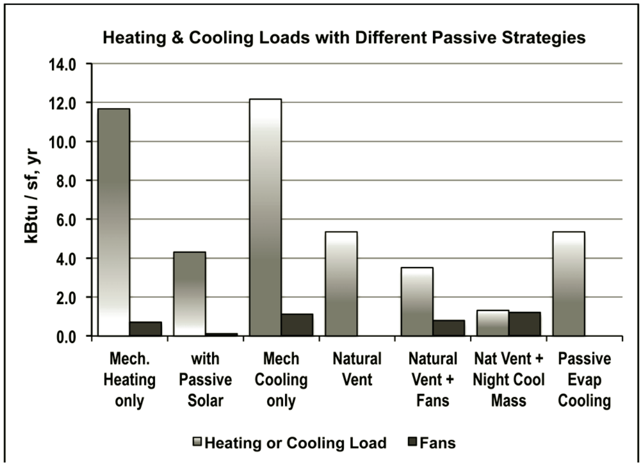
PART TWO: Estimate Annual Cooling Energy.

The heat gain rate includes many more elements than the number needed to estimate heat loss. It is the sum of gains through building skin (see **Heat Gains by Element graph**), from bringing in outdoor air, from solar gains through the glazing and from internal gains generated by people, electric lights and equipment. These are explained individually in the individual analysis techniques of:

- SKIN HEAT FLOW
- VENTILATION OR INFILTRATION GAINS
- WINDOW SOLAR GAIN
- OCCUPANCY HEAT GAIN
- ELECTRIC LIGHTING HEAT GAIN
- EQUIPMENT HEAT GAIN

The "Quick Heat Gain" method in TOTAL HEAT GAINS AND LOSSES facilitates estimating an *hourly* rate of heat gain for an average hot day or a peak design day in summer, for purposes of passive cooling. It also helps estimate *daily* heat gains that need to be stored during thermally closed periods for NIGHT-COOLED MASS. Unfortunately, these quick methods do not work well for estimating *annual* cooling energy loads.

Accurately estimating annual cooling energy is more complex than estimating annual heating energy. Designers have two basic options, a simplified spreadsheet method or a relatively sophisticated computer energy analysis method. A simplified spreadsheet method that integrates well with the other tools in *SWL* is included in ⌿ *SWL Electronic*. In the *SWL Tools* spreadsheet, see the "Detail Heat Loss & Gain" and "Annual H + C Energy" worksheets and the excerpt **Heating and Cooling Loads with Passive Strategies**.



Heating & Cooling Loads with Passive Strategies
from SWL Tools Spreadsheet

Here's how the method in the* SWL Tools *works. If this seems too technical, then skip this part. The calculation for annual heating energy can use the simple degree days method, but the annual cooling energy method on the spreadsheet uses ASHRAE's *bin method*. In the bin method, hourly temperatures for a climate location are divided into bins of 4° F (2.2° C) and the annual hours falling into each bin are tabulated. This data is available from ASHRAE for most cities (NCDC, 2000). The building UA is calculated separately for summer and winter. The summer or winter UA is then multiplied by the temperature difference for the bin times the hours for that bin. The temperature difference for the bin is the difference between the interior temperature set-point for the season and the average bin temperature.

The effect of solar gains is especially difficult to calculate accurately with simple methods. The spreadsheet uses solar heat gain factors (SHGF) for glazing along with shading coefficients (SC) of the shading design to calculate solar window heat gains. While the "Quick Heat Gain" method assumes all windows are equally and fully shaded, this method distinguishes windows by orientation and shading effectiveness. The sun also has an effect on heat gains through the walls and roof in summer. *SWL Tools* spreadsheet uses design equivalent temperature

COOLING LOADS WITH PASSIVE COOLING

	Outdoor Design Temp for Passive Strategy, F			
	80	84	90	100
	Cross or Stack Natural Vent	Cross or Stack Natural Vent + Ceiling Fans	Natural Vent + Night–Cooled Mass	Passive Evaporative Cooling
	368150	368150	368150	0
	1566783	1566783	1566783	0
	3237266	3237266	0	0
	2685899	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0	0	0
Loads w/Passive	**7858099**	**5172200**	**1934934**	**0**
kBtu/ ft^2/ yr	5.3	3.5	1.3	0.0
% Reduction	**56**	**71**	**89**	**100**

Cooling Loads with Passive Cooling
from SWL Tools spreadsheet

difference (DETD) values, which vary by orientation and construction type. This method, which combines a method from *Mechanical and Electrical Equipment for Buildings* (Grondzik et al, 2010) with the bin method from ASHRAE (2009), was adapted and expanded from a heat loss and gain spreadsheet originally developed by Professor Richard Kelso, P.E., in classes at the University of Tennessee. It has been substantially expanded here for passive strategies. See the excerpt in **Cooling Loads with Passive Cooling**.

Heat gains for lights, people and equipment are taken from the "Quick Heat Gain" method in TOTAL HEAT GAINS. In addition to the envelope heat gains used in the quick method, the annual method adds slab-on-grade floor gains (if applicable) and allows for credits taken for the cooling effect of ground contact [EARTH EDGES] and ventilation by EARTH–AIR HEAT EXCHANGERS (earth tubes). To be more conservative than the "Quick Heat Gain" method (and in line with engineering practice), the annual cooling method includes both infiltration gains *and* ventilation gains. Once the basic cooling loads are calculated, the *SWL Tools* spreadsheet also allows the user to account for the effects of various passive cooling strategies to reduce the load. The method accounts for the fan energy used under various design strategies.

The following instructions assume that you are using the* SWL Tools *spreadsheet (see "Annual H + C Energy" tab). If you use a different method to estimate annual space cooling energy, the general approach is the same:

1) Estimate annual cooling loads.

2) Estimate load reductions from passive cooling systems.

3) Estimate fan energy for the combination of systems chosen.

4) Find the total annual cooling load by subtracting passive cooling reductions from the total cooling loads and adding fan energy.

5) Convert the net loads to site energy based on the cooling equipment efficiency.

These steps are expanded below. Detailed instructions are found in the *SWL Tools* spreadsheet.

STEP 1: Estimate annual cooling loads. Follow the instructions for user inputs in the section "Annual Heating and Cooling Loads (conventional)" on the "Annual H + C Energy" worksheet. User inputs are:

+ Design temperatures
+ Conditioned volume
+ Component areas and *R*-values
+ Window solar heat gain factors (SHGF)
+ Window shading coefficients (SC)
+ Wall and roof cooling design load equivalent temperature differences (DETD)
+ Wall and roof shading coefficients
+ Walls below grade specifications
+ Slab-on-grade specifications
+ Ventilation loss and gain values
+ Infiltration loss and gain values

- + Passive cooling rates from envelope cooling strategies for EARTH-AIR HEAT EXCHANGERS and ground contact from EARTH EDGES.
- *Review the* SWL Tools *spreadsheet's calculated outputs for "Skin Gains" and "Total Internal Gains," in Btu/h*. These values are used as inputs to the "Annual Heating & Cooling Energy" worksheet.
- *On the "Annual Heating & Cooling Energy" worksheet, follow the instructions for user inputs.* User inputs are binned temperature data and the hours for your climate for each bin.
- *Review the* SWL Tools *spreadsheet's calculated outputs for "Conventional Totals."* This result, in Btu/yr, is the cooling load before passive cooling strategies are applied to reduce the load.

STEP 2: Estimate load reductions from passive cooling systems.

- *Follow the instructions for user inputs in the section "Cooling Loads with Passive Cooling,"* on the *"Detailed Heat Loss & Gain"* worksheet. User inputs are outdoor design temperatures for each different passive strategy.
- *Review the* SWL Tools *spreadsheet's calculated outputs for "Passive Loads" and "% Reduction."* The results for cooling load when using each passive option are tabulated, in Btu/yr, as is the percentage savings over conventional cooling.

STEP 3: Estimate fan energy for the combination of systems chosen. Users can input fan efficiency for different types of fans, in W/CFM, or leave the default values. The spreadsheet calculates fan energy for conventional and passive strategies.

STEP 4: Find total annual cooling load. Follow the instructions for user inputs in the section, Annual Cooling Energy with Passive Cooling on the "Annual H + C Energy" worksheet. Users select the primary passive cooling strategy from a menu, and *SWL Tools* then selects both back-up cooling load and fan energy values previously calculated.

STEP 5: Convert the annual cooling load to site energy based on HVAC equipment efficiency. If any cooling load remains after passive cooling is subtracted, these must be met by a back-up mechanical cooling system.

The site energy required to meet the cooling load will typically be *less* than the cooling load generated by the building design. For example, an Energy Star® air–air heat pump in cooling mode has a seasonal efficiency of 4.3, and an open-loop ground-source heat pump has a season efficiency up to 5.8. Equipment efficiency values greater than 1.0 will make actual units of site energy required less than the estimated load; efficiencies less than 1.0 require greater energy input to the system.

To estimate the site energy required, divide the annual cooling load in Btu/yr from step 4 by the equipment efficiency. Resulting units are also Btu/yr.

$$\mathbf{Q_{c\ site} = Q_c \div \text{Equipment Efficiency}}$$

The spreadsheet calculates this value and divides by 1000, resulting in "Site Cooling, kBtu/yr."

Efficiencies depend on the equipment type specified. Central A/C systems are rated by seasonal energy efficiency ratio (SEER) in Btuh/W, yr. Heat pumps are rated by energy efficiency ratio (EER) in Btuh/W. The "Equipment Efficiency" worksheet lists equivalent % efficiencies for input. The units are converted to W/W. If no seasonal rating is available, use the coefficient of performance (COP) rating for the equipment. These ratings express on a seasonal basis the cooling energy produced per unit of electrical energy input to the equipment. Equipment efficiency values are listed on manufacturer's data sheets; a general list is given in SYMPATHETIC HVAC. Equipment efficiency factors do not apply to fans.

STEP 6: Convert to units of Energy Demand Intensity (EDI). Divide annual cooling energy by the floor area:

$$\mathbf{EDI_c = Btu/yr \div \text{Floor Area, } ft^2}$$

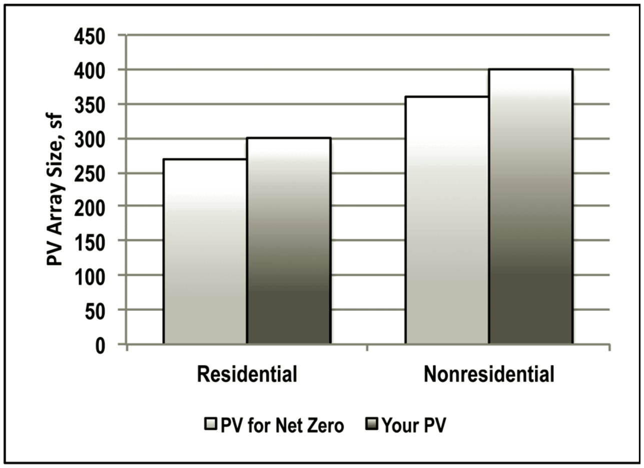
$$\mathbf{= Btu/ft^2, yr}$$

EVALUATION

P3 Buildings with a *NET-ZERO ENERGY BALANCE* produce annually renewable energy equal to the building's annual loads not met by passive design.

KEY POINTS

- EUI equals site energy demand (EDI) minus on-site renewable energy production (EPI). A net-zero building has a net site EUI = 0.
- Site energy demand is the sum of space heating, space cooling and non-space energy.
- All forms of energy are converted to electric units to estimate offsets required by PV.
- Design response to the net-zero calculation may be addressed in a variety of ways.

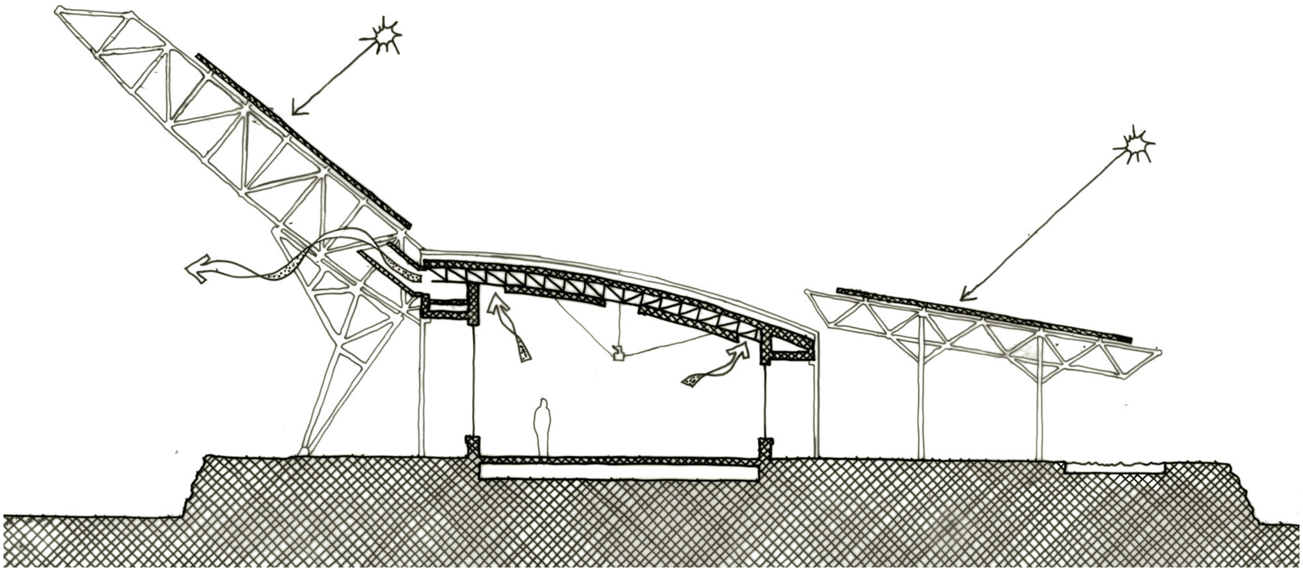


PV Sizing for Net Zero
from SWL Tools Spreadsheet

There are many current variations on the definition of a net-zero energy building (NZEB) (Crawley et al, 2009). Of the following definitions (Torcellini et al, 2006), the approach in *SWL* is based on the Site NZEB definition.

- *Site Net-Zero Energy Building:* A Site NZEB produces as much energy as it uses in a year, when accounted for at the site. A more radical version of this definition allows only for renewable energy generated within the building footprint.
- *Source Net-Zero Energy Building:* A Source NZEB produces as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a building's total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion factors. In *SWL*, source energy is accounted for in EMISSIONS TARGETS and CARBON NEUTRAL BUILDINGS.
- *Cost Net-Zero Energy Building:* In a Cost NZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is equal to the amount the owner pays the utility for the energy services and energy used over the year.
- *Emissions Net-Zero Energy Building:* An Emissions NZEB produces as much emissions-free renewable energy as it uses from emissions-producing energy sources.

Contrary to common perception, NZEBs are not rare. Eike Musall, at Bergische Universität Wuppertal, has compiled an interactive map, "Net-Zero Buildings Worldwide," documenting a growing list of over 300 NZEBs (Musall, 2012). The **Hawaii Gateway Energy Center** in Kailua-Kona uses energy efficient design strategies and a 20 kiloWatt photovoltaic system to achieve a net-zero energy building that also exports electricity, making it actually a *net-positive energy building* (AIA, 2009). The design employs full daylighting during occupied hours, a passive solar assisted stack-ventilation system and a cooling system that pumps 45° F (7° C) seawater through coils to cool incoming air.



Hawaii Gateway Energy Center, Kailua-Kona, Hawaii, 2005, Ferraro Choi & Assoc.

In 2007, metering and utility bills showed on-site renewable energy produced (EPI) was 31.1 kBtu/ft²/yr, while 27.64 was consumed (EDI), yielding a net energy export of 3.46 kBtu/ft²/yr. The building profited $0.45/ft² from sales of electricity to the utility.

The Site Energy Balance Equation

The term EUI may refer to many things. Here, unless otherwise specified, EUI means net site EUI. A building's net site Energy Use Intensity (EUI) is equal to its Energy Demand Intensity (EDI) minus its Energy Production Intensity:

EUI = EDI – EPI

Once the total energy needs of the building are known, on-site renewable energy systems can be sized to offset the demand. For a net zero building (EUI = 0):

EUI = 0 = total site Energy Demand Intensity (EDI) – on-site renewable Energy Production Intensity (EPI)

Total site EDI is the sum of energy for space heating and space cooling, plus energy for all other uses, such as appliances, cooking and hot water as estimated in ANNUAL ENERGY USE (and after accounting for systems efficiencies). On-site renewable energy production can come from a variety of sources, such as photovoltaics or wind generators (if there are sufficient resources). On-site renewable energy may also be produced from off-site renewable resources, such as wood pellets or biofuels.

Estimate the building's Energy Production Intensity (EPI). The *SWL Tools* spreadsheet is provided in ⌁ *SWL Electronic* to help with these calculations. See the "Net-Zero Energy Balance" worksheet.

SITE ENERGY — RESIDENTIAL						
	Space Conditioning	Non-Space Conditioning Energy			Total Site Energy Demand	
		Electric	Other Fuel Used			
	kWh/ day	kWh/ day	Btu/ yr	kWh/ yr equiv	kWh/ day ave	
	5.38	11	0	0	**16.4**	use to size PV
kWh/ yr	1965	4015	0	0	5980	**kWh/ yr**

PV SIZE — RESIDENTIAL							
	Yield from PV		Energy Demand	PV Array Size Required, m^2 at 12% Cell Eff.	PV Array Size for Net Zero, ft^2	YOUR PV Array Size, ft^2	Fraction of Load
City	Wh/ m^2/ day	Wh/ ft^2/ day	kWh/ day ave				
Knox TN	***500***	46.5	16.4	***27***	**291**	250	0.86
			Your % Cell Eff.	PV Array Size Required, m^2 at Your Cell Eff.			Net Zero = 1.0
			12	**27**			

Net-Zero and PV Sizing, excerpt from SWL Tools spreadsheet

STEP 1. Estimate the annual space heating energy and annual space cooling energy using the methods in ANNUAL ENERGY USE. Make sure to account for passive heating and cooling savings and the efficiency of the chosen HVAC systems when estimating space heating and cooling loads for the building. The method yields results in kBtu/yr. Add heating and cooling energy to get total space conditioning energy.

STEP 2. Convert total space conditioning energy to units for sizing PV. First multiply kBtu/yr by 1000, divide by 3412 Btu/kWh, and divide by 365 days/yr to get kWh/day of total space conditioning energy electrical equivalent:

kBtu/yr × 1000 ÷ 3412 ÷ 365 = kWh/day

The tools in PHOTOVOLTAIC ROOFS AND WALLS use different input values for residential and nonresidential PVs. The units of kWh/day may be used in the chart for sizing residential PVs. To get units for sizing *nonresidential* PVs:

kWh/day × 1000 W/kW ÷ Floor Area, ft^2 = Wh/ft^2,day

STEP 3: Estimate Non-Space Energy Use. This energy use category is large and growing in most buildings today as plug loads from appliances and electronics grow. As the building becomes more thermally in balance due to good passive energy design, its loads for heating, cooling and ventilation shrink or, in some cases, are eliminated altogether. Minimizing non-space energy is one of the keys to achieving a cost-effective net-zero design.

***Estimate the average daylight factor for the building using* DAYLIGHT APERTURES.** Daylighting reduces the need for electric lights; thus knowing the daylight factor helps in estimating electric energy use in the next step and estimating heat gains from electric lights. Daylight will have a large effect on nonresidential energy use and a smaller effect on residential energy use.

***Estimate the building's electric and nonelectric loads using the quick technique in* ELECTRIC LOADS.** Choose between the nonresidential and residential techniques. Be aware that clothes dryers take about 12% of residential energy and can be completely replaced with the sun. All net-zero buildings can heat domestic water directly with the sun because it is much more efficient and cost-effective than heating with other renewable sources, such as photovoltaics. Make sure to size collectors with the tools in SOLAR HOT WATER. Also select a load for lighting based on the building's estimated daylight factor [see DESIGN DAYLIGHT FACTOR, if needed]. Make sure to choose (and later specify) “best” efficiency for the equipment, unless you have chosen otherwise.

For residential uses, choose the load profile for “Best Electric Technology,” because you are designing for a low energy goal. If you are using solar hot water (highly recommended), reduce the value on the graph for hot water

Appliance	Gas Multiplier
Clothes dryers (no difference)	**1.0**
Cooking	**1.9**
Water heating	
electric, tankless	**0.9**
gas, storage tank	**1.5**
gas, tankless	**1.1**
solar hot water	**0.5–0.9**

Multipliers for Gas Appliances

by 50–100%, depending on your system and location.

For both residential and nonresidential uses, some appliances may use a fuel other than electricity, such as a natural gas stove, clothes dryer or hot water heater. In this case, *sum the loads for electric and nonelectric uses separately*. This will be important later when calculating the emissions impact of the building. Today, it is still generally more cost-effective to use natural gas when possible than to use electricity generated by PVs. However, electricity from renewable sources will have zero emissions, natural gas, some emissions and fossil-fuel generated electricity, very high rates of emissions.

Adjust the nonelectric portion of the load. Because gas appliances are less efficient at the site (not the source) than electric appliances, the values for their energy use have to be modified. Multiply the non-electric load (from the second part of this step) by the value in the table **Multipliers for Gas Appliances**. The multiplier is an efficiency factor based on the difference, if any, between the on-site energy efficiency of an electric appliance versus doing the same job with gas.

Sum the total non-space energy load. Finally, add the electric and non-electric values, in kWh/day or Wh/ft^2,day to get the total non-space equivalent electric load.

Convert to units of EDI. If using the residential path, non-space conditioning energy demand intensity, EDI_{ns} is found:

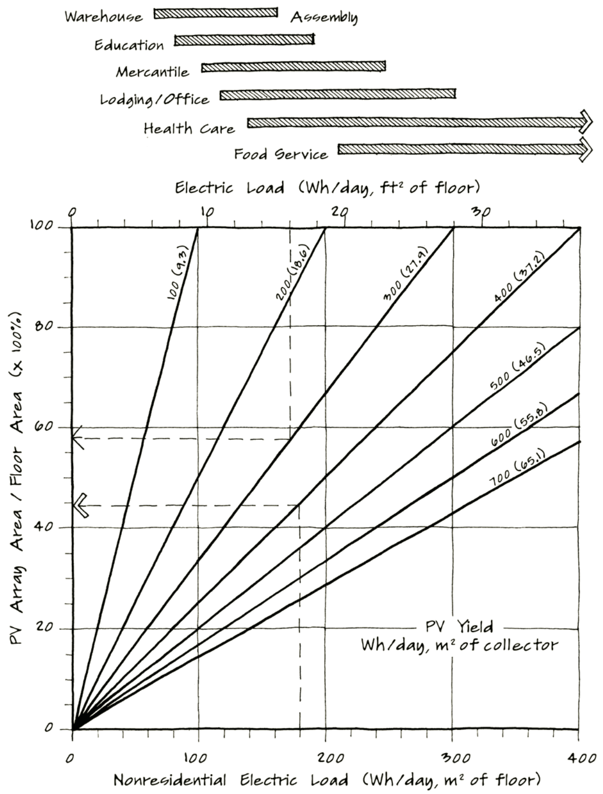
$$\mathbf{EDI_{ns} = kWh/day \times 3.412 \times 365 \div Floor\ Area,\ ft^2 = kBtu/ft^2,\ yr}$$

If using the nonresidential path:

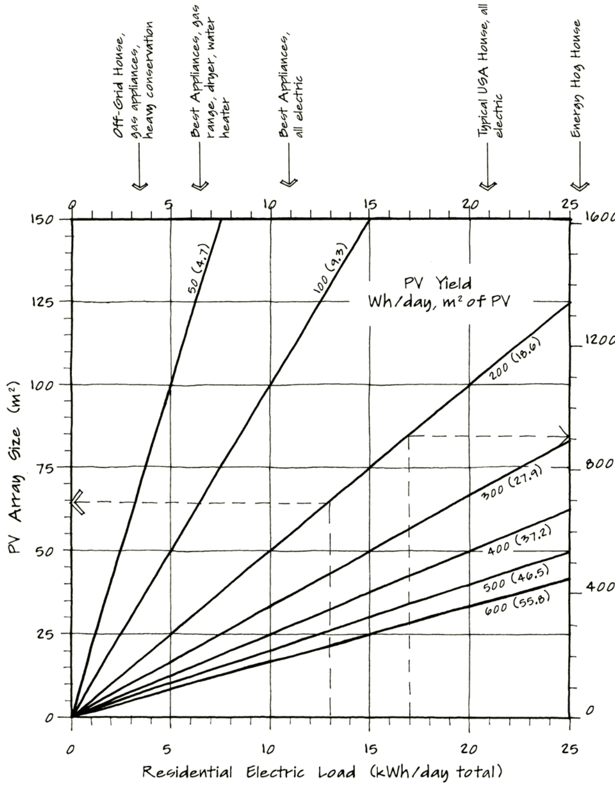
$$\mathbf{EDI_{ns} = Wh/ft^2/day \times 3.412 \div 1000 \times 365 = kBtu/ft^2,\ yr}$$

This value will be used later in step 7.

STEP 4: Add component loads to get total site daily energy demand. Add space conditioning energy (step 2) to non-space energy (step 3) to get the total load. Make sure the units are the same (kWh/day or Wh/ft^2,day). Note that this load is an electric energy equivalent, even though some of the fuel may be another source, such as natural gas.



Nonresidential PV Sizing, 12% efficiency



Residential PV Sizing, 12% efficiency

Sizing Nomographs from Photovoltaic Walls & Roofs Strategy

STEP 5: Estimate required PV array size for net zero using tools in **PHOTOVOLTAIC WALLS AND ROOFS.** Use the daily energy demand (step 3) as input to the sizing graphs in PHOTOVOLTAIC WALLS AND ROOFS. The charts yield "PV Array Size" in ft² (m²) for *residential* buildings, and in "PV Array Area/Floor Area" for *nonresidential* buildings. To find *nonresidential PV array size*, multiply the floor area (ft² or m²) by the percentage output from the graph. Make sure to account for orientation and tilt effects, and for cell efficiencies if different than the assumptions in the graphs.

STEP 6: Determine your PV array size and check for the net-zero target. The PV array size required (step 5) is the area needed to achieve the site net-zero energy target. On an annual basis, the building will then generate as much energy as it uses.

Decide where PVs can be located and if you have enough room on the building or on-site to locate the required area. See discussion in PHOTOVOLTAIC WALLS AND ROOFS. If the PV area required seems too large, consider redesigning to reduce loads further (lower EDI), almost always a less expensive strategy than investing in larger renewable energy production systems (higher EPI).

Each building situation is different and the economics of renewable energy are changing rapidly. You may choose to address meeting the net-zero energy goal in one of the following ways:

- Size PVs for a fraction of the load now but plan for later expansion as PV system prices drop.
- Size PVs to meet the net-zero goal now.
- Size PVs larger than required by the net-zero goal to make the building a net-positive energy building that exports energy for sale to the utility.

STEP 7: Estimate the building's Energy Production Intensity (EPI). Add together the Energy Demand Intensity for cooling (EDI_c) and the EDI for heating (EDI_h), which are calculated in ANNUAL ENERGY USE, with the EDI for non-space energy (EDI_{ns}) from step 3 to get the total site Energy Demand Intensity (EDI) (all units are in kBtu/ft^2, yr):

$$\mathbf{EDI = EDI_c + EDI_h + EDI_{ns}}$$

Multiply this total EDI by the ratio of the project's on-site PV area (step 6) to the required PV area for net zero (step 5) to get the project's Energy Production Intensity (EPI).

$$\mathbf{EPI = EDI \times (PV\ area \div PV\ area\ for\ net\ zero)}$$

For a net-zero building, EDI = EPI.

EVALUATION

P4 Estimate the building's *ENERGY USE INTENSITY (EUI)* to compare its energy use to the energy target.

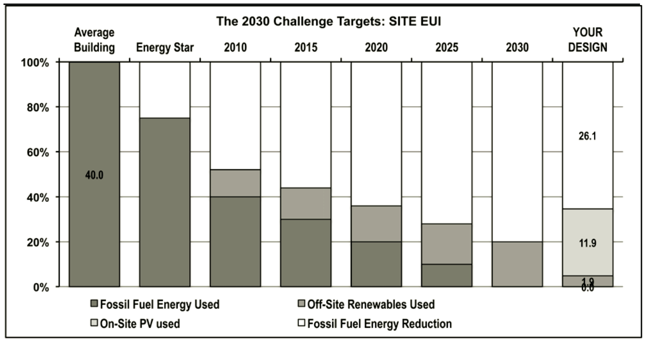
Key Points

- Fossil fuel reduction targets cannot be met with purchased renewables alone.
- A 2030 carbon-neutral target requires the use of renewable energy.
- A site NZEB target can only be met using on-site renewables to meet 100% of the annual load.

To establish a performance standard, designers need a way to compare the energy use of one building to another building of a similar occupancy type and climate location. Energy Use Intensity (EUI) describes a building's net annual energy use relative to its size on a per unit area basis. It is used as an energy performance benchmark, as outlined in ENERGY TARGETS and, unless otherwise stated, describes the building's energy use after accounting for on-site and off-site renewable energy.

Its units are kBtu/ft^2, yr, or thousands of Btus per square foot of conditioned floor area per year. Metric units are kWh/m^2, yr or MJ/m^2, yr. There are several ways to use the EUI measurement for different purposes, such as a space heating EUI, a space cooling EUI, or a total building energy EUI. The EUI can also be estimated for site energy or for source energy, which accounts for energy production and transmission inefficiencies. The energy targets in *SWL* and those used by Architecture 2030 are total building net energy site EUIs. *SWL* accounts for the source energy multiplier in EMISSIONS TARGETS and CARBON-NEUTRAL BUILDINGS.

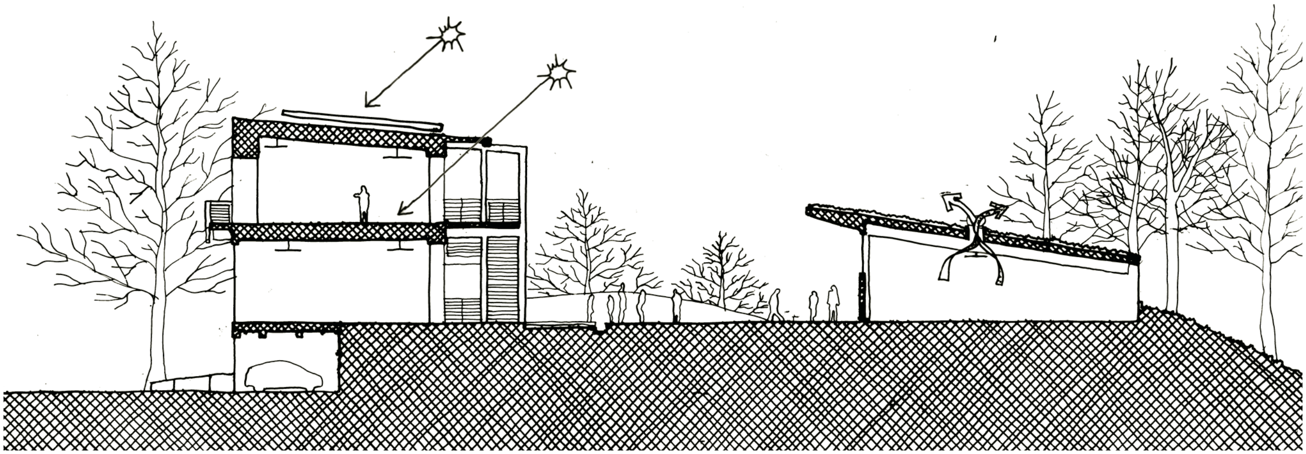
The techniques in ANNUAL ENERGY USE help the designer calculate Energy Demand Intensity (EDI) for space heating (EDI_h) and space cooling energy (EDI_c). In NET-ZERO ENERGY BALANCE the EDI for non-space conditioning uses (EDI_{ns}) is calculated and the total EDI for all these uses is found. Also in NET-ZERO ENERGY BALANCE the size of the PV array required to meet the total site energy demand can be estimated, and a goal set for what percentage of this size will be used. Finally, the project's Energy Production Intensity (EPI) can then be predicted in NET-ZERO ENERGY BALANCE. Calculations in these strategies are prerequisites to those that follow.



Site EUI and On-Site Renewables
for Analysis Building Compared to Architecture 2030 Targets
from SWL Tools spreadsheet

In this analysis technique, the EDI and EPI are combined to find the net site EUI, which is then compared to your EUI targets. Alternatively, *SWL Electronic* includes the *SWL Tools* spreadsheet to facilitate these calculations. See the "Emissions Targets" worksheet. The **Site EUI and On-Site Renewables** graph shows for each target—and for a building under analysis—bars representing the fossil fuel use and purchased off-site renewable energy up to 20% of the reduction amount (the maximum allowed by Architecture 2030 criteria).

STEP 1: Calculate the project's net site Energy Use Intensity (EUI). Subtract the building's Energy Production Intensity (EPI), estimated in NET-ZERO ENERGY BALANCE,



Nueva School, Hillsboro, California, 2007, Leddy Maytum Stacy Architects

from its total Energy Demand Intensity (EDI), also estimated in NET-ZERO ENERGY BALANCE, to get the net site EUI:

EUI = EDI – EPI

Three results are possible:

- A PV array area less than that required for net-zero (less than 100%) will result in a positive site net EUI (EUI > 0).
- PVs sized to meet the required (100%) size will result in a zero EUI (a site NZEB). EUI = 0.
- PV arrays larger than the net-zero requirement will yield a negative site EUI, meaning the building has a negative net site energy demand (EUI < 0). In other words, the building will be a net energy exporter, a *net-positive* energy building.

STEP 2: Compare the building's net site EUI to your EUI target. Ideally, the building's net site EUI from step 1 will be less than or equal to the EUI target set in ENERGY TARGETS. If the net site EUI is negative (a net-positive energy building) or zero (a net-zero energy building), then the building will have automatically met the EUI target.

If the net site EUI is greater than the EUI target, then you can either redesign to reduce loads, improve HVAC systems efficiency (lower EDI), or increase the size or efficiency of the PV system (greater EPI). If you are designing to meet Architecture 2030 targets, rather than the more strict Site NZEB energy criteria, one solution to reducing the net site EUI further is to purchase off-site renewable energy, such as bio-gas or electricity produced from renewable resources.

STEP 3: After exhausting other design possibilities and on-site renewables, consider purchasing off-site renewable power. Some sites have better access to renewable resources of sun and wind than others, therefore the Architecture 2030 targets allow for 20% of the fossil fuel reduction target to be met by purchased off-site renewable energy. To find the amount of this allowable 20%, multiply the EUI of the average building for your climate and building type [ENERGY TARGETS] by the Architecture 2030 reduction goal chosen (a percentage) and then multiply by 20%:

Purchased Renewable Energy max. =
ave. bldg. EUI × % reduction goal × 20%

For example, if the EUI for a typical 2–4 unit multifamily residence in the western United States is 47.6 kBtu/ft^2,yr and the Architecture 2030 goal chosen is a 70% reduction in fossil fuels (the 2015 target), then the allowable purchased off-site renewable energy that can be used to meet

Annual Purchased Energy Use

Fuel	Quantity	Cost($)	MMBtu	kBtu/ft2	$/ft2
Electricity	40,500 kWh		138	5.11	
Natural Gas	297 MMBtu		297	11	

Annual On-site Renewable Energy Production

Fuel	Quantity		MMBtu	kBtu/ft2	
Photovoltaics	58,900 kWh		201	7.44	

Total Annual Building Energy Consumption

Fuel		Cost	MMBtu	kBtu/ft2	$/ft2
Total Purchased			435	16.1	
Total On-Site Renewable			201	7.44	
Grand Total			**636**	**23.6**	

Annual End-Use Breakdown

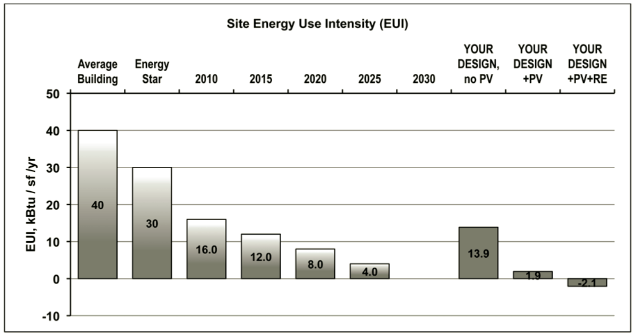
End Use	Quantity	MMBtu	kBtu/ft2
Heating	174 MMBtu	174	6.44
Cooling	7.5 MMBtu	7.5	0.278
Lighting	193 MMBtu	193	7.15
Fans/Pumps	85.6 MMBtu	85.6	3.17
Plug Loads and Equipment	53 MMBtu	53	1.96
Vertical Transport			
Domestic Hot Water	124 MMBtu	124	4.59
Other			

Nueva SChool, Annual Energy Consumption and Production Data

the target is: 47.6 x 0.7 x 0.2 = 6.7 kBtu/ft²,yr. Note that by this method, a building that meets the carbon-neutral Architecture 2030 goal can still use 20% purchased renewable energy, but will have reduced its loads by a net of 80% from the benchmark.

Alternatively, the "Emissions Targets" worksheet in the *SWL Tools* spreadsheet will facilitate all of these calculations.

The **Nueva School** in Hillsboro, California, by Leddy Maytum Stacy Architects (previous page), uses a rich variety of strategies to reduce its site Energy Demand Intensity (EDI) to 23.6 kBtu/ft²,yr (AIA, 2008). This "AIA Top Ten Green Project," employs daylighting, natural ventilation and sensitive site design, in addition to solar shading, thin plans, ceiling fans and wind-powered turbine ventilators. 85% of interior spaces are passively cooled. It employs a well-insulated skin, earth sheltering



PV= Photovoltaics

RE = Purchased, Off-site Renewable Energy

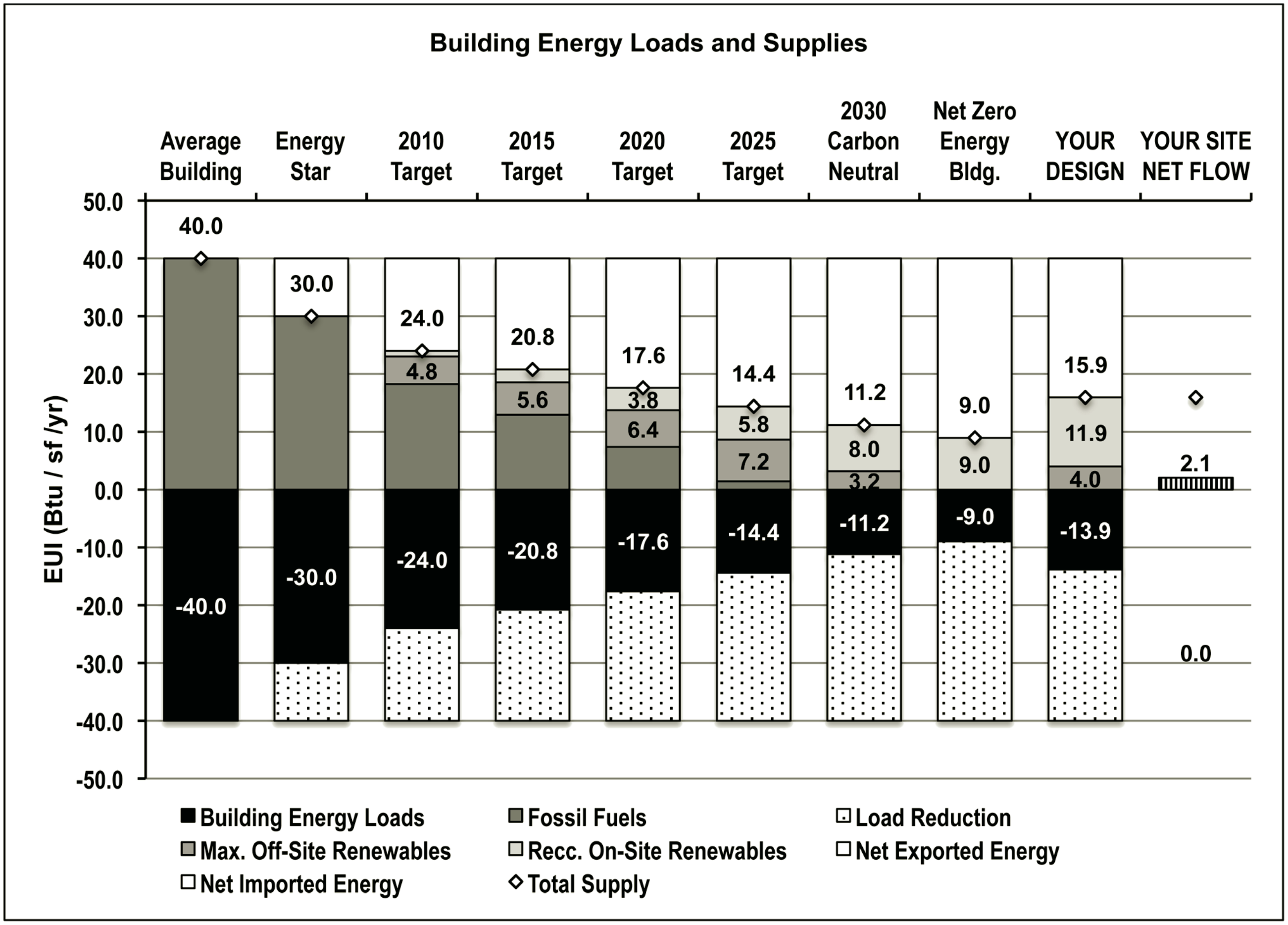
Net Site EUI with PV and Off-Site Renewables
for analysis building compared to EUI for different performance targets; from SWL Tools Spreadsheet

and high-performance glazing. Loads are met with high-efficiency gas-fired boilers and tankless water heaters, while occupancy sensors control energy-efficient lighting.

The average elementary school building in this climate Zone 3C location near San Francisco would use 51 kBtu/ft²,yr. [ENERGY TARGETS]. The **Nueva School Annual Energy Consumption and Production Data** table shows that the 30 kW photovoltaic array located on the classroom building roof has an Energy Production Intensity (EPI) of 7.4 kBtu/ft²,yr. Subtracting EPI from EDI leaves a net site EUI of 16.1 kBtu/ft²,yr, a reduction in fossil fuel use of 68%. The Architecture 2030 target for 2010 is 60% reduction, so this building, completed in 2007, meets and exceeds the 2010 target and almost meets the 2015 target.

The **Site EUI and On-Site Renewables** graph (opening page of ENERGY USE INTENSITY) shows fossil fuel use and off-site renewable energy in the form used by Architecture 2030. Note that the amount of on-site renewable energy (for example, from PV) is left up to the designer and is not shown in that graph, nor is it required to meet the target, although it is recommended. The bars for "Your Design" from this *SWL Tools* spreadsheet graph include representation of both PV and off-site renewables, if used.

The Architecture 2030 targets do not address the option for net energy exported. If a building design surpasses the



Building Energy Loads and Supplies, from SWL Tools spreadsheet

site NZEB target, it becomes a net-positive energy building. The graph of **Net Site EUI with PV and Off-Site Renewables** indicates the site EUI for fossil fuels used for each target, plus the calculated EUI for 'Your Design' under three conditions: 1) no PV; 2) PV only; and 3) PV plus off-site renewables (RE). This allows the designer to quickly explore combinations of energy saving and production strategies.

The *SWL Tools* spreadsheet's **Building Energy Loads and Supplies** graph shows the building energy loads and fossil fuels saved as negative values (below the zero line) and the kinds of energy supplied to meet those loads as positive values (above the line). It also adds recommended amounts of on-site renewables for each target. Without the use of renewables, the building loads would have to be extremely small to meet some targets and would have to be zero (virtually impossible) to meet others. Targets may be met by using a combination of on- and off-site renewables. Note that the Architecture 2030 carbon neutral target cannot be met without some form of renewables and that a site NZEB can *only* be accomplished using 100% on-site renewables for its energy supply.

CRITERIA

P5 *EMISSIONS TARGETS* set goals to reduce greenhouse gas emissions due to fossil fuel consumption, relative to benchmarks for the building's type and climate.

KEY POINTS

- Emissions targets measured as *Carbon Use Intensity (CUI)* allow us to make emissions comparisons between buildings on a per unit area basis.
- Emissions targets account for varying pollution rates associated with different fuel types and for the difference between site and source energy.
- Select an emission target as a percentage reduction of the emissions rate for an average building in your situation.
- Buildings that achieve energy targets of net-zero energy, net-positive energy, or Architecture 2030's carbon-neutral target will have a target CUI = 0.

Electricity generated from wind, hydro or solar power produces no greenhouse gas emissions (GHGs), while grid-supplied electricity is typically generated from a high percentage of burning fossil fuels. Fossil fuel combustion produces GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The Carbon Use Intensity (CUI) analysis technique helps the designer set an emissions target for the building. It is designed to help reduce not only energy use but also the pollution and global climate change effects of energy use.

As outlined in ENERGY TARGETS, Architecture 2030 targets challenge designers to gradually reduce fossil fuel use over time, leading to a carbon-neutral goal for new buildings and major renovations by 2030. A *carbon-neutral* building would meet all site energy demand with on-site or off-site renewable energy, and thus its net emissions would be zero. A *site net-zero energy* building meets its site energy demand with all *on-site* renewables and so also has zero net emissions. If one accounts for the grid-supplied energy emissions displaced by the clean renewable energy exported to the utility company by a net-positive energy building, then its CUI < 0. One way to think of a negative CUI is that such a building is reducing (or consuming) the GHG emissions of *other* buildings.

Energy Source	Conversion Factor, CO_2e lb/kWh (kg/kWh)
Grid delivered electricity, USA	1.670 (0.758)
Grid delivered electricity, CANADA	0.440 (0.200)
LPG or propane	0.686 (0.312)
Fuel oil (distillate)	0.822 (0.373)
Natural Gas	0.510 (0.232)
Wood	0.699 (0.317)

Sample CO_2e Emissions Factors
Canada values from NRC Canada, 2009; wood from EPA, 2004; other values from ASHRAE, 2009a

Different fuels produce different amounts of emissions. Grid-delivered electricity in the U.S. produces roughly three times more emissions than fuel burned on-site, such as natural gas. This is much less true in some Canadian provinces where hydroelectric power is more dominant. The inefficiency is due in part to large-scale centralized electrical production. It also a result of distribution and the mix of fuels, including a large percentage of coal, used to produce the electricity.

The global warming potential of various greenhouse gases can be converted to a single measure referred to as *carbon dioxide equivalent*, or CO_2e, as shown in **Sample CO_2e Emissions Factors**. In specific terms, CO_2e "approximates the time-integrated warming effect of a unit mass of a given greenhouse gas, relative to that of carbon dioxide (CO_2)" (ASHRAE, 2009a) and are based on the pollutant's global warming potential (GWP). GWP is an index

for estimating the relative global warming contribution of atmospheric emissions of 1 kg of a particular greenhouse gas compared to emissions of 1 kg of CO_2. The following GWP values are used based on a 100-year time horizon: 1 for CO_2, 23 for methane (CH_4) and 296 for nitrous oxide (N_2O) (ASHRAE, 2009a).

To fairly compare energy use of buildings of the same occupancy type located in the same climate zone, ENERGY TARGETS set an energy use intensity (EUI) target in kBtu/ft²,yr (kWh/m²,yr) based on an average building. This can be converted to a c*arbon use intensity* (CUI) in units of CO_2e lb/ft²,yr (kg/m²,yr), that is, mass of CO_2 equivalent gases produced by the building's energy use over a year, per unit of floor area. The CUI target allows designers to fairly compare the emissions rate of a building design as compared to an average building—again, of the same occupancy type located in the same climate zone. CUI not only accounts for differences in fuel types but also accounts for the difference between energy *used at the site* and the *source energy* needed to produce and deliver that energy to the site.

To convert site EUI to Carbon Use Intensity (CUI), divide kBtu/ft²,yr by 3.412 kBtu/kWh and multiply by the CO_2e conversion factor:

$$\text{CUI} = (\text{EUI} \div 3.412) \times CO_2e \text{ conversion factor}$$

The building's EUI is estimated in ENERGY USE INTENSITY, while EUI targets are found in ENERGY TARGETS. Sample CO_2e conversion factors are given in the table **Sample CO_2e Emissions Factors**. More extensive emissions factors can be found in CARBON-NEUTRAL BUILDING. The total CUI is the sum of CUIs for each fuel used. For example, if the building uses some natural gas and some electricity, as many buildings do, then the EUI attributable to each fuel is used to find a CUI for gas and a CUI for electricity and then these are added to get the total building CUI. See details in CARBON NEUTRAL BUILDING.

EPA's Target Finder tool (EPA, 2012) gives the typical percentage mix of gas and electricity use for the building's region. These percentages can be used along with the average building EUI from* ENERGY TARGETS *to establish a benchmark CUI (Bryan, 2009):

Primary Space / Building Type	Ave. % Electric	Site CUI		
		med	70%	90%
Education	63	27.6	8.3	2.8
College / University (campus-level)	63	43.6	13.1	4.4
Food Sales	86	99.4	29.8	9.9
Convenience Store (w/ or w/o gas)	90	109.8	32.9	11.0
Food Service	59	122.9	36.9	12.3
Fast Food	64	196.0	58.8	19.6
Restaurant / Food Market	53	99.6	29.9	10.0
Health Care: Inpatient (specialty hospitals, excluding children's)	47	70.2	21.1	7.0
Health Care: Outpatient	72	28.8	8.6	2.9
Clinic / Other Outpatient Health	76	34.3	10.3	3.4
Mall (strip mall and enclosed)	71	41.8	12.5	4.2
Public Assembly	57	22.7	6.8	2.3
Entertainment / Culture	63	34.5	10.4	3.5
Library	59	36.4	10.9	3.6
Recreation	55	21.9	6.6	2.2
Social / Meeting	57	17.8	5.4	1.8
Public Order & Safety	57	30.9	9.3	3.1
Fire Station / Police Station	56	26.5	8.0	2.7
Service (vehicle repair / postal service)	63	28.0	8.4	2.8
Storage / Shipping/ Non-refrigerated warehouse	56	25	8	3
Self-storage	44	4	1.2	0.4

Carbon Use Intensity (CUI) Targets,U.S. Commercial Buildings, National Averages, CO_2e lbs/ft²-yr
Use for occupancy type not found in "Target Finder" or in tables of Carbon Use Intensity (CUI) Targets, by Building Type and Climate Zone on the next page.

$$\text{CUI}_{\text{elec.}} = (\text{site EUI} \div 3.412) \times \%\text{ electric} \times 1.67$$

$$\text{CUI}_{\text{gas}} = (\text{site EUI} \div 3.412) \times \%\text{ gas} \times 0.51$$

$$\text{CUI}_{\text{total}} = \text{CUI}_{\text{elec.}} + \text{CUI}_{\text{gas}}$$

EUI units are kBtu/ft², yr. CUI is in units of CO_2e/ft², yr.

ASHRAE Climate Zones	City	Small Office 5,500 sf / 1 story			Medium Office 53,628 sf / 3 story			Large Office 498,588 sf / 12 story			Medical Office 40,946 sf / 3 story			Primary School 73,960 sf / 1 story			Secondary School 210,887 sf / 2 story			Hospital (general medical & surgical) 241,351 sf / 5 story			Senior Care Facility 20,025 sf / 1 story			Hotel (small) 43,200 sf / 4 story		
		med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%
1A	Honolulu, HI	25.3	7.6	2.5	35.7	10.7	3.6	42.1	12.6	4.2	57.1	17.1	5.7	18.3	5.5	1.8	28.4	8.5	2.8	82.3	24.7	8.2	49.5	14.8	4.9	25.8	7.7	2.6
1A	San Juan, PR	24.8	7.4	2.5	35.3	10.6	3.5	41.5	12.4	4.1	55.8	16.8	5.6	12.7	3.8	1.3	22.4	6.7	2.2	82.1	24.6	8.2	49.1	14.7	4.9	25.6	7.7	2.6
1A	Miami, FL	25.9	7.8	2.6	36.7	11.0	3.7	43.1	12.9	4.3	62.9	18.9	6.3	13.2	4.0	1.3	25.0	7.5	2.5	84.2	25.3	8.4	51.4	15.4	5.1	27.4	8.2	2.7
2A	Houston, TX	24.5	7.3	2.4	35.3	10.6	3.5	41.3	12.4	4.1	49.8	14.9	5.0	22.1	6.6	2.2	28.4	8.5	2.8	79.2	23.8	7.9	47.7	14.3	4.8	25.4	7.6	2.5
2B	Phoenix, AZ	26.3	7.9	2.6	37.2	11.2	3.7	43.4	13.0	4.3	62.3	18.7	6.2	21.8	6.5	2.2	32.4	9.7	3.2	82.9	24.9	8.3	51.0	15.3	5.1	27.8	8.3	2.8
3A	Atlanta, GA	22.9	6.9	2.3	33.7	10.1	3.4	39.7	11.9	4.0	38.7	11.6	3.9	22.1	6.6	2.2	23.2	7.0	2.3	73.9	22.2	7.4	44.2	13.3	4.4	23.7	7.1	2.4
3B-CA	Los Angeles, CA	18.2	5.5	1.8	28.7	8.6	2.9	34.9	10.5	3.5	24.9	7.5	2.5	19.7	5.9	2.0	16.6	5.0	1.7	67.7	20.3	6.8	37.5	11.3	3.8	17.8	5.3	1.8
3B-other	Las Vegas, NV	25.2	7.6	2.5	32.5	9.8	3.3	41.8	12.6	4.2	50.4	15.1	5.0	22.4	6.7	2.2	28.1	8.4	2.8	78.6	23.6	7.9	47.6	14.3	4.8	26.3	7.9	2.6
3C	San Francisco	19.8	5.9	2.0	30.2	9.1	3.0	36.4	10.9	3.6	26.3	7.9	2.6	18.8	5.6	1.9	18.1	5.4	1.8	67.2	20.1	6.7	38.5	11.5	3.8	20.0	6.0	2.0
4A	Baltimore, MD	23.7	7.1	2.4	34.1	10.2	3.4	40.5	12.2	4.1	37.1	11.1	3.7	22.4	6.7	2.2	21.7	6.5	2.2	72.1	21.6	7.2	43.5	13.0	4.3	24.7	7.4	2.5
4B	Albuquerque, NM	23.6	7.1	2.4	34.1	10.2	3.4	40.3	12.1	4.0	38.2	11.5	3.8	22.4	6.7	2.2	22.1	6.6	2.2	72.3	21.7	7.2	43.8	13.1	4.4	24.7	7.4	2.5
4C	Seattle, WA	22.1	6.6	2.2	32.5	9.8	3.3	38.7	11.6	3.9	29.5	8.9	3.0	20.3	6.1	2.0	18.1	5.4	1.8	67.2	20.1	6.7	40.3	12.1	4.0	23.1	6.9	2.3
5A	Chicago, IL	24.8	7.4	2.5	35.3	10.6	3.5	41.5	12.4	4.1	37.3	11.2	3.7	22.4	6.7	2.2	20.1	6.0	2.0	69.7	20.9	7.0	43.9	13.2	4.4	26.6	8.0	2.7
5B	Boulder, CO	24.4	7.3	2.4	34.9	10.5	3.5	41.1	12.3	4.1	36.4	10.9	3.6	22.4	6.7	2.2	20.0	6.0	2.0	69.9	21.0	7.0	43.5	13.0	4.3	26.0	7.8	2.6
5C	Ketchican, AK	25.6	7.7	2.6	36.0	10.8	3.6	42.2	12.7	4.2	34.9	10.5	3.5	16.6	5.0	1.7	21.8	6.5	2.2	66.9	20.1	6.7	43.1	12.9	4.3	27.8	8.3	2.8
6A	Minneapolis, MN	26.2	7.9	2.6	36.7	11.0	3.7	42.8	12.8	4.3	39.9	12.0	4.0	22.7	6.8	2.3	20.4	6.1	2.0	69.7	20.9	7.0	45.1	13.5	4.5	28.0	8.4	2.8
6B	Helena, MT	25.2	7.6	2.5	35.6	10.7	3.6	41.8	12.6	4.2	35.3	10.6	3.5	21.8	6.5	2.2	18.8	5.6	1.9	68.0	20.4	6.8	43.1	12.9	4.3	26.9	8.1	2.7
7	Duluth, MN	26.5	8.0	2.7	37.4	11.2	3.7	36.7	11.0	3.7	37.6	11.3	3.8	21.7	6.5	2.2	18.6	5.6	1.9	67.3	20.2	6.7	44.2	13.3	4.4	29.2	8.8	2.9
7.5	Kenai, AK	27.1	8.1	2.7	37.6	11.3	3.8	43.8	13.1	4.4	37.8	11.3	3.8	16.9	5.1	1.7	22.1	6.6	2.2	66.9	20.1	6.7	44.1	13.2	4.4	30.0	9.0	3.0
8	Fairbanks, AK	29.4	8.8	2.9	40.3	12.1	4.0	46.5	13.9	4.6	42.9	12.9	4.3	20.9	6.3	2.1	19.4	5.8	1.9	67.2	20.1	6.7	46.3	13.9	4.6	33.5	10.0	3.3

Carbon Use Intensity (CUI) Targets, U.S. Commercial Buildings, by Building Type and Climate Zone, CO_2e lbs/ft²-yr   na = not available in EPA Target Finder

A CUI target may be calculated for any building in this way, or you can use the precalculated tables. If using the* SWL Tools *spreadsheet, enter the target CUI on the "Emissions Targets" tab.

Remember that your CUI target will be a fraction of the average building's CUI based on your goal, such as Architecture 2030's 70% reduction goal for the year 2020. Of course a net-zero energy building will have a CUI = 0 by definition and if that is the case there is no need to go further in this technique. Because of the way "Target Finder" defines CO_2e emissions factors, we *do not recommend* using the emissions calculations there at this time (2012). This is explained in CARBON-NEUTRAL BUILDINGS.

United States, Commercial Buildings

CUI targets for U.S. commercial buildings NOT found in either "Target Finder" or in the DOE reference building models are given as U.S. national averages (not by

Hotel (large) 12,202 sf / 6 story			Residence Hall / Dormitory 100,000 sf / 4 story			Mid-Rise Apartment 33,740 sf / 4 story			Warehouse (unrefrigerated) 52,045 sf / 1 story			Warehouse (refrigerated) 52,045 sf / 1 story			Courthouse, federal 395,000 sf			Bank / Financial Institution 4,100 sf / 1 story branch			Supermarket / Grocery 45,000 sf / 1 story			Retail 24,962 sf / 1 story			Strip Mall 22,500 story / 1 story			House of Worship 17,000 sf / 1 story		
med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%
29.2	8.8	2.9	32.5	9.8	3.3	13.8	4.1	1.4	9.7	2.9	1.0	62.8	18.8	6.3	42.1	12.6	4.2	44.1	13.2	4.4	127.5	38.3	12.8	30.3	9.1	3.0	23.2	7.0	2.3	9.2	2.8	0.9
26.3	7.9	2.6	31.9	9.6	3.2	na	na	na	9.6	2.9	1.0	62.7	18.8	6.3	41.5	12.4	4.1	43.4	13.0	4.3	125.3	37.6	12.5	29.9	9.0	3.0	na	na	na	9.2	2.7	0.9
36.2	10.9	3.6	35.2	10.6	3.5	na	na	na	10.3	3.1	1.0	68.0	20.4	6.8	43.1	12.9	4.3	45.0	13.5	4.5	134.1	40.2	13.4	30.8	9.3	3.1	na	na	an	10.3	3.1	1.0
28.9	8.7	2.9	31.1	9.3	3.1	13.8	4.1	1.4	10.2	3.1	1.0	53.5	16.1	5.4	41.3	12.4	4.1	43.3	13.0	4.3	120.2	36.1	12.0	30.3	9.1	3.0	24.0	7.2	2.4	8.8	2.7	0.9
27.9	8.4	2.8	36.9	11.1	3.7	11.9	3.6	1.2	10.7	3.2	1.1	64.8	19.5	6.5	43.4	13.0	4.3	45.3	13.6	4.5	133.8	40.1	13.4	31.9	9.6	3.2	23.6	7.1	2.4	10.6	3.2	1.1
27.2	8.1	2.7	27.2	8.2	2.7	13.4	4.0	1.3	10.2	3.1	1.0	39.6	11.9	4.0	39.7	11.9	4.0	41.7	12.5	4.2	104.8	31.4	10.5	29.4	8.8	2.9	25.7	7.7	2.6	7.1	2.1	0.7
20.3	6.1	2.0	18.1	5.4	1.8	9.7	2.9	1.0	8.5	2.6	0.9	22.3	6.7	2.2	34.9	10.5	3.5	36.8	11.0	3.7	74.7	22.4	7.5	24.5	7.3	2.4	18.2	5.5	1.8	2.5	0.8	0.3
26.8	8.0	2.7	32.8	9.8	3.3	11.3	3.4	1.1	10.7	3.2	1.1	53.0	15.9	5.3	41.8	12.6	4.2	43.8	13.1	4.4	121.0	36.3	12.1	31.1	9.3	3.1	23.6	7.1	2.4	9.5	2.8	0.9
22.0	6.6	2.2	20.9	6.3	2.1	10.3	3.1	1.0	9.8	2.9	1.0	20.2	6.1	2.0	36.4	10.9	3.6	38.4	11.5	3.8	79.9	24.0	8.0	27.0	8.1	2.7	22.0	6.6	2.2	4.1	1.2	0.4
28.0	8.4	2.8	29.0	8.7	2.9	14.8	4.5	1.5	11.1	3.3	1.1	33.7	10.1	3.4	40.5	12.2	4.1	42.5	12.8	4.3	103.8	31.2	10.4	31.1	9.3	3.1	30.7	9.2	3.1	7.8	2.3	0.8
25.6	7.7	2.6	29.4	8.8	2.9	11.6	3.5	1.2	11.2	3.4	1.1	35.3	10.6	3.5	40.3	12.1	4.0	42.2	12.7	4.2	105.1	31.5	10.5	31.1	9.3	3.1	26.5	8.0	2.7	7.9	2.4	0.8
24.1	7.2	2.4	25.6	7.7	2.6	11.9	3.6	1.2	11.0	3.3	1.1	20.9	6.3	2.1	38.7	11.6	3.9	40.7	12.2	4.1	89.7	26.9	9.0	30.3	9.1	3.0	28.6	8.6	2.9	6.3	1.9	0.6
24.9	7.5	2.5	32.4	9.7	3.2	13.6	4.1	1.4	12.1	3.6	1.2	29.5	8.8	2.9	41.5	12.4	4.1	43.5	13.1	4.4	106.6	32.0	10.7	32.8	9.8	3.3	25.6	7.7	2.6	8.9	2.7	0.9
26.5	8.0	2.7	31.6	9.5	3.2	12.8	3.8	1.3	12.1	3.6	1.2	28.1	8.4	2.8	41.1	12.3	4.1	43.0	12.9	4.3	104.1	31.2	10.4	32.8	9.8	3.3	29.9	9.0	3.0	8.5	2.6	0.9
27.9	8.4	2.8	35.3	10.6	3.5	na	na	na	13.7	4.1	1.4	20.2	6.1	2.0	42.2	12.7	4.2	44.2	13.3	4.4	104.4	31.3	10.4	35.7	10.7	3.6	na	na	na	9.8	2.9	1.0
25.9	7.8	2.6	36.4	10.9	3.6	15.6	4.7	1.6	13.0	3.9	1.3	29.5	8.8	2.9	42.8	12.8	4.3	44.9	13.5	4.5	112.0	33.6	11.2	35.3	10.6	3.5	30.4	9.1	3.0	10.2	3.1	1.0
27.2	8.2	2.7	33.5	10.0	3.3	15.0	4.5	1.5	12.8	3.8	1.3	23.1	6.9	2.3	41.8	12.6	4.2	43.8	13.1	4.4	103.8	31.1	10.4	34.4	10.3	3.4	36.9	11.1	3.7	9.2	2.7	0.9
26.7	8.0	2.7	38.4	11.5	3.8	17.0	5.1	1.7	13.9	4.2	1.4	22.5	6.8	2.3	43.5	13.1	4.4	45.2	13.6	4.5	110.3	33.1	11.0	36.9	11.1	3.7	34.1	10.2	3.4	10.7	3.2	1.1
29.4	8.8	2.9	40.6	12.2	4.1	na	na	na	14.6	4.4	1.5	20.2	6.1	2.0	43.8	13.1	4.4	45.7	13.7	4.6	110.9	33.3	11.1	37.7	11.3	3.8	na	na	na	11.4	3.4	1.1
32.0	9.6	3.2	51.0	15.3	5.1	23.8	7.1	2.4	16.3	4.9	1.6	20.5	6.2	2.1	46.5	13.9	4.6	48.4	14.5	4.8	121.7	36.5	12.2	41.1	12.3	4.1	64.7	19.4	6.5	13.9	4.2	1.4

Carbon Use Intensity (CUI) Targets, U.S. Commercial Buildings, by Building Type and Climate Zone, CO_2e lbs/ft²-yr

na = not available in EPA "Target Finder"

***region or climate zone) in* Carbon Use Intensity (CUI) Targets, U.S. Commercial Buildings, National Averages** (previous page).

***To select a CUI for common commercial building types, use the tables of* Carbon Use Intensity (CUI) Targets, U.S. Commercial Buildings, by Building Type and Climate Zone.**

The tables are based on applying conversion factors and fuel mix proportions (gas and electric only) to the EUI values from the tables in ENERGY TARGETS. Cities are representative of the climate zone. The fuel mix of electricity and gas used to create the tables are from "Target Finder." The method is based on and modified from methods to determine CUI in Bryan (2009). Canadian cities in the same climate zone may have a *very* different mix of fuels; Canadian CO_2e emissions factors for electricity can be very different than the U.S. national average value used

Commercial Space / Building Type	Site CUI med	Site CUI 70%	Site CUI 90%
ATLANTIC			
Wholesale Trade	107.1	32.1	10.7
Retail Trade	129.5	38.9	13.0
Transportation & Warehousing	81.5	24.5	8.2
Information & Cultural Industries	136.8	41.0	13.7
Offices	100.0	30.0	10.0
Educational Services	109.0	32.7	10.9
Healthcare & Social Assistance	181.7	54.5	18.2
Arts, Entertainment & Recreation	122.2	36.7	12.2
Accommodation & Food Service	177.7	53.3	17.8
Other Services	96.1	28.8	9.6
QUEBEC			
Wholesale Trade	83.8	25.1	8.4
Retail Trade	89.7	26.9	9.0
Transportation & Warehousing	69.9	21.0	7.0
Information & Cultural Industries	124.1	37.2	12.4
Offices	72.4	21.7	7.2
Educational Services	88.7	26.6	8.9
Healthcare & Social Assistance	143.3	43.0	14.3
Arts, Entertainment & Recreation	104.8	31.4	10.5
Accommodation & Food Service	141.7	42.5	14.2
Other Services	80.6	24.2	8.1
ONTARIO			
Wholesale Trade	53.5	16.0	5.3
Retail Trade	54.0	16.2	5.4
Transportation & Warehousing	45.5	13.6	4.5
Information & Cultural Industries	62.1	18.6	6.2
Offices	48.6	14.6	4.9
Educational Services	56.5	16.9	5.6
Healthcare & Social Assistance	91.5	27.5	9.2
Arts, Entertainment & Recreation	70.0	21.0	7.0
Accommodation & Food Service	78.3	23.5	7.8
Other Services	57.9	17.4	5.8

Commercial Space / Building Type	Site CUI med	Site CUI 70%	Site CUI 90%
MANITOBA			
Wholesale Trade	46.6	14.0	4.7
Retail Trade	57.2	17.2	5.7
Transportation & Warehousing	37.9	11.4	3.8
Information & Cultural Industries	56.2	16.8	5.6
Offices	45.0	13.5	4.5
Educational Services	53.6	16.1	5.4
Healthcare & Social Assistance	81.3	24.4	8.1
Arts, Entertainment & Recreation	47.8	14.3	4.8
Accommodation & Food Service	82.9	24.9	8.3
Other Services	47.9	14.4	4.8
SASKATCHEWAN			
Wholesale Trade	63.8	19.1	6.4
Retail Trade	81.5	24.4	8.1
Transportation & Warehousing	60.3	18.1	6.0
Information & Cultural Industries	76.7	23.0	7.7
Offices	60.0	18.0	6.0
Educational Services	72.1	21.6	7.2
Healthcare & Social Assistance	89.7	26.9	9.0
Arts, Entertainment & Recreation	63.0	18.9	6.3
Accommodation & Food Service	94.0	28.2	9.4
Other Services	68.6	20.6	6.9
ALBERTA			
Wholesale Trade	36.8	11.0	3.7
Retail Trade	44.6	13.4	4.5
Transportation & Warehousing	26.3	7.9	2.6
Information & Cultural Industries	45.3	13.6	4.5
Offices	33.9	10.2	3.4
Educational Services	37.7	11.3	3.8
Healthcare & Social Assistance	54.0	16.2	5.4
Arts, Entertainment & Recreation	41.5	12.4	4.1
Accommodation & Food Service	63.3	19.0	6.3
Other Services	34.8	10.4	3.5

Carbon Use Intensity (CUI) Targets, Canadian Commercial Buildings, Provincial Averages, kg $CO_2e/^2$, yr
Derived from Natural Resources Canada, Office of Energy Efficiency, Comprehensive Energy Use Database.

Commercial Space / Building Type	Site CUI		
	med	70%	90%
BRITISH COLUMBIA & TERRITORIES			
Wholesale Trade	27.8	8.3	2.8
Retail Trade	32.8	9.8	3.3
Transportation & Warehousing	24.8	7.4	2.5
Information & Cultural Industries	41.2	12.4	4.1
Offices	31.7	9.5	3.2
Educational Services	35.6	10.7	3.6
Healthcare & Social Assistance	54.6	16.4	5.5
Arts, Entertainment & Recreation	61.1	18.3	6.1
Accommodation & Food Service	76.5	23.0	7.7
Other Services	34.2	10.3	3.4

in these calculations [see **Sample CO_2e Emissions Factors** table on first page of EMISSIONS TARGETS].

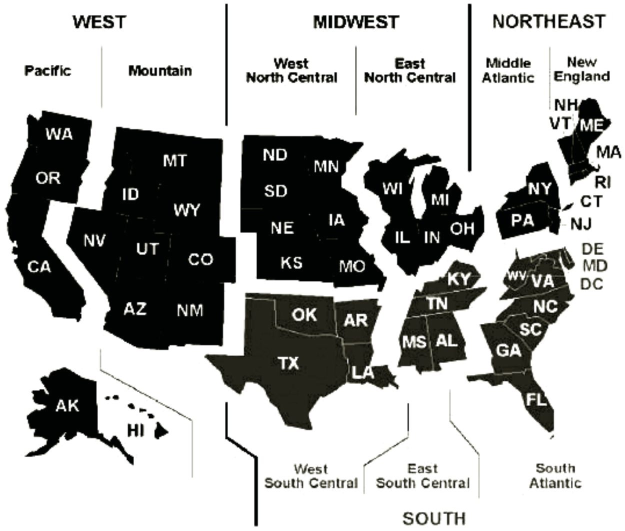
Tables show a "med" value for the median building in the CBECS (EPA, 2011a) data, representing typical practice, along with 70% and 90% reduction targets from this median value. For details of climate zones, representative cities and building definitions, see the discussion in ENERGY TARGETS. For **International Climate Zone Maps of United States, Alaska and Canada,** see "Navigation by Climate" in Part II. CO_2e emissions factors used are 1.670 lb/kwh for electricity and 0.51 lb/kwh for natural gas.

Canada, Nonresidential Buildings

CUI targets for *Canadian nonresidential buildings* are given by province for 10 building types in the table **Carbon Use Intensity (CUI) Targets, Canadian Commercial Buildings, Provincial Averages.** Tables show a "med" value for the median building in the Comprehensive Energy Use Database (CEUD) data, representing typical practice, along with 70% and 90% reduction targets from this median value (NRC, 2009).

Be aware that climate may vary significantly within a province. This is particularly true in the category for British Columbia and Territories, which covers relatively mild Vancouver, British Columbia, up to the Yukon Territory and across to extreme climates like Resolute, Nunavut. A similar benchmarking tool to "Target Finder" is currently being developed by Natural Resources Canada based on the U.S. EPA methods.

The tables are based on applying conversion factors and fuel mix proportions to the EUI values from the tables in ENERGY TARGETS. The fuel mix used to create the tables is from the CEUD. The fuel mix data for Canada provides for a wider range of fuel types than data for the United States, and includes natural gas, electricity, fuel oil, propane and wood. Calculations are based on the Canadian national average CO_2e emissions factor for grid-supplied electricity and CO_2e factors for on-site combustion fuels as shown in the table **Sample CO_2e Emissions Factors** (first page of EMISSIONS TARGETS).



U.S. Census Regions
Use for CUI US Residential Regional Targets

United States Residential Buildings

CUI targets for *U.S. residential buildings* by geographic region for five categories of housing are shown in the table **Carbon Use Intensity (CUI) Targets, U.S. Residential Buildings, Regional Averages.** This table is based on 2009 EUI data as given in ENERGY TARGETS and the most recent fuel mix data from the U.S. Energy Information Agency (EIA, 2009, 2005), which is from 2005. The CUI targets are based on **U.S. Census Regions**; new EIA analyses will likely use the more preferable climate zones.

Canada, Residential Buildings

CUI targets for *Canadian residential buildings* are given by province for four housing types in the table **Carbon Use Intensity (CUI) Targets, Canadian Residential Buildings, Provincial Averages.** The tables are based on applying conversion factors and fuel mix proportions to the EUI values from the tables in ENERGY TARGETS. The fuel mix used to create the tables are from the *Comprehensive Energy Use Database (NRC, 2009)*. CO_2e factors used are from the table **Sample CO_2e Emissions Factors**.

Be aware that climate may vary significantly within a province.

Residential Space / Building Type	Site CUI		
	med	70%	90%
Northeast	23% electric		
Single-Family Detached	10.0	3.0	1.0
Single-Family Attached	11.5	3.4	1.1
Multi-Family, 2 to 4 units	18.3	5.5	1.8
Multi-Family, 5 or more units	17.4	5.2	1.7
Mobile Homes	17.6	5.3	1.8
Midwest	32% electric		
Single-Family Detached	12.0	3.6	1.2
Single-Family Attached	13.0	3.9	1.3
Multi-Family, 2 to 4 units	20.8	6.2	2.1
Multi-Family, 5 or more units	17.1	5.1	1.7
Mobile Homes	22.1	6.6	2.2
South	64% electric		
Single-Family Detached	14.5	4.3	1.4
Single-Family Attached	14.8	4.4	1.5
Multi-Family, 2 to 4 units	18.6	5.6	1.9
Multi-Family, 5 or more units	15.7	4.7	1.6
Mobile Homes	19.5	5.9	2.0
West	41% electric		
Single-Family Detached	11.9	3.6	1.2
Single-Family Attached	12.4	3.7	1.2
Multi-Family, 2 to 4 units	14.5	4.4	1.5
Multi-Family, 5 or more units	12.1	3.6	1.2
Mobile Homes	19.0	5.7	1.9

Carbon Use Intensity (CUI) Targets, U.S. Residential Buildings, Regional Averages, CO_2e lbs/ft^2-yr
Based on 2009 EUI data and 2005 fuel mix data from the Energy Information Administration Residential Energy Consumption Survey. The survey data is available at www.eia.doe.gov.

Commercial Space / Building Type	Site CUI		
	med	70%	90%
CANADA, averages			
Single Family, Detached	53.0	15.9	5.3
Single Family, Attached	44.0	13.2	4.4
Apartments	47.3	14.2	4.7
Mobile Homes	74.5	22.3	7.4
NEWFOUNDLAND			
Single Family, Detached	63.8	19.2	6.4
Single Family, Attached	65.7	19.7	6.6
Apartments	51.8	15.5	5.2
Mobile Homes	84.6	25.4	8.5
PRINCE EDWARD ISLAND			
Single Family, Detached	63.8	19.1	6.4
Single Family, Attached	58.8	17.6	5.9
Apartments	54.2	16.2	5.4
Mobile Homes	90.7	27.2	9.1
NOVA SCOTIA			
Single Family, Detached	61.3	18.4	6.1
Single Family, Attached	56.6	17.0	5.7
Apartments	53.7	16.1	5.4
Mobile Homes	93.4	28.0	9.3
NEW BRUNSWICK			
Single Family, Detached	79.9	24.0	8.0
Single Family, Attached	64.8	19.4	6.5
Apartments	56.1	16.8	5.6
Mobile Homes	111.7	33.5	11.2
QUEBEC			
Single Family, Detached	84.7	25.4	8.5
Single Family, Attached	66.7	20.0	6.7
Apartments	61.6	18.5	6.2
Mobile Homes	119.2	35.8	11.9

Commercial Space / Building Type	Site CUI		
	med	70%	90%
ONTARIO			
Single Family, Detached	41.8	12.5	4.2
Single Family, Attached	38.6	11.6	3.9
Apartments	38.5	11.5	3.8
Mobile Homes	57.4	17.2	5.7
MANITOBA			
Single Family, Detached	62.5	18.7	6.2
Single Family, Attached	56.6	17.0	5.7
Apartments	47.4	14.2	4.7
Mobile Homes	86.9	26.1	8.7
SASKATCHEWAN			
Single Family, Detached	48.9	14.7	4.9
Single Family, Attached	40.5	12.1	4.0
Apartments	35.7	10.7	3.6
Mobile Homes	63.8	19.1	6.4
ALBERTA			
Single Family, Detached	46.6	14.0	4.7
Single Family, Attached	32.7	9.8	3.3
Apartments	37.3	11.2	3.7
Mobile Homes	62.1	18.6	6.2
BRITISH COLUMBIA			
Single Family, Detached	38.2	11.5	3.8
Single Family, Attached	34.8	10.5	3.5
Apartments	32.4	9.7	3.2
Mobile Homes	52.1	15.6	5.2
TERRITORIES			
Single Family, Detached	58.6	17.6	5.9
Single Family, Attached	57.0	17.1	5.7
Apartments	44.8	13.4	4.5
Mobile Homes	80.4	24.1	8.0

Carbon Use Intensity (CUI) Targets, Canadian Residential Buildings, Provincial Averages, kg CO_2e/m^2, yr
Derived from Natural Resources Canada, Office of Energy Efficiency, Comprehensive Energy Use Database (CEUD).

EVALUATION

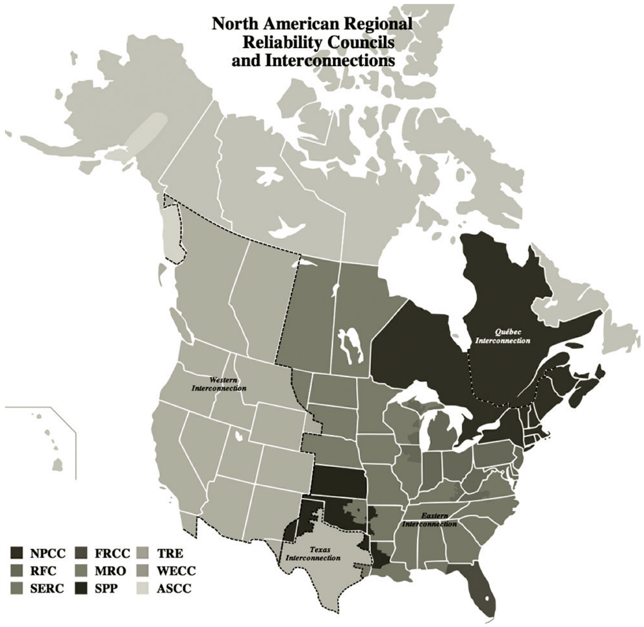
P6 *CARBON-NEUTRAL BUILDINGS* use no net greenhouse gas emitting energy to operate. Calculate the building's carbon use intensity (CUI) to compare its performance to the building's emission target.

KEY POINTS

- EUI is fuel-type neutral. CUI accounts for the GHG global warming potential of energy use and source energy to site energy ratios in a single metric.
- Each fuel has a different emissions factor; grid-supplied electricity creates the most GHG emissions.
- Renewables displace fossil fuel generated electricity and have *negative* emissions.

Once the amount and type of energy consumed and produced at the site is known, along with the amount of renewable energy purchased from the utility, if any, the *Carbon Use Intensity* (CUI) of the building can be estimated. The building's CUI can then be compared to the target CUI from EMISSIONS TARGETS to determine if the targets are met.

The CUI calculation is based on the energy consumed using each fuel and the emissions factor of the fuel as outlined in EMISSIONS TARGETS. While the carbon dioxide equivalent (CO_2e) emissions factors for on-site combustion ARE essentially the same everywhere, different regions will produce electricity with different mixes of fuels and technologies. For example, the U.S. Pacific Northwest has abundant hydroelectric resources. The EPA's "Target Finder" will calculate CO_2e for a building based on its energy use and regional "e-GRID factors" for U.S. subregions which attempt to account for these regional differences in fuel mix (EPA 2011b). There is much current debate about whether regional or national CO_2e factors are more accurate or fair. ASHRAE, in its *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings* (ASHRAE, 2009a), has decided in favor of national factors for two reasons: 1) Electricity is routinely transported across regional borders; and 2) Existing power from major hydro dams and cleaner natural gas



Electrical Grid Interconnection Regions

plants has been allocated already, so new buildings will tend to be responsible for new power sources, typically from less-expensive coal. In most cases, *SWL* recommends using the national **Emissions Factors by Fuel, USA** as shown in the table (ASHRAE, 2009a).

While the EPA "Target Finder" calculates CO_2e emissions, it does so using complex subregions and without considering the precombustion emissions of the fuels, and is therefore *not recommended*. Instead, the approached used by ASHRAE, ANSI and the Green Building Initiative (GBI) is to use emissions factors that include both *precombustion* (upstream from the power plant or site mechanical plant) and *combustion* emissions. Values in the **Emissions**

USA CO_2e EMISSIONS, NATIONAL AVERAGES	
Fuel Type	**Emissions Rate CO_2*e* lbs / kWh (kg / kWh)**
Electricity, grid displaced	–1.835 (–0.083)
Electricity, off-site renewable	–1.670 (–0.758)
Electricity, USA, average	1.670 (0.758)
Coal (lignite)	1.287 (0.584)
#1,2,4 Light/Distillate Oil	0.822 (0.373)
Coal (nonlignite/bituminous)	0.822 (0.373)
Wood	0.699 (0.317)
LPG/Propane	0.686 (0.311)
Gasoline	0.681 (0.309)
#5+6 Heavy/Residual Oil	0.614 (0.279)
Other Fuels	0.602 (0.273)
Natural Gas	0.510 (0.231)

USA CO_2e EMISSIONS FOR ELECTRICITY, REGIONAL AVERAGES	
Regional Grid Interconnection	**Emissions Rate CO_2*e* lb / kWh (kg / kWh)**
Hawaii	1.91 (0.866)
ERCOT (Texas)	1.84 (0.835)
Eastern US	1.74 (0.789)
Alaska	1.71 (0.776)
Western US	1.31 (0.594)

Emissions Factors by Fuel, U.S.
based on ASHRAE, 2009; Torcellini, P. and S. Deru (2007)

CANADA CO_2e EMISSIONS, NATIONAL AVERAGES	
Fuel Type	**Emissions Rate CO_2*e* lbs / kWh (kg / kWh)**
Electricity, grid displaced	N/A
Electricity, off-site renewable	–0.441 (–0.200)
Electricity, Canada, average	0.441 (0.200)
#1,2,4 Light/Distillate Oil	0.615 (0.279)
Wood	0.699 (0.317)
#5+6 Heavy/Residual Oil	0.688 (0.279)
Other Fuels	0.604 (0.274)
Natural Gas	0.511 (0.232)

CANADA CO_2e EMISSIONS FOR ELECTRICITY, PROVINCIAL	
Province	**Emissions Rate CO_2*e* lb / kWh (kg / kWh)**
Newfoundland & Labrador	0.044 (0.020)
Nova Scotia	1.742 (0.790)
New Brunswick	1.104 (0.460)
Quebec	0.004 (0.002)
Ontario	0.375 (0.170)
Manitoba	0.022 (0.010)
Saskatchewan	1.565 (0.710)
Alberta	1.940 (0.880)
British Columbia	0.044 (0.020)
Yukon, NWT, Nunavut	0.132 (0.060)

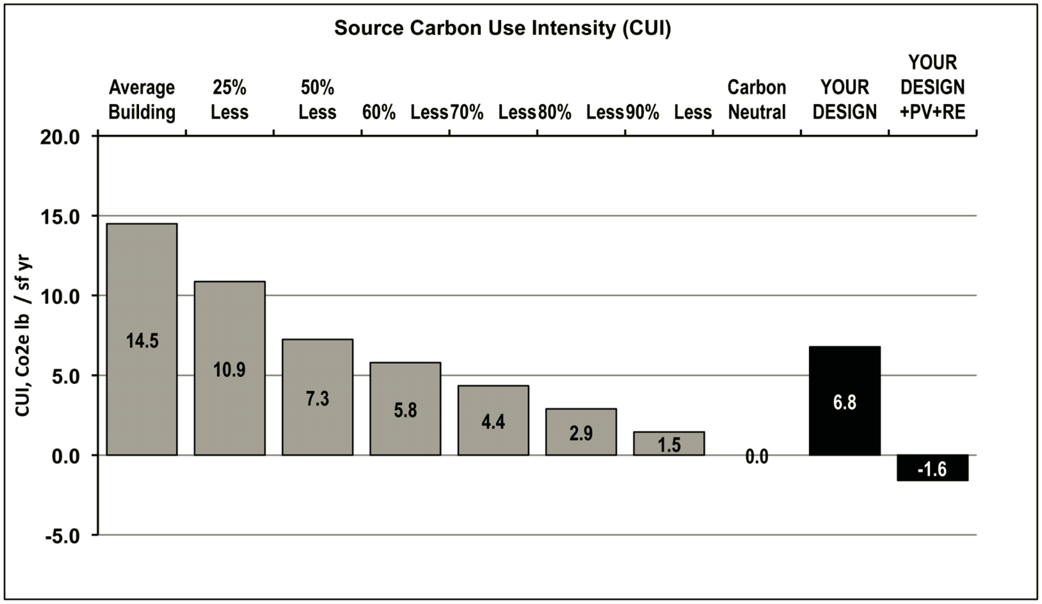
Emissions Factors by Fuel, Canada
based on Environment Canada (2010) and NRC (2008)

Factors by Fuel, U.S. table are from the ASHRAE method.

Additionally, depending on the comparison being made, a building may also be evaluated using regional electricity emissions rates. The table of **Emissions Factors by Fuel, USA** gives average values for five regions shown in the map of **Electric Grid Interconnection Regions** (NARC, 2009). Electricity is not transferred between these regions. Values are based on NREL (Deru and Torcellini, 2007) and *do* include precombustion emissions.

The table **Emissions Factors by Fuel, Canada** (NARC, 2009)**,** shows that on-site combustion fuels have similar values to those in the United States, however national average emissions from grid-supplied electricity are much lower in Canada than in the United States. Average provincial emissions rates for electricity are included in the table and vary widely based on the region's fuel mix. Quebec, for example, has very low emissions rates based on a very high percentage of hydroelectric power.

Calculation of the CUI for a building design is facilitated by the *SWL Tools* spreadsheet. Its "Emissions Targets" worksheet (see **Emissions Targets and CUI Calculations**, 2 pages forward). is linked to previously calculated EDIs for heating, cooling, other uses, on-site (PV) production (EPI) and off-site (purchased) renewables (RE). Calculation with the spreadsheet is relatively simple and is explained in detail within it. The calculations can also be



Net Site CUI with PV and Off-Site Renewables

for analysis building compared to CUI for different performance targets; from SWL Tools spreadsheet

done by hand. The logic of the spreadsheet is as follows:

To find the building's CUI and evaluate whether it meets the emissions target CUI:

STEP 1: Find the target CUI in EMISSIONS TARGETS.

STEP 2: Select CO_2e rates for each fuel used from the table for **Emissions Factors by Fuel** (USA or Canada).

STEP 3: Find source CUI for each fuel by multiplying the site EDI for each fuel (such as natural gas for heating), from NET-ZERO ENERGY BALANCE, by the CO_2e emissions rate for that fuel. In most cases, heating and cooling will use only one fuel each, while non-space energy may be all electric or a mix of electricity and another fuel, usually gas.

$$\text{site EDI}_{gas} \times CO_2e_{gas} = CUI_{gas}$$

where,
Site EDI is in kWh/ft², yr (kWh/m², yr)
CO_2e is in lb CO_2e/kWh (kg CO_2e/kWh) for the fuel
CUI is in lb CO_2e/ft², yr (kg CO_2e/m², yr)

STEP 4: Find the total Source CUI for the building design by adding together the CUI for each fuel. For example:

$$CUI_{gas} + CUI_{electric} = CUI_{design}$$

STEP 5: Estimate the emissions savings from on-site renewables, in CUI units, by multiplying the on-site renewable EPI by the emissions rate for on-site renewables:

$$EPI_{\text{on-site RE}} \times CO_2e_{\text{on-site RE}} = CUI_{\text{on-site RE}}$$

Estimate the annual energy from on-site renewable energy systems (such as PV), in units of EPI, as outlined in NET-ZERO ENERGY BALANCE.

STEP 6: Estimate the emissions savings from off-site renewables, in CUI units, by multiplying the off-site renewable EPI by the emissions rate for off-site renewables:

$$EPI_{\text{off-site RE}} \times CO_2e_{\text{off-site RE}} = CUI_{\text{off-site RE}}$$

Estimate the annual energy from purchased off-site renewable energy systems (such as wind-generated energy provided by the utility), in units of EPI, as outlined in NET ZERO ENERGY BALANCE.

STEP 7: Find the net Source CUI by subtracting credits for on-site (step 5) and off-site (step 6) renewable energy

EMISSIONS FACTORS

Fuel	Emissions Rate CO_2e lbs/ kWh	Fuel	Emissions Rate CO_2e lbs/ kWh	Fuel	Emissions Rate CO_2e lbs/ kWh
Electricity, off-site, purchased RE	-1.670	LPG / Propane	0.686	Gasoline	0.681
Electricity, on-site RE, grid displacing	-1.835	Wood	0.699	Coal, nonlignite	0.822
Electricity, grid	1.670	#4-6 Heavy / Residual Oil	0.614	Coal, lignite	1.287
Natural Gas	0.510	#1, #3 Light / Distillate Oil	0.822	Other Fuels	0.602

CUI & GHG EMISSIONS – including on-site RE & off-site RE

Fuel Type (select)	End Use	Site EUI kBtu/ ft^2, yr	Emissions Rate CO_2e lbs/ kWh	Greenhouse Gases CO_2e lbs/ yr	Source CUI CO_2e lbs/ ft^2, yr
Electricity, grid	Heating	2.2	1.670	1554	1.1
Electricity, grid	Cooling	2.4	1.670	1727	1.2
Electricity, grid	Other, non-space	9.3	1.670	6705	4.6
Electricity, grid	Other, non-space	0.0	1.670	0	0.0
Totals	All	**13.9**		9986	**6.8**
On-Site RE Produced	PV electric	11.9	-1.835	(9443)	**(6.41)**
Off-Site, Purchased RE	Utility, RE electric	4.0	-1.670	(2882)	**(1.96)**
Net		(2.1)		(2338)	(1.6)

CARBON NEUTRAL BUILDINGS

Target % Emissions Reduced from Typical Bldg.	Target CUI	Targets Achieved?	
Typical Building	14.5	NA	
25%	10.9	NA	
50%	7.3	YES	
60%	5.8	YES	
70%	4.4	YES!	GOOD WORK!
80%	2.9	**YES!!**	**CLIMATE STEWARD!**
90%	1.5	YES!!	NEAR CARBON NEUTRAL BUILDING
Carbon Neutral	0.0	YES!!!	CARBON CONSUMING BUILDING!

Emissions Targets and CUI Calculations, excerpt from SWL Tools spreadsheet

from the gross total CUI for the building design (step 4).

$$\mathbf{CUI_{design} - CUI_{on\text{-}site\ RE} - CUI_{off\text{-}site\ RE} = CUI_{net\ source}}$$

STEP 8: Compare the building's calculated net source CUI (step 7) to the target CUI (step 1). If the net source CUI is less than or equal to the target CUI, then the target is met:

$$\mathbf{CUI_{net\ source} \leq CUI_{target}}$$

The following additional interpretations apply to CUI:

- A net source CUI = 0 means a carbon neutral building by the *SWL* EMISSIONS TARGETS criteria.
- A net source CUI < 0 means a 'carbon consuming building,' which helps offset greenhouse gases generated elsewhere in the utility grid by other buildings.

Graphic results from *SWL Tools* are shown in **Net Site CUI with PV and Off-Site Renewables**.

APPENDICES

Appendices located in *SWL Printed*:

Appendices located in *SWL Electronic*:

Appendix A

SWL Printed Contents

detailed*

* All of the *SWL Printed* material is also included in electronic format in *SWL Electronic*

Appendix B
SWL Electronic Contents
detailed*

* All of the *SWL Printed* material is also included in electronic format in ⌿ *SWL Electronic*.

Appendices

Appendix C

Abbreviations and Unit Conversions

ABBREVIATIONS USED IN TEXT

°	degrees
ac	acre
ACH	air changes per hour
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BRADA	Boston Redevelopment Authority Daylight Access
BRK	broken (clouds) sky condition
Btu	British thermal units (energy)
Btu/DDF,ft^2	British thermal units per degree days Fahrenheit per square foot of floor area (heat loss conservation rate or criteria)
Btu/ft^2	British thermal units per square foot (solar radiation)
Btu/h	British thermal units/hour (power)
Btu/h,ft^2	British thermal units/hour per square foot of floor area (heat gain or loss rate, or solar radiation)
Btu/h,ft^2,fc	British thermal units/hour per square foot of floor area per foot-candle (thermal efficacy of electric lighting)
°C	degrees Celsius
CBECS	Commercial Building Energy Consumption Survey (USA)
CE	catching efficiency (wind catchers)
CEUD	Comprehensive Energy Use Database (Canada)
CF	conservation factor
cfm	cubic feet per minute (air flow)
CLR	clear sky condition
cm	centimeters
CO_2e	carbon dioxide equivalent (greenhouse gas emissions)
COP	coefficient of performance
CUI	carbon use intensity
D	depth
d	day
du	dwelling units
DD	degree days
DD18	degree days base 18 °C
DD65	degree days, base 65 °F
delta T	change or difference in temperature, also written as ΔT
DF	daylight factor
DOE	U.S. Department of Energy
E	east or eastern
e	emissivity
E–W	east-west orientation
EBI	energy balance index
EDI	energy demand intensity
EPI	energy production intensity
ERC	external reflected component of DF
ERV	energy recovery ventilator
EUI	energy use intensity
°F	degrees Fahrenheit
FAR	floor area ratio
fc	foot-candles
fpm	feet per minute

ft	feet
g	grains of moisture
gal	gallons
GBI	Green Building Initiative
GHG	greenhouse gases
H	height, also written as h
hr	hour
hrs	hours
horiz	horizon or horizontal
HCVL	heating, cooling, ventilation and lighting
HDD	heating degree days
HSPF	heating season performance factor
HVAC	heating, ventilation and air-conditioning
H/W	height to width ratio
IC	indirect component of DF
IES	Illumination Engineering Society
ILD	internal-load-dominated
in	inches
I-P	inch-pound units
IRC	internal reflected component of DF
ISMCS	*International Station Meteorological Summary, CD-ROM*
k	1000
kBtu	thousands of Btus
kBtu/ft^2,yr	thousands of Btus per square foot of floor area per year, a measure of EUI, EDI and EPI
K	degrees Kelvin
kg	kilograms
klux	kilolux (illuminance)
klux/h	kilolux per hour (illuminance)
kWh	kilowatt-hours
kWh/m^2,yr	kilowatt-hours per square meter of floor area per year, a measure of EUI, EDI and EPI
L	liters, or length, depending on use
lat	latitude
lb	pounds
LCR	load collector ratio
LP	liquid petroleum gas
L/s	liters per second (air flow)
LSG	light-to-solar-gain ratio (of glazing)
m	meters
MEC	*Model Energy Code*
mid	midnight
min	minutes
MJ	megaJoules (energy)
mm	millimeters
mph	miles per hour
MRT	mean radiant temperature
m/s	meters per second
N	north or northern
N–S	north-south orientation
NCDC	National Climatic Data Center
NCP	night cooling potential
NFRC	National Fenestration Rating Council
NH	Northern Hemisphere
N.I.	night insulation
NREL	National Renewable Energy Laboratory
NZEB	net-zero energy building
OVR	overcast sky condition
p	profile angle
PAF	power adjustment factor
PCM	phase change material
PDEC	passive downdraft evaporative cooling
PT CD	partly cloudy sky condition
PV	photovoltaic cells, panels, or array
R	ft^2, F, hr/Btu (I-P units of thermal resistance)
R_b	blockage ratio
RE	renewable energy
RECS	Residential Energy Conservation Survey
RH	relative humidity
RSI	m^2, K/W (SI units of thermal resistance)
S	south or southern
s	second
SC	shading coefficient
SC	sky component of daylight factor
SCT	scattered (clouds) sky condition
SkC	sky component of daylight factor
SH	Southern Hemisphere
SHGC	solar heat gain coefficient
SHGF	solar heat gain factor
SI	standard international units
SIF	solar intercept factor
SLD	skin-load-dominated
SRI	solar reflectance index
SSF	solar savings fraction
SSIC	stress skin insulated core panels
SVF	sky view factor
T	temperature
T_b	balance point temperature
T_{bu}	buffer zone temperature
T_{db}	dry bulb temperature
T_i	indoor temperature
TI	transparent insulation
T_m	mass temperature
T_{min}	minimum temperature

T_o	outdoor temperature
T_{db}	wet bulb temperature
ΔT	change or difference in temperature, also "delta T"
tan	tangent of an angle
TI	translucent insulation
TMY	typical meteorological year
typ	typical
U	or *U*-factor, Btu/hr, F, ft^2 (I-P units of thermal conductance)
USI	W/K, m^2 (SI units of thermal conductance, *U*-factor)
V	wind velocity
v	sky view angle or factor
VS	vertical surface
VT	visible transmittance
W	Watts, west, western, or width, depending on use
WB	wet bulb temperature
WI	skylight well index
W/DDK,m^2	Watts per degree days Kelvin per square meter of floor area (heat loss conservation rate or criteria)
Wh	Watt-hours
Wh/m^2	Watt-hours per square meter (solar radiation)
W/K, m^2	Watt-hours per degree Kelvin per square meter (SI units of thermal conductance, *U*-factor)
W/m^2	Watts per square meter of floor area, (heat loss or heat gain rate, or solar radiation)
WI	skylight well index
yr	year
Ψ	comfort parameter

UNIT CONVERSIONS FOR MEASURES USED IN TEXT

Variable	Multiply	By	To Get	Multiply	By	To Get
temperature	°F – 32	0.555	°C	°C	1.8	+ 32 = °F
temperature change,	°F	0.5556	°C	°C	1.8	°F
degree days	DD65 °F	0.5556	DD18.3 °C	DD18.3 °C	1.8	DD65 °F
wind speed	mph	0.447	m/s	m/s	2.237	mph
air velocity	fpm	0.00503	m/s	m/s	199	fpm
	ft/s	0.305	m/s	m/s	3.279	ft/s
air flow rate	cfm	0.02832	m3/h	m3/h	35.317	cfm
	cfm	0.472	l/s	l/s	2.119	cfm
air flow rate per flr. area	cfm/ft^2	5.081	L/s per m^2	L/s per m^2	0.197	cfm/ft^2
length	ft	0.305	m	m	3.281	ft
	in	25.4	mm	mm	0.039	in
area	in^2	645.2	mm^2	mm^2	0.00155	in^2
	in^2	6.452	cm^2	cm^2	0.155	in^2
	ft^2	0.0929	m^2	m^2	10.76	ft^2
area x 1000	k-ft^2	0.0929	k-m^2	k-m^2	10.76	k-ft^2
element area/unit flr. area	in^2/ft^2	69.45	mm^2/m^2	mm^2/m^2	0.0144	in2/ft^2
volume-solid	in^3	16.39	cm^3	cm^3	0.061	in^3
	ft^3	0.028	m^3	m^3	35.32	ft^3
volume-liquid	gal (gallons)	3.785	L (liters)	L (liters)	0.2642	gal (gallons)
	ft^3	28.32	L (liters)	L (liters)	0.03532	ft^3
density	lb/ft^3	16.02	kg/m^3	kg/m^3	0.06242	lb/ft^3

Variable	Multiply	By	To Get	Multiply	By	To Get
power	Btu/hr	0.0928	W	W	3.412	Btu/hr
energy	Btu	0.000293	kWh	kWh	3413	Btu
energy transfer	Btu/hr, ft^2	3.512	W/m^2	W/m^2	0.3172	Btu/hr, ft^2
solar radiation	Btu/ft^2	0.003152	kWh/m^2	kWh/m^2	317.2	Btu/ft^2
	Btu/ft^2	0.01135	MJ/m^2	MJ/m^2	88.11	Btu/ft^2
	Btu/ft^2	0.271	langleys	langleys	3.69	Btu/ft^2
	kWh/m^2	3.60	MJ/m^2	MJ/m^2	0.278	kWh/m^2
	kWh/m^2	86.04	langleys	langleys	0.01162	kWh/m^2
electric loads	Wh/ft^2	0.0929	Wh/m^2	Wh/m^2	10.76	Wh/ft^2
illuminance	fc	10.76	lux	lux	0.0929	fc
	fc	0.01076	klux	klux	92.9	fc
R-value (resistance)	ft^2, F, hr/Btu	0.1763	m^2, K/W	m^2, K/W	5.673	ft^2, F, h/Btu
R-value/unit thickness	R/in	0.0693	RSI/cm	RSI/cm	14.43	R/in
U-factor (conductance)	Btu/hr, F, ft^2	5.673	W/K, m^2	W/K, m^2	0.1763	Btu/hr, F, ft^2
solar mass ratio (masonry)	ft^3 mass/ft^2 flr.	0.3014	m^3 mass/m^2 flr.	m^3 mass/m^2 flr.	3.318	ft^3 mass/ft^2 flr.
solar mass ratio (water) and water consumption	gal/ft^2 flr.	40.74	L/ft^2 flr.	L/ft^2 flr.	0.02455	gal/ft^2 flr.

Appendix D

Glossary

ABSORPTANCE/ABSORPTIVITY
The fraction of the incident radiation striking a surface that is absorbed by the surface. The term can refer to either the full solar radiation spectrum or a portion such as the visible spectrum or the infrared spectrum. Range is 0–1.0. See also *Emittance*.

ACTIVE SYSTEM
A heating or cooling system that uses mechanical devices such as fans and pumps to distribute heat, or an electric lighting system.

AIR-AIR HEAT EXCHANGER
A mechanical device that, in winter, recovers heat from outgoing exhaust air and transfers it to incoming ventilation air. In summer, the process works in reverse, precooling the incoming air. The preheating or precooling of ventilation air reduces the need for heating and cooling energy.

AIR CHANGES
A measure of the air exchange in a building due to infiltration or ventilation. One air change occurs when the building's entire volume of air has been replaced.

AIR COLLECTOR
A glazed facade or roof-integrated panel that collects solar radiation to heat air circulated behind the glass, which is then moved to thermal storage remote from the collector. The air is usually circulated next to an absorber plate.

ALTITUDE, Solar
The angle of the sun above the horizon, as seen in a section view parallel to the sun's azimuth.

AMBIENT LIGHT
General illumination in a room, usually diffuse and often at lower illuminance than lighting for specific activities. See also *Task Lighting*.

AMBIENT TEMPERATURE
Surrounding air temperature, as in a room or around a building, in contrast to a local or modified temperature.

ANGLE OF INCIDENCE
The angle between the sun and the perpendicular of the receiving surface, or depending on the system used, the angle between the sun and the receiving surface.

APERTURE
An opening in a wall or roof that admits sun, wind, or light. See also *Solar Aperture*.

ASHRAE
American Society of Heating, Refrigerating and Air-conditioning Engineers.

ASPECT RATIO
Ratio between two sides of a rectangular object, such as the height: width of a duct or an atrium.

ASPECT, Solar
The geometric relationship between the sun and a surface, often the ground, including both the orientation (declination) and tilt (slope) of the surface.

ATRIUM
A usually large and multistoried, glass-roofed room used to bring daylight to the interior of thick buildings where sidelight alone cannot penetrate. The atrium may be enclosed on two, three, or four sides by the rooms it helps light.

ATTACHED SUNSPACE
A room that doubles as a solar collector. The term attached also implies a space that shares one common wall with the associated building. See also *Sunspace* and *Semi-Enclosed Sunspace*.

AUXILIARY HEAT
Heat delivered to a building by active systems to supplement solar heat.

AZIMUTH, Solar
The angle of the sun, as seen in plan, measured in degrees from south (or from north in the Southern Hemisphere); also, the orientation of a building. Used in this book, an azimuth of zero describes a glazing or wall that faces due south, so north orientation = 180˚, west orientation = 90˚ west and east orientation = 90˚ east. See also *Altitude*.

BALANCE POINT TEMPERATURE
The outside temperature at which a building shifts from a need for cooling to a need for heating, or vice versa. It is the temperature at which the sum of solar heat gains and internal heat gains balances envelope heat transfer from the skin and infiltration/ventilation, to maintain a desired indoor temperature.

BRIGHTNESS
The subjective human perception of luminance. See also *Luminance*.

Btu (British thermal unit)
A unit of heat; specifically, the heat needed to raise the temperature of one pound of water by 1 °F. See also *Joule*.

Btu/hr (British thermal units per hour)
A measure of the rate of energy flow (power) commonly used to express heat loss or heat gain or the size of heating and cooling equipment. 1 Btu/hr = 0.2929 W. See also *Watt*.

Btu/hr, ft^2, ˚F (British thermal units per hour, per square foot, per degree Fahrenheit of temperature difference.)
A measure of heat flow (thermal conductance). The I-P units of *U*-factor.

BUNDLE
A set of related design strategies that work together to resolve commonly occurring design problems.

CANDELA (cd)
An SI unit of luminous intensity. An ordinary candle has a luminous intensity of one candela. See also *Candlepower*.

CANDLEPOWER (cp)
An I-P unit of luminous intensity. An ordinary candle has a luminous intensity of one candlepower. See also *Candela*.

CARBON-NEUTRAL BUILDING
A building that uses no fossil fuels to operate. Some definitions include allowance for off-site renewable energy, while others require the renewable energy to be produced on-site.

CLEAR SKY
A sky condition with few or no clouds, usually taken as 0–2 tenths covered in clouds. Clear skies have high luminance and high radiation, and create strong shadows relative to more cloudy conditions. The sky is brightest nearest the sun; and away from the sun, it is about three times brighter at the horizon than at the zenith. See also *Overcast Sky* and *Partly Cloudy Sky*.

CLO
Clothing factor, a measure of the insulating value of clothing. For example, 0.3 Clo is typical for light summer clothing; 0.8 is typical for heavy winter clothing.

COMFORT PARAMETER (Ψ)
An indicator of human comfort in relation to wind; it is a relative reference value, accounting for both wind speed and turbulence, based on the ratio of wind speed at a location near a building to the wind speed that would be present at the same point with no building. In winter, a higher Ψ means less comfortable (overspeed) conditions; in summer, however, it indicates increased comfort. Range is 0–2.0.

COMFORT ZONE
On the bioclimatic chart, the area of combined temperatures and humidities that 80% of people find comfortable. People are assumed to be in the shade, fully protected from wind, engaged in light activity and wearing moderate levels of clothing that increase slightly in winter.

CONDENSATION
The process of vapor changing into liquid. In the process, it releases heat.

CONDITIONED AND UNCONDITIONED SPACES
Conditioned spaces need air treatment such as heat addition, heat removal, moisture removal, or pollution removal. Unconditioned spaces do not need such air conditioning, and no effort is made to control infiltration.

CONDITIONED FLOOR AREA
See *Floor Area, Conditioned*.

CONDUCTANCE
See *Thermal Conductance*.

CONDUCTION
The transfer of heat through a static medium, usually a solid such as concrete. See also *Radiation, Evaporation and Convection*.

CONDUCTIVITY
See *Thermal Conductivity*.

CONSERVATION FACTOR
A relative factor, based on regional climate and fuel costs, used to recommend insulation and air tightness levels

CONTRAST
A qualitative perception of the difference between two elements in the visual field, especially of their luminance. The subjective assessment of the difference in appearance of two parts of a field of view seen simultaneously or successively.

CONVECTION
Heat transferred between a surface and an adjacent fluid (usually air or water) by the circulation of that fluid, induced by a temperature differential.

COOLING DEGREE DAYS (CDD)
See *Degree Days*.

COOLING LOAD
A total load with net cooling required. See also *Total Load* and *Heat Load*.

COOL TOWER
See *Downdraft Evaporative Cooling Tower*.

CROSS-VENTILATION
Ventilative cooling of people and spaces driven by the force of wind. When outside air is cooler than inside air, heat can be transferred from the space to the ventilation air. Cross-ventilation also removes heat from people by convection and by increasing the rate of perspiration evaporation. The cooling rate from cross-ventilation is determined by wind speed, opening sizes and the temperature difference between inside and outside. See also *Stack-Ventilation*.

DAYLIGHT/DAYLIGHTING
Illuminance from radiation in the visible spectrum from the diffuse sky, reflected light and direct sun that lights a room.

DAYLIGHT ENVELOPE
The maximum buildable volume on a site that will not unduly restrict daylight available to adjacent buildings.

DAYLIGHT FACTOR (DF)
The proportion of interior horizontal illuminance (usually taken on a work plane) to exterior horizontal illuminance under an unobstructed sky. It is the sum of the *Sky Component, External Reflected Component* and the *Internal Reflected Component*. Range is 0–100%, but for most rooms is usually limited to 1–10%.

DEGREE DAY (DD)
The difference, measured in degrees F or C, between a base temperature and the average outdoor temperature for a single day. For heating degree days, outdoor temperature is always below the base. For cooling degree days, outdoor temperature is always above the base. Heating degree days are often calculated from the building's balance point temperature: 45, 55, 65 ˚F (7.2, 12.8, 18.3 ˚C). Cooling degree days can be calculated from a base at the balance point (usually 65 ˚F/18.3 ˚C) or from the top of the comfort zone (usually 80 or 83 ˚F/26.7 or 28.3 ˚C).

DELTA T (ΔT)
A difference in temperature, usually referring to the difference between indoor and outdoor temperatures.

DEGREE DAYS, Annual
The sum of degree days, for either heating (HDD) or cooling (CDD), for the entire year in a given location. It is determined by adding together the degree days for each individual day.

DESIGN STRATEGY
See *Strategy*.

DIFFUSE RADIATION
The component of solar radiation that has been scattered by atmospheric particles. Diffuse radiation is assumed to be evenly distributed throughout the sky dome. See also *Sky Light*.

DIFFUSE REFLECTANCE
Reflectance is the ratio of reflected radiation to incident radiation. Diffuse reflectance spreads incident flux over a range of reflected angles/directions. See also *Specular Reflectance*.

DIRECT GAIN
The transmission of sunlight through glazing directly into the space to be heated, where it is converted to heat by absorption on interior mass surfaces. See also *Indirect Gain* and *Isolated Gain*.

DIRECT MASS
Thermal mass used to store solar heat and located so that the sun strikes the mass or so that the mass is located somewhere in the room that collects sun. Heat transfer is primarily by radiation. Contrast to *Indirect Mass*.

DIRECT RADIATION

The component of solar radiation that comes directly from the sun without being diffused or reflected.

DIRECT SUNLIGHT

The component of visible spectrum radiation that comes directly from the sun without being diffused or reflected.

DISTRIBUTION

The process of moving heat or cool from its source to where it is needed, or to and from thermal storage. Radiation and convention are the most common types of delivery for heat distribution. Distribution can also refer to the building components.

DIURNAL

Relating to a 24-hour cycle. A diurnal temperature swing is the cycle of temperature over the course of one 24-hour period.

DIURNAL HEAT CAPACITY

The daily amount of heat, per unit of surface area, that is stored and then given back, per unit of temperature swing. Units are Btu/ft^2, F.

DOWNDRAFT EVAPORATIVE COOLING TOWER

A cooling system that humidifies and cools warm dry air by passing it though a wetted pad at the top of a tower. The cooled air, being denser, falls down the tower and into the occupied space below, drawing in more air through the pads in the process. Thus, no distribution fans are required.

DRY-BULB TEMPERATURE

The air temperature measured using a conventional thermometer. See also *Wet-Bulb Temperature*.

EARTH–AIR HEAT EXCHANGERS

A strategy of pretempering fresh air for ventilation, and in some cases, providing building cooling by passing incoming air through buried ducts.

EARTH CONTACT

The strategy of placing building surfaces in contact with the ground to reduce the temperature difference between inside and outside, reduce infiltration, and/or use the subsurface soil temperatures to cool the building.

EARTH TUBES

See *Earth–Air Heat Exchangers*.

EMITTANCE/EMISSIVITY

A measure of a material's ability to emit (lose heat by) radiation at a given temperature. Range is 0–1.0. Emissivity is usually proportionally inverse to absorptance.

ENERGY BALANCE INDEX (EBI)

A spectrum of energy demand versus on-site energy supply. Energy Balance Index = Energy Production Intensity minus Energy Use Intensity (building energy demand). [EBI = EPI - EUI].

ENERGY PRODUCTION INTENSITY (EPI)

The annual energy generated within the boundaries of the site, on a per unit floor area basis, based on available climate resources for photovoltaic panels, wind turbines or other renewable power generation methods.

ENERGY USE INTENSITY (EUI)

The amount of energy required by a building, on a per unit floor area basis, calculated by dividing the total annual energy use by the total floor area of the building. The EUI may, depending on its context of use, refer to either the building's (gross) energy demand before accounting for renewable energy production or, to its net energy use after accounting for renewable energy production.

ENVELOPE HEAT GAIN or LOSS

Heat transferred through the skin or via infiltration/ventilation. See also *Internal Gain* and *Solar Gain*.

ENVELOPE LOAD

The demand for energy required at any moment to compensate for the difference between desired indoor conditions and heat gains or losses from conduction transfer through the skin and infiltration/ventilation. See also *Total Load, Solar Load* and *Internal Load*.

EQUATOR-FACING

South-facing in the Northern Hemisphere; north-facing in the Southern Hemisphere. The opposite of *Polar-Facing*.

EQUINOX

Meaning literally "equal night." The dates during the year when the hours of daylight are equal to the hours of darkness. The equinoxes fall on or near March 21 and September 21. On the equinox, the sun rises from the horizon at due east and sets due west.

EVAPORATION

Phase change of a material from liquid to vapor. In the process evaporative cooling occurs.

EVAPORATIVE COOLING

A heat removal process in which water vapor is added to air, increasing its relative humidity while lowering its temperature. The total amount of heat (enthalpy) in the air stays constant but

is transferred from sensible heat in the air to latent heat in the moisture. In the process of shifting from liquid to vapor (evaporating), the water must absorb large amounts of heat.

EVAPORATIVE COOLING, Direct
A cooling process where warm, dry air is moved through a wetted medium to evaporate moisture into the air. The cooler, more humid air is then used to cool a space.

EVAPORATIVE COOLING, Indirect
A cooling process where the evaporative process is remote from the conditioned space. The cooled air is then used to lower the temperature of a building surface, such as in a roof spray, or is passed through a heat exchanger to cool indoor air. The indirect process has the advantage of lowering temperatures without adding humidity to the air, thus extending the climatic conditions and regions in which evaporative cooling is effective.

EXTERNALLY REFLECTED COMPONENT
The portion of the daylight factor (at a point indoors) that is contributed by light reflected from external surfaces such as the ground and adjacent buildings. See also *Daylight Factor, Sky Component* and *Internally Reflected Component*.

FLOOR AREA, Conditioned
The portion of a building that is heated and/or cooled. Does not include attics, unheated basements, outdoor spaces, garages, unheated buffer zones, etc. See also *Conditioned and Unconditioned Spaces*.

FOOT-CANDLE (fc)
An I-P measure of illuminance; specifically, the amount of direct light from one candle falling on one square foot of surface one foot away (lumens/ft^2). Foot-candle x 10.764 = lux. See also *Lux*.

FOOTLAMBERT (fL)
A measure of the luminance (photometric intensity) from a light source. 1 footlambert = 0.318 candelas/ft^2. See also *Luminance*.

GLARE
The perception caused by a very bright light or a high contrast of light, making it uncomfortable or difficult to see. See also *Contrast*.

GLAZING
Transparent or translucent materials, usually glass or plastic, used to cover an opening without impeding (relative to opaque materials) the admission of solar radiation and light.

GREENHOUSE, Solar
In energy terms, a sunspace where plants are also grown. See *Sunspace*.

GREEN POWER
See *Renewable Energy*

HEAT CAPACITY
Also known as volumetric heat capacity. A measure of the ability of an element of thermal storage mass to store heat per unit of volume. It is the product of the material's density and specific heat. Units are Btu/ft^3, °F (kJ/m^3, ˚C). Water has a heat capacity of 62.4 (4181); masonry, about 15–23 (1000–1550). See also *Specific Heat*.

HEAT GAIN
The gross amount of heat that is introduced into a space, whether from incoming radiation, air infiltration, ventilation, or internal sources such as occupants, lights and equipment. See also *Heat Loss*.

HEATING DEGREE DAYS (HDD)
See *Degree Day*.

HEAT ISLAND
The increased temperatures, relative to surrounding open land, found in center cities and areas of high development density. Heat islands are caused by concentrations of heat sources, decreased vegetation cover, increased massive and dark surfaces, decreased wind flows and narrow sky view angles.

HEAT LOAD
A total load with net heating required. See *Cooling Load* and *Load, total*.

HEAT LOSS
The gross amount of heat that leaves a space by heat flow through the building envelope, air infiltration, or ventilation.

HORIZON
All points at zero degrees solar altitude from an observing point.

HVAC
Mechanical systems for heating, ventilating and air-conditioning that control temperature, humidity and air quality.

HYBRID SYSTEM
A solar heating or cooling system that combines passive and active elements.

HYPOCAUST
Massive floors with channels through which solar heated air passes, giving up its heat to the mass for storage and radiation to the floor surface above and/or the ceiling below. Originally, a Roman system of under-floor heating in which combustion gases from a wood fire were passed under a massive floor. See also *Murocaust*.

ILLUMINANCE
The measure of light intensity striking a surface. Specifically, the concentration of incident luminous flux, measured in footcandles (I-P) or lux (SI). *See also Luminance.*

ILLUMINATION
Lighting of a surface by daylight or electric light. See also *Illuminance.*

INCIDENT ANGLE
See *Angle of Incidence.*

INDIRECT GAIN
The transfer of solar heat into the space to be heated from a collector that is coupled to the space by an uninsulated, conductive, or convective medium; for example, thermal storage walls and roof ponds. See also *Direct Gain* and *Isolated Gain.*

INDIRECT MASS
Mass used for thermal storage that is located remote from solar collection and uses air (convection) to transfer heat between collection and storage. Because convention transfer rates are lower than for radiation, indirect mass is less effective and thus must be larger than direct mass. Contrast with *Direct Mass.*

INFILTRATION LOAD
Air exchange between interior spaces and the outdoors, resulting in heat loss or gain. It is driven by the difference in pressure between inside and outside; buildings exposed to higher wind speeds and buildings with looser construction have increased rates of infiltration. Heat transfer from infiltration is proportional to the volume of air entering and to the temperature difference between inside and outside.

INSOLATION
The total amount of direct, diffuse and reflected solar radiation that strikes a surface. This total radiation is also known as global radiation. Insolation is usually measured in Btu per square foot per hour or per day (Btu/ft^2, hr—sometimes written Btu/hr ft^2, or Btu/ft^2, day). Metric (SI) units are usually kilowatt-hours per square meter per day (kWh/m^2, day).

INSULATION
Any low mass material with high thermal resistance used to slow the transfer of heat via conduction. May also refer to materials used to reflect radiant heat (reflective insulation). See also *Internal Sources.*

INTEGRATED DESIGN
The synthesis of climate, use loads and systems to achieve a more comfortable and productive environment for the occupants, and a building that is more energy efficient than current best practices.

INTERNAL HEAT GAIN
Heat generated inside the building by sources other than the space-heating equipment, usually by appliances, lights and people. See also *Internal Sources.*

INTERNAL LOAD
The demand for energy required at any moment to compensate for the difference between desired indoor conditions and heat gains from the internal sources of electric lights, people and equipment. See also *Solar Load, Envelope Load* and *Load, total.*

INTERNAL-LOAD–DOMINATED BUILDING (ILD)
A building with a balance point well below the desired interior temperature and having a heat load profile in which internal gains or solar gains are much larger than the envelope load. See also *Skin-Load–Dominated Building.*

INTERNALLY REFLECTED COMPONENT
The portion of the daylight factor contributed by light reflected from internal surfaces such as walls, floor and ceiling. See also *Daylight Factor, Sky Component,* and *Externally Reflected Component.*

INTERNAL SOURCES
The sources of internal heat gain other than the space-heating equipment, such as appliances, lights and people. See also *Internal Heat Gain.*

I-P UNITS
Inch-pound units, the "American standard," system of measurement used in the United States. Also known as (English) imperial units. See also *SI Units.*

ISOLATED GAIN
The transfer of heat into a space from a collector that is thermally isolated either by physical separation or insulation. Examples include convective loop collectors and attached sunspaces with an insulated common wall. See also *Direct Gain* and *Indirect Gain.*

JOULE
A metric (SI) unit of heat; specifically, the 1/4.184 of the heat needed to raise the temperature of one gram of water by 1 °C. 1000 joules = 1 kilojoule (kJ); 1 kJ = 0.9478 Btu. See also *Btu* and *Watt.*

LATENT HEAT
A change in heat content that occurs without a corresponding change in dry bulb temperature, usually accompanied by a

change of state, as when water vapor in the air condenses.

LATITUDE
The angular distance north or south of the earth's equator, measured in degrees along a meridian. The equator is 0 degrees; the North Pole is 90˚ North latitude. Latitudes farther from the equator have lower sun angles, less radiation and illuminance per hour, and more variation in sun path between summer and winter. See also *Longitude*.

LEE
The downwind side of a building or obstruction that faces away from the direction from which the wind blows, usually subjected to lower pressure, reduced wind speeds and higher turbulence. See also *Windward*.

LIGHT SHELF
A horizontal reflector dividing upper and lower glazing, used to reflect light to the ceiling, even daylight distribution in a room, and reduce glare.

LIGHT-TO-SOLAR-GAIN RATIO (LSG)
A relative expression of the "coolness" of a glazing, obtained by dividing its visible transmittance (VT) by its solar heat gain coefficient (SHGC). A daylit building in a hot climate would ideally use a glazing with high VT and low SHGF.

LOAD COLLECTOR RATIO (LCR)
The ratio of the building load coefficient (heat load per degree day) to the collection area. LCR is an expression of the relationship between energy conservation and solar gain and can be used to compare buildings within the same locality.

LOADS
Heating, cooling, lighting, ventilation and electricity demands placed on building systems that require energy to satisfy.

LOAD, Total
The demand for energy required at any moment to compensate for the difference between desired indoor conditions and the net of heat gains and losses from *Internal Loads, Solar Loads and Envelope Loads*. See also *Cooling Load* and *Heating Load*.

LONGITUDE
Angular distance on the earth's surface, measured east or west from the prime meridian (0 degrees) at Greenwich, England, to the meridian passing through a position, expressed in degrees. St. Louis, Missouri, is at 90˚ West longitude. Range is 0–180, East or West. See also *Latitude*.

LUMEN (lm)
Unit measuring the rate of light flow (luminous flux). Each square foot (square meter) of spherical surface surrounding a one candela (candlepower) light source receives one lumen of light flux. Lumen is the unit used in both I-P and SI units. One lumen produces a 1 foot-candle (lux) illuminance.

LUMINANCE (L)
The luminous intensity (photometric brightness) of a light source or reflecting surface, including factors of reflection, transmission and emission. Units are candelas per square foot (cd/ft^2) and candelas per square meter (cd/m^2). An unobstructed sky of 1 footlambert luminance produces an illuminance of 1 foot-candle on a horizontal surface. See also *Brightness, Illuminance* and *Footlambert*.

LUMINOUS FLUX
The flow of light from a source to a receiving surface, measured in lumens (lm).

LUX
A metric (SI) measure of illuminance; specifically, the amount of direct light from one candle (one candela) falling on one square meter of surface one meter away ($lumens/m^2$). 1 lux x 0.0929 = 1 foot-candle. See also *Foot-candle*.

MASONRY
Concrete block, brick, adobe, stone, concrete and other similar massive materials.

MASS-AREA-TO-GLAZING-AREA RATIO
The ratio of the surface area of massive elements in a solar heated building to the total solar collection area. Massive elements include all floors, walls, ceilings and other high-density interior objects.

MASS, Thermal
See *Thermal Mass*.

MEAN RADIANT TEMPERATURE (MRT)
The weighted average temperature of surrounding surfaces, based on the angular size between a person (or other surface) and those surfaces. A lower MRT of room surfaces, such as with earth contact, can give the perception of comfort at higher air temperatures than when the surfaces are near the temperature of the indoor air. Similarly, in a passively heated building, a person will feel comfortable in a room with warm thermal mass (higher MRT) at lower air temperatures than if in a room with no mass.

MET
Human metabolic rate of heat gain. A measure of the heat produced by a seated sedentary person, and therefore added to the space the person occupies. One met unit = 18.4 Btu/hr, ft^2 (58.2 W/m^2).

MOVABLE INSULATION
Operable thermal insulating shades or shutters placed over windows only at night to reduce convective and radiant losses through the glazing at night. Movable insulation greatly increases the solar savings fraction in passive solar heated buildings, because more of the heat captured during the day is retained for use during the night.

MUROCAUST
Massive walls with vertical channels through which solar-heated air passes, giving up its heat to the mass for storage and radiation to the interior wall surface(s). See also *Hypocaust*.

NATURAL CONVECTION
Heat transfer between a surface and adjacent fluid (usually air or water), by the circulation of the fluid induced by temperature differences only and not by mechanical means.

NET-POSITIVE ENERGY BUILDING
A building that produces, on an annual basis, more energy than it consumes. In *SWL,* this means a "site net-positive energy building," which is a building that produces on-site more energy than it consumes.

NET-ZERO ENERGY BUILDING
A building that produces as much energy as it consumes during a given time period. Specifically in *SWL,* a building that produces, on an annual basis, as much energy as it consumes. In *SWL,* this means a "site net-zero energy building," which is a building that produces on-site as much energy as it consumes. See also *Peak-Zero, Net-Positive Energy Building*.

NIGHT INSULATION
See *Movable Insulation*.

NIGHT SKY RADIATION
A reversal of the daytime insolation principle. Just as the sun radiates energy during the day through the void of space, so heat energy can travel unhindered at night, from the earth's surface back into space. On a clear night any warm object can cool itself by radiating long-wave heat energy to the cooler sky. On a cloudy night, the cloud cover acts as an insulator and prevents the heat from traveling to the cooler sky.

NIGHT VENTILATION OF MASS
A cooling process where a building is closed during the hot daytime hours, its heat gains are stored during that time in the building's structure or other thermal mass, and then at night the building is opened, and cooler outdoor air is used to flush heat from the mass, lowering its temperature to prepare for another cycle.

OPAQUE
Not able to transmit light; for example, unglazed walls.

OVERCAST SKY
The condition in which the sky is completely covered in clouds and the sun cannot be seen. Usually taken as 8–10 tenths covered in clouds. Overcast skies generally have lower luminance, lower radiation and create weak shadows and more diffuse lighting, relative to clearer conditions. The sky is about three times brighter at the zenith than at the horizon. See also *Partly Cloudy Sky* and *Clear Sky*.

PARTLY CLOUDY SKY
The sky condition between overcast and clear conditions, which varies from mostly cloudy with patches of clearness to mostly clear with a few clouds. Partly cloudy skies are highly variable and difficult to predict. Usually taken to be 2–8 tenths covered in clouds. See also *Cloudy Sky* and *Clear Sky*.

PASSIVE SYSTEM
A system that uses nonmechanical, nonelectrical means to satisfy heating, lighting or cooling loads. Purely passive systems use radiation, conduction, and natural convection to distribute heat and daylight for lighting.

PEAK LOADS
The highest system demands during a given period, often occurring when extreme climatic and high occupancy factors coincide. Peak loads may be daily, seasonal, or annual.

PEAK-ZERO, NET-POSITIVE ENERGY BUILDING
A building that produces at least as much energy as it uses at its peak load hour during the year. Depending on the building and climate, the peak load hour may be during the heating season (usually at night) or during the cooling season (usually during the afternoon). A peak-zero energy building is also a *net-positive energy building*.

PERCENTAGE OF POSSIBLE SUNSHINE
The total actual time that sunshine reaches the surface of the earth is expressed as the percentage of the maximum time possible from sunrise to sunset with clear sky conditions.

PHASE CHANGE MATERIAL (PCM)
Materials that melt and solidify at designated temperatures, capable of storing and releasing large amounts of energy during the change of phase. PCMs can be used to store heat or cool in buildings.

PHOTOVOLTAICS (PV)
A means of generating electricity from sunlight using semiconductors that exhibit the photovoltaic effect.

POLAR-FACING
North-facing in the Northern Hemisphere; South-facing in the Southern Hemisphere. The opposite of *equator-facing*.

PROFILE ANGLE
The angle used to size overhangs or spacing between buildings for shade; specifically, the vertical shadow angle of an overhang made by the angle between a horizontal from the bottom of a window and a line between the bottom of the window and the end of the overhang. It is the geometric translation of the solar altitude of the sun at a particular time into the plane normal to the window. When the sun's azimuth is perpendicular to the window, the profile angle is equal to the sun's altitude. When the sun is at any other angle, the profile angle and solar altitude will be different.

RADIANT TEMPERATURE
The average temperature of surfaces surrounding a person or surface with which the person or surface can exchange thermal radiation. See also *Radiation, Thermal* and *Mean Radiant Temperature*.

RADIATION, Solar
See Solar Radiation.

RADIATION, Thermal
The transfer of heat by electromagnetic waves. It does not require material contact (as does *Conduction*) or a fluid medium (as does *Convection*). Any two surfaces with a direct line of sight between them and a temperature difference will have a radiant exchange. *See also Solar Radiation and Night Sky Radiation*.

REFERENCE NONSOLAR BUILDING
A building similar to a solar building but with an energy-neutral wall in place of the solar wall and with a constant indoor reference temperature. Used as a reference for assessing the performance of solar buildings.

REFLECTANCE
The ratio of radiation reflected by a surface to the radiation incident on it. Range is 0–1.0.

RELATIVE HUMIDITY
The percentage of water vapor in the atmosphere relative to the maximum amount of water vapor that can be held by the air at a given temperature.

REMOTE STORAGE/REMOTE MASS
Thermal mass or other thermal storage located outside occupied spaces, such as in a rock bed. It is normally used to increase the thermal storage capacity beyond what can be stored in the building's massive walls, floors, roofs, or structure.

RENEWABLE ENERGY (RE)
Energy produced from renewable sources (not from burned fossil fuels), such as sun, biomass and wind. RE may be produced on-site or purchased from a power utility.

ROCK BED/ROCK STORAGE SYSTEM
A solar energy storage system in which the collected heat or cold is stored in a rock bin for later use. This type of storage can be used in an active, hybrid, or even passive system.

ROOF POND SYSTEM
An indirect gain heating and cooling system in which the mass, which is water in plastic bags, is located on the roof of the space to be heated or cooled and covered with a movable insulation. A roof pond system absorbs solar radiation for heating in the winter and radiates heat to the night sky for cooling in the summer.

***R*-VALUE (*R*)**
A measure of the thermal resistance of a building element. *R* is the number of hours needed for 1 Btu to flow through one square foot of skin, given a temperature difference of 1 ˚F. The units for *R* are ft^2, ˚F, hr/Btu (or m^2, K/W). The reciprocal of *R* is the *U*-factor. See also *Thermal Resistance* and U-*Factor*.

SELECTIVE SURFACE
A surface used to absorb and retain solar heat in a solar heating system such as a trombe wall or in a solar collector. Often a dark metallic surface, selective surfaces have high absorptance and low emittance. See also *Absorptance* and *Emittance*.

SEMI-ENCLOSED SUNSPACE
A sunspace that shares three common walls with the associated building. See also *Attached Sunspace* and *Sunspace*.

SENSIBLE HEAT
Heat that results in a change in air temperature, in contrast with latent heat.

SHADING COEFFICIENT (SC)
The total amount of radiation transmitted though a glazing, relative to clear, 1/8 in (3 mm) single glass, which has, by definition, a shading coefficient of 1.0. Also used to define the fraction of incident radiation transmitted by an internal or external shading device. For glazing, SC ≈ 1.15 x Solar Heat Gain Coefficient. See also *Solar Heat Gain Coefficient (SHGC)*.

SIDELIGHT
Daylight from apertures in a wall. *See also, Toplight*.

SIMPLE PAYBACK PERIOD
The time (usually measured in years) for an investment in an energy saving system or design to pay for itself by the cost of energy saved. It is determined by dividing the initial cost by the annual rate of savings.

SITE NET-ZERO ENERGY BUILDING
See *Net-Zero Energy Building*.

S-I UNITS
Standard international units; the metric system. See also *I-P Units*.

SKIN-LOAD–DOMINATED BUILDING (SLD)
A building with a balance point near the desired interior temperature and having a heat load profile in which the envelope load is much larger than the solar load or internal load. See also *Internal-Load–Dominated Building*.

SKY COMPONENT
The portion of the daylight factor (at a point indoors) contributed by luminance from the sky, excluding direct sunlight. See also *Daylight Factor, Internally Reflected Component,* and *Externally Reflected Component*.

SKY COVER
A measure of the fraction of the sky covered in clouds. Range is 0–10 tenths. See also *Overcast Sky, Partly Cloudy Sky,* and *Clear Sky*.

SKY LIGHT
Daylight from the sky dome only, excluding the direct sun. See also *Sunlight*.

SKYLIGHT
A roof window, horizontal or sloped.

SKY LUMINANCE DISTRIBUTION—THE C.I.E. STANDARD OVERCAST SKY
A completely overcast sky for which the ratio of luminance at an altitude q above the horizon to the luminance at the zenith is assumed to be $(1 + 2 \sin q) /3$. This means that the luminance at the zenith is three times brighter than at the horizon.

SKY VIEW FACTOR (*v*)
The sector of the sky as seen from a daylight aperture or building surface. It can be measured in either section or as a three-dimensional solid angle. Specifically, for daylighting calculations, v is the angle subtended, in the vertical plane perpendicular to the window, by sky visible from the center of the window. The larger the area of sky seen by a window, the more illuminance available from the sky and the higher the daylight factor in the room. The sky view factor can be reduced by obstructions such as buildings, trees and landforms. For a surface that needs to lose heat by radiation to the night sky, the sky view angle determines the rate of cooling. Urban streets and building facades often have their view of the sky blocked by adjacent buildings of the urban canyon.

SOLAR ABSORPTANCE
The fraction of incident solar radiation that is absorbed by a surface. The radiation not absorbed by an opaque surface is reflected. Range is 0–1.0. See also *Emittance* and *Absorptance*.

SOLAR APERTURE
That portion of the solar wall covered by glazing. The orientation of the opening should be within 30° of south (30° of north in the Southern Hemisphere) to be considered a solar aperture.

SOLAR COLLECTOR/COLLECTION
The component/s of a solar heating system that captures solar radiation. Collectors may be architectural, such as windows in a direct gain system or engineered products, such as in a solar hot water system.

SOLAR ENVELOPE
The maximum buildable volume on a site that will not shade adjacent sites during specified dates and times.

SOLAR GAIN
Heat transferred to a space by solar radiation through glazing. See also *Internal Gain* and *Envelope Gain*.

SOLAR HEAT GAIN COEFFICIENT (SHGC)
The fraction of incident solar radiation (for the full spectrum) which passes though an entire window assembly, including the frame, at a specified angle. Range is 0–0.85. A higher SHGC is preferred in solar heating applications to capture maximum sun, whereas in cooling applications, a low SHGC reduces unwanted solar heat gain.

SOLAR HEAT GAIN FACTOR (SHGF)
The amount of solar heat transmitted though a standard glazing (single or double) per unit of glazing area, for a given latitude or location, time, date and orientation. Depending on the source, SHGFs may be given for either single glazing or double glazing, and either by latitude, in which case average clear days are assumed, or by specific city, in which case, average sky condition is used. The amount of radiation transmitted depends on the angle of the sun with respect to the window and on the intensity of the radiation incident. Units are Btu/hr, ft^2 (W/m^2). See also *Shading Coefficient*.

SOLAR LOAD
The demand for energy required at any moment to compensate for the difference between desired indoor conditions and heat gains from solar radiation. *See also Envelope Load, Internal Load* and *Load, Total*.

SOLAR RADIATION
Radiation emitted by the sun, including infrared radiation, ultraviolet radiation and visible light.

SOLAR REFLECTANCE INDEX (SRI)
A measure of a material's ability to reject solar heat, as shown by its temperature rise under full sun. It is defined so that a standard black (reflectance 0.05, emittance 0.90) has an SRI of 0 and a standard white (reflectance 0.80, emittance 0.90) has an SRI of 100. Materials with higher SRI values are cooler.

SOLAR SAVINGS FRACTION (SSF)
The percentage of annual heating energy saved by using solar energy to space heat a building, compared to a nonsolar building with similar thermal characteristics.

SOLAR TIME
Time of day adjusted so that the sun is due south at noon.

SOLSTICE
The dates of the shortest and longest days of the year. Winter solstice is on or around December 21 (June 21 in the Southern Hemisphere); summer solstice is on or around June 21 (December 21 in SH). Sun altitude is lowest at winter solstice and highest at summer solstice. Daily azimuth variation is greatest at summer solstice and least at winter solstice.

SPECIFIC HEAT
A measure of the ability of a material to store heat, specifically, the amount of heat in Btus required to raise the temperature of one pound of a material 1 °F. Units are Btu/lb, ˚F (kJ/kg, ˚C). In I-P units, water, by definition, has a specific heat of 1.0. Masonry materials are about 0.2. The heat capacity of a heat storage material is a product of its density and specific heat. See also *Heat Capacity*.

SPECULAR REFLECTANCE
Reflectance is the ratio of reflected radiation to incident radiation. Specular reflection redirects incident flux like a mirror at one specific angle where the angle of incidence is equal to the angle of reflection. See also *Diffuse Reflectance*.

STACK VENTILATION
The cooling process of natural ventilation induced by the chimney effect, where a pressure differential occurs across the section of a room. Air in the room absorbs heat gained in the space, expands and loses density, thus rising to the top of the space. When it exits through high outlet openings, a lower pressure is created low in the space, drawing in cooler outside air from low inlets.

STRATEGY
A generalized solution to a recurring design problem that connects architectural form to performance in ways that allow for design flexibility.

STRATIFICATION
The tendency of fluids, like air and water, to form layers when unevenly heated. The warmer fluid rises to the top of the available enclosure, and the cooler fluid drops to the bottom.

SUNDIAL
A latitude-specific chart used with a physical model for predicting shadow patterns on a site or sun penetration for a building design.

SUNLIGHT
Beam daylight from the sun only, excluding diffuse light from the sky dome. See also *Sky Light*.

SUN PATH DIAGRAM
A latitude-specific chart mapping the apparent movement of the sun and used to determine solar altitude and azimuth angles for a given time and date.

SUNSPACE
A room that doubles as a solar collector; also called greenhouse or solarium. Sunspaces concentrate solar radiation collection and heat storage in one room used to heat surrounding rooms. See also *Semi-enclosed Sunspace* and *Attached Sunspace*.

SYNERGY
A design concept based on relationships among climate, use, design and/or systems strategies that creates benefits greater than the sum of effects resulting from individual design strategies.

TASK LIGHT
Lighting on a specific area used for a specific task. Task lighting is usually from an electric source and is a higher illuminance level than the surrounding ambient light level. It is a good strategy to combine task light with ambient daylight. See also *Ambient Light*.

THERMAL BREAK (THERMAL BARRIER)
An element of low thermal conductivity placed within a composite envelope construction in such a way as to reduce the flow of heat across the assembly. See also *Thermal Bridge*.

THERMAL BRIDGE
An element of high thermal conductivity within a construction of otherwise low thermal conductivity. Small areas of materials that conduct heat at high rates can substantially reduce the insulating effectiveness of an assembly. Examples are metal frame windows without thermal breaks and metal stud walls, where the metal conducts heat at a much higher rate than the insulation between. See also *Thermal Break*.

THERMAL CONDUCTANCE (*C*)
A measure of the ease with which heat flows though a specified thickness of a material by conduction. Units are Btu/hr, ft^2, ˚F (or W/m^2, ˚C). See also U-*Factor* and *Thermal Conductivity*.

THERMAL CONDUCTIVITY (*k*)
A measure of the ease with which heat flows though a unit thickness of a material by conduction; specifically, the heat flow rate in Btu per inch of material thickness, square foot of material area and degree of temperature difference. Units are Btu, in/ft^2, hr, ˚F (W/m, ˚C). See also U-*Factor* and *Thermal Conductance*.

THERMAL MASS
Materials with high heat capacity, such as masonry or water, used to store heat or cool when there is an excess of a resource for use later when there is a need.

THERMAL RADIATION
Energy transfer in the form of electromagnetic waves from a body by virtue of its temperature, including infrared radiation, ultraviolet radiation and visible light.

THERMAL RESISTANCE
A measure of the insulation value or resistance to heat flow of building elements or materials; specifically, the reciprocal of the thermal conductance. See also R-*Value* and U-*Factor*.

THERMAL STORAGE MASS
High-density building elements, such as masonry or water in containers, designed to absorb solar heat during the day for release later when heat is needed.

THERMAL STORAGE WALL
A trombe wall or water wall.

THERMOCIRCULATION
The circulation of a fluid by convection. For example, the convection from a warm zone (sunspace or trombe wall air space) to a cool zone through openings in a common wall.

TOPHEAT
Solar heat gain admitted from skylights, monitors, cupolas, or clerestories.

TOPLIGHT
Daylight from skylights, monitors, cupolas, or clerestories. See also *Sidelight*.

TOTAL LOAD
See *Load, total*.

TROMBE WALL
A solar heating system consisting of a masonry thermal storage wall placed between the solar aperture and the heated space. Heat is transferred into the space by conduction through the masonry, radiation from its inner surface and, if vents are provided, by natural convection.

***U*-FACTOR (COEFFICIENT OF HEAT TRANSFER)**
A measure of heat flow, specifically, the number of Btus that flow through one square foot of building skin, in one hour, when there is a 1 ˚F difference in temperature between the inside and outside air, under steady-state conditions. The units for *U* are Btu/hr, ˚F, ft^2 (or W/K, m^2). The *U*-factor is the reciprocal of the resistance or *R*-value. See also *Thermal Conductance* and R-*Value*.

VENTILATION LOAD
The energy required to bring outdoor air to the desired indoor conditions. In this book, ventilation load refers to fresh air ventilation, which may be provided either naturally or by a mechanical system. The rate of required ventilation varies with the use of the space and the number of occupants. Ventilation load depends on the rate of fresh air ventilation and on the temperature difference between inside and outside. It may be reduced by pretempering or the use of heat exchangers.

VENTILATION (NATURAL)
Air flow through and within a space stimulated by either the distribution of pressure gradients around a building or thermal forces caused by temperature gradients between indoor and outdoor air. See also *Cross-Ventilation* and *Stack-Ventilation*.

VISIBLE TRANSMITTANCE (VT)
The fraction of incident visible light that passes though glazing. A higher VT is better for daylighting. A low solar heat gain coefficient (SHGC) that rejects heat can reduce VT, but not necessarily. Some spectrally selective glazings have both low SHGC and high VT. Range is 0–1.0. See also *Light-to-Solar-Gain Ratio*.

VOLUMETRIC HEAT CAPACITY
See *Heat Capacity*.

WATER WALL
A solar heating system consisting of a thermal storage wall of water in containers placed between the solar aperture and the heated space. Heat is transferred into the space by conduction and convection through the water and by radiation from the inner wall surface to the room.

WATT (W)
A measure of power commonly used to express heat loss or heat gain or to specify electrical equipment. It is the power required to produce energy at the rate of one joule per second. 1 W = 3.412 Btu/hr. See also *Btu/hr*.

Watt/m^2, ˚C
Watts, per square meter, per degree centigrade of temperature difference. A measure of heat flow (thermal conductance). The SI units of *U*-factor. See also, U-*Factor*.

WET-BULB TEMPERATURE
The air temperature measured using a thermometer with a wetted bulb moved rapidly through the air to promote evaporation. The evaporating moisture, changing phase, lowers the temperature measured, relative to that measured with a dry bulb. Wet-bulb temperature accounts for the effects of moisture in the air. It can be used, along with the dry-bulb temperature on a psychrometric chart to determine relative humidity. See also *Dry-Bulb Temperature*.

WINDWARD
The upwind side of a building or obstruction that faces the direction from which the wind blows, usually subjected to higher pressure. See also *Lee*.

WORKING PLANE (REFERENCE PLANE)
The horizontal work surface, usually at about 30–36 inches (0.8–0.9 m) from the floor, at which illumination is specified and measured.

ZENITH
The top of the sky dome. A point directly overhead, 90˚ in altitude angle above the horizon.

Appendix E

SWL Printed Bibliography

see also *SWL Electronic* Bibliography

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