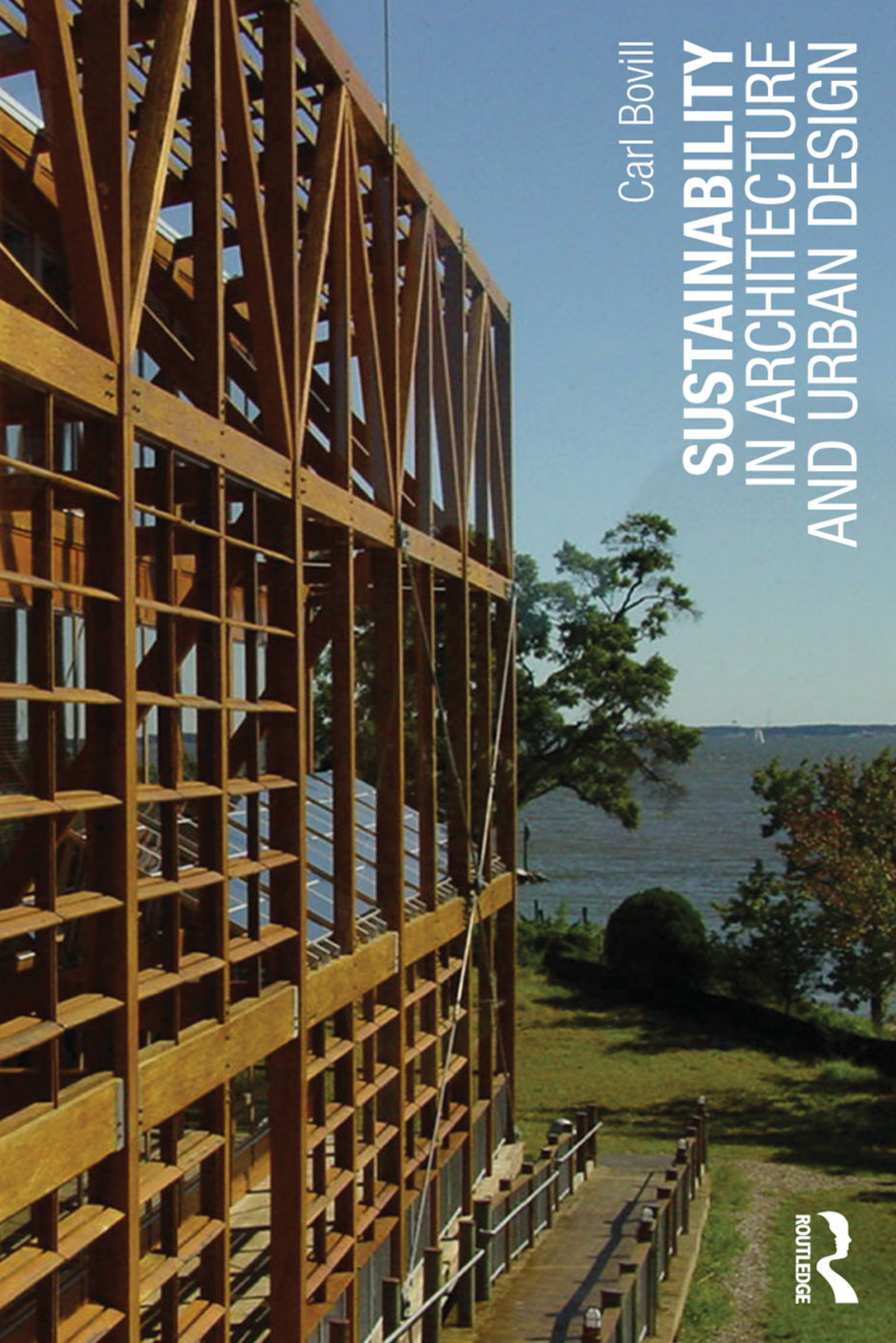

Carl Bovill

SUSTAINABILITY IN ARCHITECTURE AND URBAN DESIGN

ROUTLEDGE

SUSTAINABILITY IN ARCHITECTURE AND URBAN DESIGN

Sustainability in Architecture and Urban Design will help you understand the nature of the sustainability problem and show you how to implement your design for a sustainable future. Organized in six parts: the problem, the environment, the residential scale, the commercial scale, the urban scale, and energy sources, the book presents essential information in context so that you can get the full picture. Hundreds of drawings, sketches, charts, and diagrams illustrate points author Carl Bovill makes in his clear and direct style, which communicates the basics in a concise way.

You will learn:

- about environmental economics;
- how sustainable architectural design relates to ecology;
- how fractal geometry can lead to a new understanding of the structure of the world around us;
- how to design energy-efficient houses and commercial buildings;
- how to design and live in our cities to lower energy use per person;
- about LEED points at all scales;

A glossary and reading lists encourage you to explore the topics further.

Carl Bovill is an associate professor in the School of Architecture, Planning, and Preservation at the University of Maryland where he teaches materials, environmental controls, and sustainability. His publications include *Architectural Design: Integration of Structural and Environmental Control Systems* (1991) and *Fractal Geometry in Architecture and Design* (1996).

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PREFACE

Making a transition from a mass production, mass consumption, high energy use, growth-addicted society, to a society that can sustain itself indefinitely into the future will be difficult but must be done. This book is an attempt to outline the nature of the problem, and to point toward solutions. Part I, "The Global Sustainability Problem," after a short historical survey, explores the issues presented by exponential growth and global warming. Part II, "Ecology and the Environment," looks at ecosystems and how architecture relates to ecological patterns followed by how economics relates to environmental issues, and concludes with an overview of fractal geometry, which provides a way of seeing that is helpful in observing nature. After this the book provides guidance on the design of residential scale buildings, commercial scale buildings, and on the layout of urban environments that minimize energy use in Parts III, IV, and V, respectively. Finally, Part VI provides an overview of conventional fuels and alternative energy sources. If one takes a long view of human history and assuming we have a similarly long future, the fossil fuel use epoch that we are currently in is a short blip in time. To insure a long future, humanity needs to make adjustments.

I would like to thank the students who have taken my sustainability class for their discussions. I also need to thank the faculty of the School of Architecture, Planning, and Preservation for their guidance and for the sabbatical semester that allowed me to initiate the writing process. At Routledge I would like to thank Wendy Fuller, who guided me through the proposal process, and Laura Williams, Emma Gadsden and Grace Harrison, who have guided me through the production process. And most importantly, I need to thank my wife Jean and my daughters Mia and Anna who are always an inspiration. The future belongs to the young. It is important that society presents them with one.

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INTRODUCTION

There are books that cover the nature of the sustainability problem. There are books that cover climate change from greenhouse gases. There are books about nature and ecosystems as models of sustainability. There are books about environmental economics. There are books about fractal geometry and chaos. There are books about the passive solar heating and cooling of residential scale buildings. There are books about heating, cooling and lighting commercial buildings and about their indoor air quality. There are books about urbanism and transit oriented development. There are books about conventional and alternative energy sources. I have been teaching a course on sustainability in the School of Architecture at the University of Maryland for almost 20 years. I cover all of the topics listed above but I am reluctant to ask the students to buy 10 or 15 books. This book is a response to this problem. It is intended to cover the broad range of topics necessary to understand why sustainability is a problem and to suggest strategic responses that architecture and urban design can provide.

The path to sustainability is not an algorithm. There are multiple overlapping paths to a sustainable future. Nature provides the pattern for a resilient sustainability. Nature is a complex overlay of countless living and nonliving components interacting in a balanced nonlinear fashion. Most of human society is monoculture and many of our attempts at sustainability are linear, like making cars more efficient rather than creating a more diverse system of getting around. Creating a complex nonlinear response to sustainability issues requires a broad understanding of the problem and a broad understanding of multiple solution paths.

Part I is an overview of the global sustainability problem. A history of energy use through time puts our current high energy using industrial society in the context of the long history of human existence. For most of human history we were embedded in nature, followed fairly recently by using knowledge of plants to create agriculture. The industrial revolution discovered that it was more efficient to burn fossil fuels than to burn wood or to use water or wind power to drive the machines of production. Industrialization has improved the standard of living resulting in exponential population growth. In 1960 there were 3 billion people; 40 years later, in 2000, there were 6 billion people. Currently there are a little more than 7 billion people, and UN estimates suggest that the population will not stabilize until we reach 10 billion. Industrial production per person is also increasing at an exponential rate. Exponential growth cannot continue on a planet with limited resources. *Beyond the Limits*, by Meadows et al. (1992), uses a computer model of modern society to explore the necessary steps to creating a sustainable future. Exponential growth of population and industrial output has to stop, and society needs to become more efficient in all aspects, from agriculture to industry. Another way to illustrate sustainability is with an analysis of the ecological footprint of various societies. The fair share of the earth per person is 1.8 hectares, which is 4.4 acres. An average citizen of the United States has a footprint of 8 hectares, which is four and a half times our fair share. The fossil fuels that we use to create the industrial wealth we enjoy have been and continue to fill the atmosphere with carbon dioxide. Current projections indicate that a global temperature rise of 4 degrees Centigrade will cause a sea level rise of one meter. The consequences for coastal cities are not good.

Part II starts to point toward solutions. The ecosystems of the world provide guidance for the design of a sustainable human society. A close look at how nature responds to climate can guide architectural and urban design responses to climate. One key feature of nature we need to learn from is that there is no waste in nature. Waste from one entity is food for another. Plants breathe in carbon dioxide and exhale oxygen. Animals breathe in oxygen and exhale carbon dioxide. Economic theory assumes unlimited resources that can be used to create products. Economic theory also assumes unlimited sinks to dispose of waste. Environmental issues are included as externalities and must be monetized to be compatible with standard economic theory. The current economic system requires exponential growth of 3 to 4 percent per year to be healthy. Nature provides opportunities for species survival without exponential growth. Understanding nature as a model of sustainability requires a way of seeing that is compatible with its complexity. Fractal geometry and chaos theory provides this way of seeing.

Part III of the book provides strategic design information for residential scale buildings. Residential scale building energy use is dominated by heat flows out of the envelope of a building in winter and into the envelope of the building in summer. Bioclimatic design provides guidance on the orientation and the shape of residential buildings. Passive solar heating and cooling requires knowledge of where the sun is in the sky and how to let the sun in in winter and exclude it in summer. However, high insulation levels are the most cost effective method of saving energy.

Part IV of the book covers strategies to minimize energy use in commercial buildings. Commercial buildings generate significant energy use from their internal functioning. Lighting and equipment use energy and generate heat. People also generate heat. Computer simulations show that heating, cooling, and lighting energy use can be significantly reduced through good design. Minimizing heating energy is mainly achieved by insulating exterior walls. Minimizing lighting energy comes from a combination of daylighting and artificial lighting design. The heating, ventilating, and air conditioning systems of commercial buildings are more complex to design and maintain with indoor air quality as an important issue. Good indoor air quality is a function of appropriate outside air ventilation and choice of interior finishes.

Part V of the book points out that urban design, especially density in urban design related to public transit, has a large effect on energy use. An urban lifestyle uses one-quarter of the energy of a suburban lifestyle. New urbanism and transit oriented development provide guidelines to a greener way of life.

Part VI of the book gives an overview of conventional and alternative energy sources. Making a transition to a no carbon energy system would go a long way toward creating a sustainable way of life, toward controlling greenhouse climate change, and toward long-term national security.

In conclusion, this book is arranged to define the severity of the problems we face creating a sustainable future followed by strategic design information at the residential, commercial, and urban scales. The intent is to guide early schematic design in the right direction. The information provided is not intended to be used for the final design of buildings or urban layouts. The reader needs to apply professional expertise and consult original sources.

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PART I

The Global Sustainability Problem

Historically human civilization has been sustainable. It had to be powered by local resources and agriculture. It is only since the industrial revolution that power from fossil fuels has been harnessed to drive global development. Industrial development and advancements in science created better public health and nutrition, which caused the population to increase rapidly. Exponential growth rates reached 2 percent per year during the mid-1960s. The population which took 10,000 years to grow from 5 million to 500 million, jumped from 1 billion in 1800 to 7 billion in 2010. The current population growth rate is about 1.1 percent which doubles the population in 62.7 years. Industrial production per person is also growing at an exponential rate. At some point there will not be enough resources in the ecosystem of the earth to support this growth. For a sustainable future both population and industrial output per person need to stabilize and agriculture and industry need to operate more efficiently. The use of fossil fuels to drive our industrial society has had the side effect of pushing the carbon dioxide levels in the atmosphere to concentrations not seen in 800,000 years. This has a high potential to create climate changes that may not be pleasant.

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1

SOLAR ENERGY USE THROUGH TIME

Ultimately the Sun (Figure 1) is the only sustainable source of energy and is most likely the safest place to site a thermonuclear reactor. Everything that drives life on Earth comes from the Sun; the wind, the tides, the waves, the temperature difference in the oceans; and of course photosynthesis, which turns sunlight into plant material, is the basis of all life. Plant material created long ago by photosynthesis is the source of the coal, oil, and natural gas that we use to power our society today (Behling and Behling 1996, 25–31).

Humans were designed for the slightly warm climate of the African savannas. However we have learned to use fire, shelter and clothing to expand our territory over much of the Earth. The Earth can be classified into eleven different climate areas. From cold to hot, the climate areas are ice caps, tundra, mountains, continental, marine west coast, Mediterranean, subtropical, rain forest, savannas, steppes, and deserts (Behling and Behling 1996, 36–43).

The indigenous response to creating survivable shelter in these climates is a study in contrast. The ice caps are a difficult place to survive, and the primary building material is compacted snow used to create igloos. There are few animals that survive the cold. The tundra is also a cold artic climate zone but there is more life around. Human settlements are a mix of partially underground, semi-permanent dwellings and light weight transportable tent-like shelters that can be carried along a nomadic lifecycle following the source of food. A mountainous climate is a mix of mild summers and cold snowy winters. The building response is sturdy timber and stone construction to hold off the harsh winter. A continental climate is somewhat similar to the mountainous climate with large temperature swings daily and seasonally, but with less snow. The building response is heavy materials, log and earth construction with forests providing plenty of wood for fuel. The west coast marine climate is relatively mild but characterized by cloud cover and ocean storms. The thermal mass of the oceans creates the mild conditions. The building response is

FIGURE 1.1 The Sun is the source of all life on Earth.

Source: NASA Solar Dynamics Observatory.

good sheltering roofs and relatively large windows to bring in light from cloudy skies. The window to wall ratio of Georgian architecture is well suited to this environment providing the proper mix of light and insulation. The Mediterranean climate is close to perfect. Warm summers and mild winters create the conditions for indoor–outdoor living. The building response is diverse but often contains thermal mass to balance the daily temperature swings and arcades to create shaded outdoor space. A subtropical climate, think areas of the southern United States, requires shade and ventilation to create passive comfort. The rain forest environment is hot and humid with ventilation being the only means of cooling. The plantation houses of the Caribbean have deep layered verandas and large openings to provide shade from the sun and access to the wind. The savannas are a warm wet climate. This is the climate humans were designed for. People can survive with very little clothing or shelter. Shelter can be simple and permeable. The steppes are a hot dry climate with diurnal temperature swings. The indigenous buildings have high thermal mass and use evaporative cooling. Shade is important and often occupants move to different parts of the building from day to night. Deserts are the opposite of the ice caps but are similar in their difficult living conditions. The building response is a mix of heavy mass with narrow streets to provide shade and protection from hot winds, and tent structures used by nomadic people following the limited resources (Behling and Behling 1996, 42–65).

The first solar structure was agriculture (Figure 1.2). The Neolithic revolution collected solar energy in the form of food in such large quantities that cities emerged to control the distribution of the new found abundance. Egypt is an example of

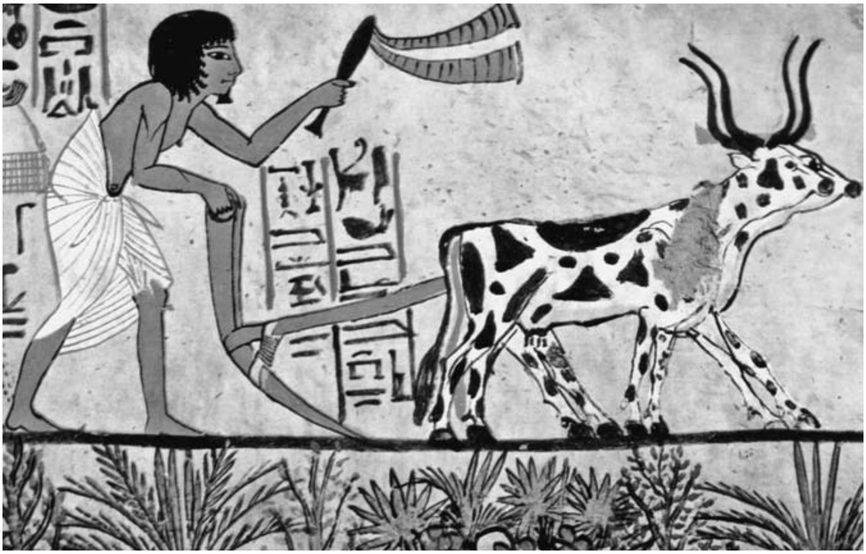


FIGURE 1.2 The first human collection of solar energy on a massive scale was agriculture.

Source: Wikimedia Commons, Public Domain. Author: Yorck Project. Originally painted in 1200 BCE. http://en.wikipedia.org/wiki/Agriculture (accessed August 20, 2014).

this growth of city based societies. The Sun was part of the religious system in Egypt and calendar making was high tech and important for agricultural success. Egyptian residential neighborhoods were laid out with south exposure. Babylon's hanging gardens were a celebration of the ability to harvest solar energy in food crops. The civilization at Angkor Wat created vast lakes to store the large amounts of water necessary for rice production. With less dependence on monsoon rains, rice production tripled. Feng Shui in China prescribed urban layouts in squares with southern orientation. In the Americas, Teotihuacan is laid out in cardinal orientation, and the two main pyramids are to the Sun and the Moon. The Anasazi built cliff pueblos that faced south with the cliff overhang protecting the pueblo from summer sun while letting in the winter sun. Pueblo Bonito, 600 AD, was a free standing structure facing south. Colonial Greek cities, such as Priene, around 400 BC, were laid out with south facing housing units. When the city grew to a size that began taxing the tributary land area needed to support the city, a new city was formed in another area. It was necessary to live on nearby resources (Behling and Behling 1996, 71–87).

The architecture with a capital A that developed in Greece was an extension of the south facing *megaron* house with its shaded porch. The grand buildings like the Parthenon are all about light and shade. In Rome, Hadrian's Villa and Trajan's Market were designed for indirect light and cross ventilation. Light is a form of solar energy and so is air motion. In the Greek world, commerce took place under covered porches that were brought inside in the Roman Basilicas. The Pantheon is possibly the most spectacular solar illuminated building in the world, with the oculus projecting a beam of sunlight that moves around the building on a daily and seasonal cycle. In the Baths of Caracalla the hot baths faced the south for maximum solar gain. The Roman Coliseums were shaded with cloth and rope structures called *vela*, meaning sails. The Christian churches took on the Roman basilica and developed it into an uplifting image of heavenly light. Solar energy was used to reinforce religious intent. This progression peaked with the Gothic churches with their flying buttresses, allowing the walls to be filled with stained glass windows. In Renaissance Europe the wall became habitable space with covered arcades. The Costozza Villas were built on the lower slopes of a hill that contained a cave. The cave was opened into the villas to provide ground source gravity driven cooling air flow. The Baroque style brought with it the use of indirect lighting that creates magical glowing surfaces. Louis XIV referred to himself as the Sun King and built Versailles and its gardens. However, Frederick the Great at his palace at San Souci in Potsdam built a cascade of south facing greenhouses to allow the growing of grapes for wine in a cool climate. He used the Sun rather than naming himself after it (Behling and Behling 1996, 91–125).

All around the world daylight, ventilation, and water were also used in grand architectural expressions. The Alhambra is a masterful composition in bouncing light off interior surfaces and using a combination of cross ventilation and water features to create thermal comfort (Figure 1.3). In China, the Forbidden City is a sequence of sun, shade, and calm. In Japan, the Katzura Palace presents a sophisticated relationship between inside and outside, and a masterful use of diffuse daylight through translucent movable screen walls. The grand mosques of the Near East bring daylight in from above, gently illuminating the interior. In Persia, the Garden Pavilion of Hasht Bihisht combines appropriate shade, diffuse daylight, cross ventilation, and cooling water with a perfumed garden surround. Mogul screens let filtered light and cross ventilation in, while providing privacy (Behling and Behling 1996, 91–125).

The industrial revolution began with sustainable energy sources. The mills were driven by water power, illuminated with daylight and thermally conditioned by controlled ventilation. The goods were transported to market on canals. Then coal and the steam engine combined to begin the fossil fuel age and create the connection between mass production and mass consumption. However, there are some gems of solar architecture from this time. Paxton's great Conservatory at Chatsworth House, his Bictom Gardens Palm House in Devon, and the great Palm House at Kew Gardens used solar energy to create the warm conditions to grow tropical plants in cool Britain. But the most spectacular solar building of the time was the Crystal Palace, built in 1851. It was constructed of standardized parts in 22 weeks. An artificial Mediterranean climate was created by the balance between solar gain and ventilation. The great railway stations were daylighted through transparent roofs that incorporated stack ventilation. Milan's Galleria provided light and stack ventilation to a shopping environment (Behling and Behling 1996, 128–151).

FIGURE 1.3 The Alhambra Patio de la Acequia (Court of the Long Pond) is an example of a designed microclimate.

Source: Wikimedia Commons, Attribution-Share Alike 2.0. Photograph by Andrew Dunn, May 11, 2006. http://en.wikipedia.org/wiki/Alhambra (accessed August 20,2014).

World War I focused industrial production on guns, bombs, and ships. After the war the modern movement began its exploration of how to use the new materials that were available. Steel and concrete frames allowed the wall to become more open to daylight. Le Corbusier (Charles-Édouard Jeanneret-Gris), Mies van der Rohe, Frank Lloyd Wright, and Richard Neutra all explored opening architecture to sun and light. Buckminster Fuller explored efficient use of materials with his Dymaxion House. Later in life, he pointed out that we are all on Spaceship Earth long before pictures from the moon showed the entire Earth floating in dark cold space. Albert Kahn's factory designs for the Ford Motor Company were masterpieces of daylighting. Suburban life began with Broad Acre City and Radburn, New Jersey. The idea was to bring the maximum open space, air and daylight to where people lived (Behling and Behling 1996, 152–167).

World War II brought with it wide ranging technological advances and has been followed by an American domination of consumer society. Home appliances and air conditioning drove up electricity use and Eisenhower's interstate highway system provided the blueprint for how to build super highways to move people from suburbs to the city. Charles and Ray Eames, Marcel Breur, Paul Rudolph, and others produced houses with modern materials and forms that responded to their sites with appropriate orientation and solar control. Frank Lloyd Wright's

FIGURE 1.4 Earth rise taken from the Apollo 8 mission around the Moon, Christmas 1968.

Source: NASA, Apollo 8 Mission. Photo by Bill Anders.

Jacobs House is close to a diagram of a passive solar house. South facing windows with a horizontal overhang allow winter sun penetration and block summer sun. A concrete and stone interior provides thermal mass to spread the solar gain from day into night, and the north wall is set into the earth to minimize heat loss. Hassan Fathy, an Egyptian architect, conceived and built residential settlements for less advantaged populations using the indigenous methods of adobe construction, sun control, evaporative cooling, and night ventilation cooling. However, most commercial architecture took the form of the glass box highrise that depends on artificial light and air conditioning (Behling and Behling 1996, 168–189).

The beginnings of a new way of looking at the Earth began at Christmastime in 1968 when the Apollo mission to orbit the Moon sent back pictures of the Earth as a glorious blue ball floating in the endless blackness of space (Figure 1.4). After the energy crisis of the 1970s there was a push to make buildings more energy efficient and use the natural forces of sun and wind to provide passive conditioning. Unfortunately, when oil prices decreased the economic incentive to keep pushing energy efficiency became less intensive. As the century came to an end, two forces came together to bring energy efficiency back to prominence. Oil prices rose to new heights and stayed there, and it has become apparent that the use of fossil fuels is beginning to cause global warming. Architects like Ken Yang, Richard Rogers, and Renzo Piano have been leaders in the exploration of new commercial building forms that control and use wind and sun to become more efficient thermal machines. Complex echo-tech double skin wall systems to control sun, daylighting, and natural ventilation have become a symbol of corporate power in northern Europe. Theatrical daylight demonstrated by Norman Foster at the Reichstag in Berlin and at the Hong Kong Bank Building brought awareness to the public of a new way of doing things. Computer aided simulations of energy use, visual comfort, and thermal comfort in buildings have expanded rapidly and are becoming more integrated with the new generation of three dimensional building information management computer design programs. At the regional and national scale, wind farms, photovoltaics, and bio fuels are on the rise (Behling and Behling 1996, 194–229).

The future is pointing in the right direction.

2

UNCONTROLLED GROWTH CAUSES UNCONTROLLABLE PROBLEMS

Exponential growth is when a quantity grows in proportion to its size. Exponential growth has the characteristic that it has a doubling time that is related to the growth rate. The equation for instantaneous growth is $dN/dt = rN$ where N is the number of individuals in the population, and r is the rate of growth. For a population this is births minus deaths. The time period is given by t. The solution to this differential equation is $N = N_0e^{rt}$. When the population has doubled, $N = 2N_0$. Thus $2N_0 = N_0e^{rt}$, which becomes $2 = e^{rt}$. Taking the natural log of both sides of the equation results in $\ln(2) = rt$, which is $0.69 = rt$. Rearranging terms to solve for the doubling time results in $t = 0.69/r$. Thus, if a population is growing at a rate of 1.1 percent per year, the doubling time will be $t = 0.69/0.011 = 62.7$ years.

It took 10,000 years for the human population to grow from 5 million to 500 million. It then took 150 years to double, reaching 1 billion in 1800. This is a growth rate of ($r = 0.69/150$ years $= 0.0046$) 0.46 percent per year. In 1930, 130 years later, there were 2 billion people. In 1960, 30 years later, there were 3 billion people. Improvements in agriculture pushed the population to 4 billion in 1980. In 1990, 10 years later, the population reached 5 billion, and, in 2000, the population reached 6 billion. The growth rate from 3 billion in 1960 to 6 billion in 2000 is ($r = 0.69/40$ years $= 0.173$) 1.73 percent per year. The current population, as of 2013, is slightly over 7 billion (Figure 2.1) (Emmott 2013, 12–43).

The United States Census Bureau (www.census.gov/population/international/publications) reports that the world population growth is increasing at 1.1 percent per year. The current population of the Earth is approximately 7 billion. The growth rate is slowly declining resulting in a likely population of 9.5 billion in 2050 (Figure 1.2).

The population growth rate in the developed world is close to zero, and in some countries in Europe and in Japan the population growth rate is negative. A negative growth rate will slowly reduce the population. In the developing world

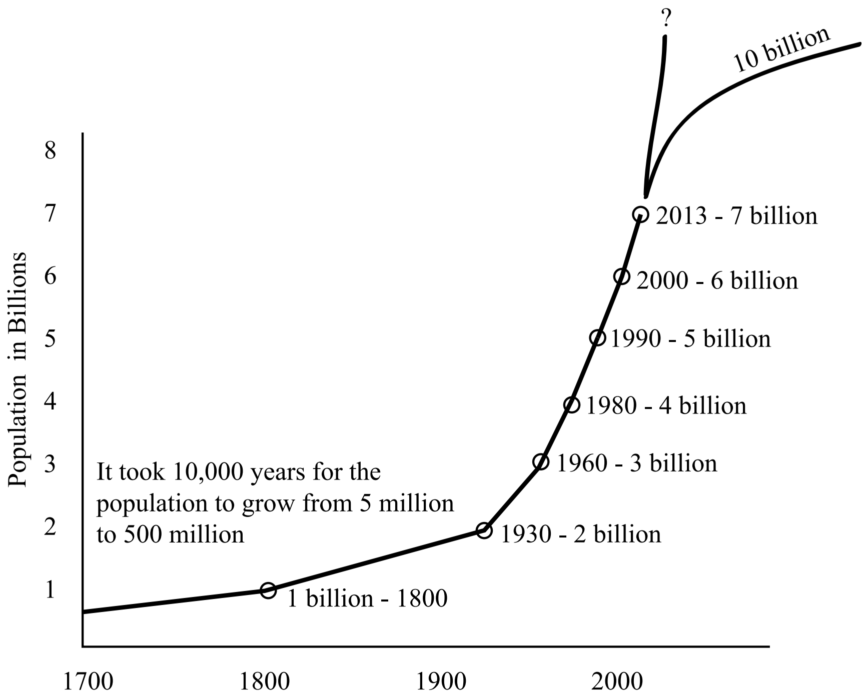


FIGURE 2.1 World population since 1700.

Source: Emmott 2013.

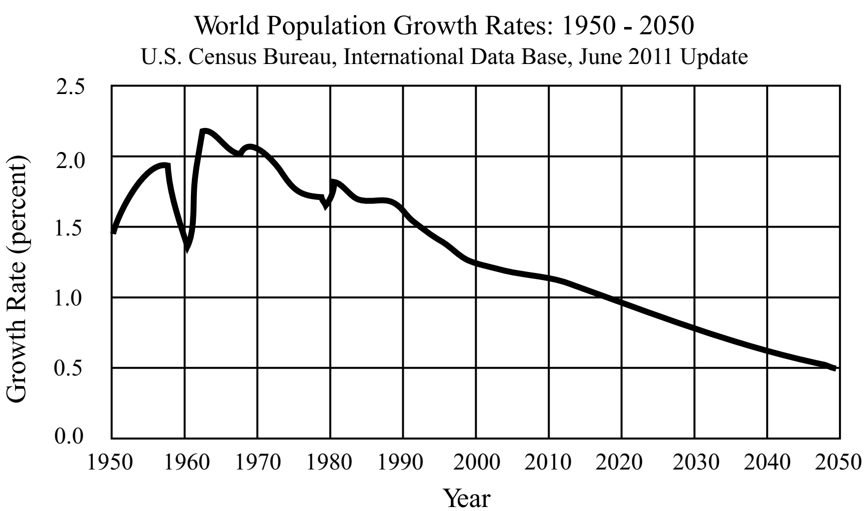


FIGURE 2.2 World population growth rates.

Source: U.S. Census Bureau, International Population Reports. Global Population Growth. www.census.gov/population/international/publictaions (accessed August 20, 2014).

the population growth rates are high. This is the result of a transition caused by improved nutrition and public health. Before the improved nutrition and public health there were high birth rates and high death rates. Improved public health and nutrition causes the death rate to drop but it takes a generation or more for the birth rate to also drop. This causes an explosion in population (Meadows et al. 1992, 28–29).

Industrial output is also growing at an exponential rate. Industrial output per person is growing at the exponential rate of 1.5 percent per year (Meadows et al. 1992, 5). Environmental impact is driven by population size and the amount of affluence per person. This combined impact can be magnified or reduced by the quality of the technology used to produce the affluence. Environmental Impact = Population × Affluence × Technology (Meadows et al. 1992, 100–103).

Exponential growth can only continue indefinitely if there is an unlimited supply of materials to grow on, and an infinite sink capacity to absorb the waste produced. This has been the case through most of human history. We were such a small part of the environment that the resources and sinks were effectively infinite. Currently our numbers are so large that there are environmental limits. There are three ways that an exponentially growing population can approach environmental limits, sigmoid growth, overshoot and oscillation, and overshoot and collapse.

Sigmoid growth provides a smooth transition from exponential growth to a stable population size and or stable economic output. This type of transition can only happen when signals about physical ecological limits are understood and acted on immediately.

Overshoot and oscillation is a more likely response and happens when the signals and responses are delayed by human decision-making and or the nature of ecosystems. In addition, for the oscillation to occur after the overshoot, the ecological limits need to be un-erodible or be able to recover quickly.

Collapse happens when signals and or responses are delayed and the environmental limits cannot recover quickly enough. The overuse causes such long term and deep damage to the ecosystem that population and or economic output collapse.

Population growth is determined by births minus deaths. Preindustrial societies typically have high birth rates and high death rates, which results in a low population growth rate. Deaths are distributed through all age groups and are especially high in infants. The resulting age distribution diagram looks like a pyramid (Figure 2.3). Societies as they industrialize, which brings with it better nutrition and health care, see a decrease in death rates before a decrease in birth rates (Figure 2.4). There is a population surge that eventually levels off with a decrease in birth rates. During the surge the age distribution diagram is very wide at the base because children are no longer dying young. The developed countries of Europe and North America have gone through this transition to low death rates and low birth rates. The resulting age distribution diagram is a vertical column indicating that almost everyone lives to a reasonable old age (Figure 2.5). The population of the world needs to make it through this transition without creating too many more people. (Meadows et al. 1992, 28–32) Runaway population growth in the developing world also creates a development problem. If population grows faster than food supplies

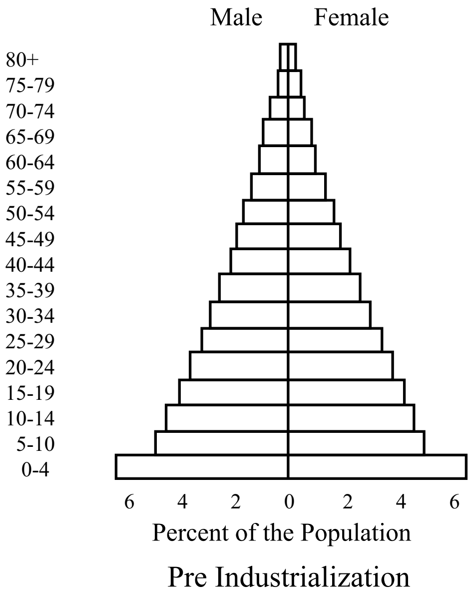


FIGURE 2.3 Population age distribution for a pre-industrial society.

Source: U.S. Census Bureau, International Population Reports. Global Population Composition. www.census.gov/population/international/publictaions.

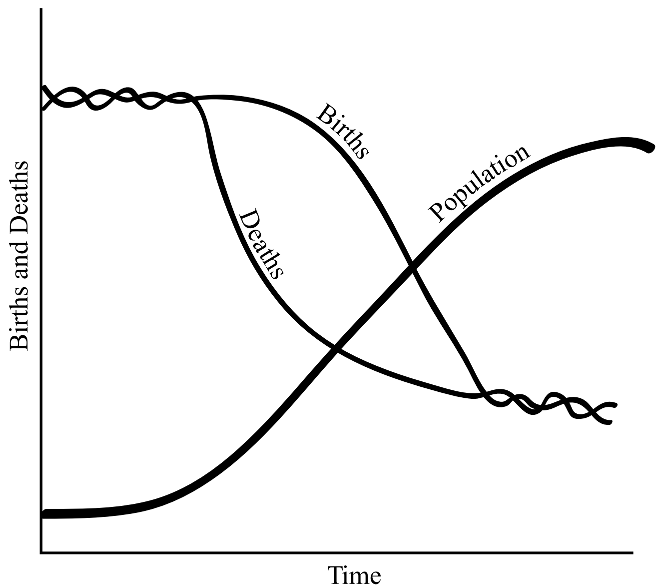


FIGURE 2.4 Demographic transformation.

Source: Wikimedia, Public Domain. Author Charmed88 and NikNaks. Created February 1, 2009. Wikimedia, Demographic Transition. http://en.wikipedia.org/wiki/Demographic_transition.

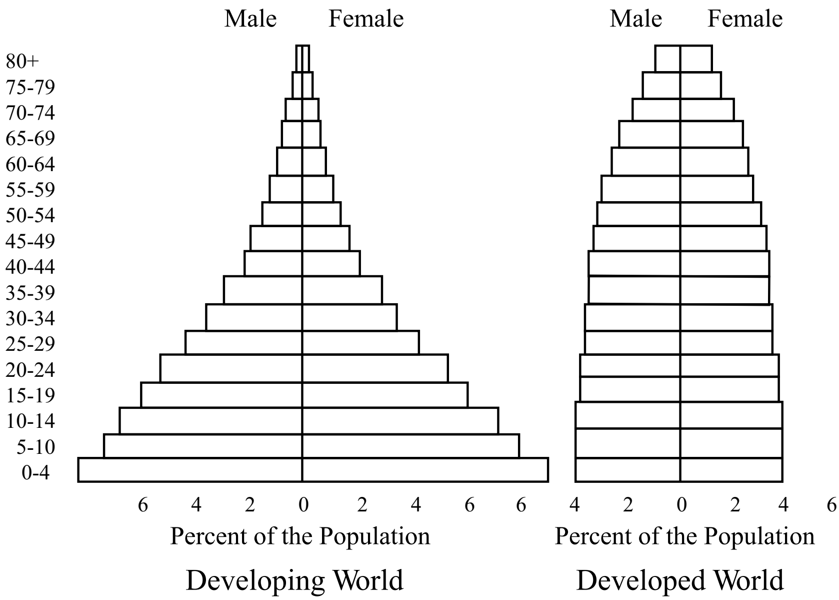


FIGURE 2.5 Population age distributions for a society in transition and for a modern industrial society.

Source: United States Census Bureau, Global Population Profile 2002.

and wealth production, a developing country will be unable to provide an improving standard of living for its population. If standards of living don't increase, the transition to low birth rates and low death rates won't happen.

The economic system we currently have depends on taking materials and energy out of the earth (sources), processing them into consumer goods and then returning the waste materials back to the earth. When human society was small in relation to this flow the earth could supply the materials and energy and absorb and process the wastes. At the size of the current economic system, it is clear that material and energy sources are becoming scarce and that the earth's capacity to absorb the waste stream is overtaxed.

On the energy side, estimates of the world's known reserves of oil are 922 billion barrels. If this number is doubled to account for undiscovered reserves, the amount of usable oil is 1,844 billion barrels. At a use rate of 21.3 billion barrels per year in 1988, the world has 87 years of oil left (Meadows et al. 1992, 71). However this is not quite correct. There will come a time when oil production peaks and then starts decreasing. This happens when the world has used up half the available oil. Estimates of peak oil production are within the next decade or so if we haven't already hit peak production (Allmendinger 2007). The problem is that demand for oil will continue to grow while supply drops off causing a rapid rise in the price of oil (Figure 2.6). At some point oil will become useless as a fuel to burn.

The United States has reserves of natural gas through fracking, which we are told can supply our needs for 100 years, and we have large coal reserves. Even if

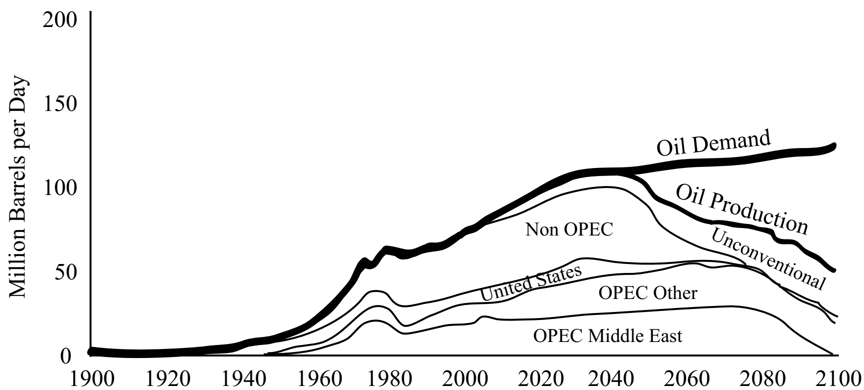


FIGURE 2.6 Intermediate projections of world oil supply and demand through 2100.

Source: United States Energy Information Administration. Long Term Global Oil Scenarios: Looking Beyond 2030. www.eia.gov.

this is true, the waste side of the economic equation presented above comes into play. All combustion produces carbon dioxide. Carbon dioxide is accumulating in the atmosphere faster than the atmosphere and ecosystem can process it. The result will be global warming. The estimates of how much global warming vary, but the warming will happen. This illustrates an important issue that society needs to understand. As we approach the limits of the earth's ability to sustain our society, solving one problem with a technical fix can be quickly followed by another problem that often is unforeseeable.

The reason that solving one problem rapidly brings up another problem is that, as society approaches sustainable limits, the costs of taking materials or energy out of the earth or cleaning up waste streams before dumping them in our rivers and oceans increases exponentially. At some point the process becomes unaffordable. As an example, consider the relationship between the grade of ore mined and the tons of waste produced. As we use up the easy to find raw materials, finding and producing the materials society needs becomes more expensive at an accelerating rate and produces more waste at an accelerating rate (Meadows et al. 1992, 84–87).

In the book *Beyond the Limits*, a computer model is presented that interrelates population growth with food supplies, industrial output, capital investment, resource use, and pollution production, and their interaction with the environment. For example, as population grows, more land and capital resources have to be given over to food production, which can reduce industrial output, or, as industrial output grows, more pollution is produced that the environment has to absorb (Meadows et al. 1992, 33–35, 105–119).

To maintain our standard of living, capital resources are used to extract resources from the earth, to manufacture consumer goods, to produce food, to provide services like health care, and finally there need to be enough capital resources left over to replace the industrial capital that produces all of the above as it wears out (Meadows et al. 1992, 34).

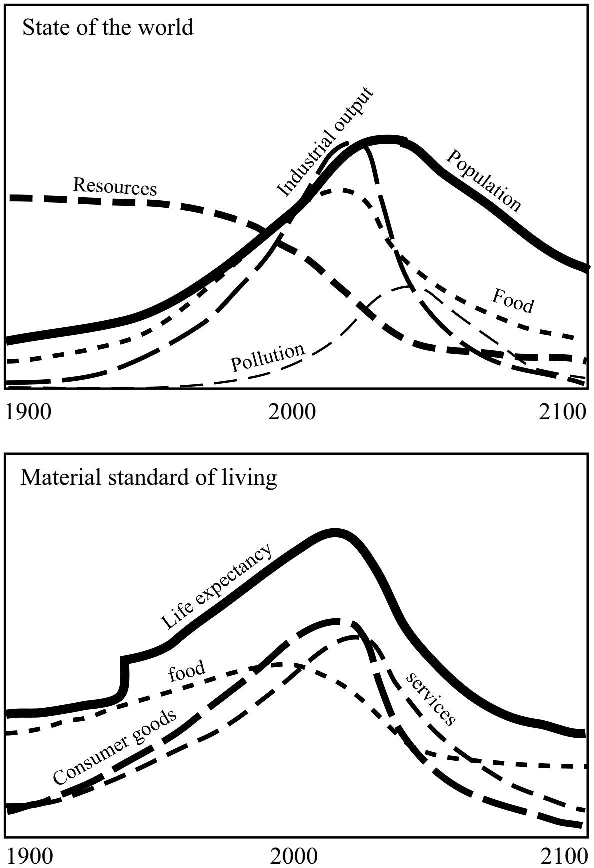


FIGURE 2.7 *Beyond the Limits* computer simulation results for continuing with the current population and industrial growth patterns.

Source: Reprinted from Meadows et al. 1992, with permission by Chelsea Green Publishing Company (www.chelseagreen.com).

The first run of the computer model of the world's economy assumed that the current exponential growth rates of population and industrial output continue into the future. The result (see Figure 2.7) is that

> Population and industrial output grow until a combination of environmental and natural resource constraints eliminate the capacity of the capital sector to sustain investment. Industrial capital begins to depreciate faster than the new investment can rebuild it. As it falls, food and health services also fall decreasing life expectancy and raising the death rate.
>
> (Meadows et al. 1992, 132–133)

The computer model is then used to test various scenarios that might avoid the crash. The first test was to double the amount of resources assumed in the model. This is instructive on two levels. The first is that it is difficult to predict the level of resources available so doubling them is a good test of the model's sensitivity. The second, and probably more important, is that exponential growth eventually overtakes any finite amount of resources. In this scenario with doubled resources,

> Industry can grow 20 years longer. Population rises to 9 billion in 2040. These increased levels generate much more pollution, which reduces land yield and forces much greater investment in agriculture. Eventually declining food raises the population death rate.
>
> (Meadows et al. 1992, 134–135)

The next scenario tested is to apply technical improvements to control pollution, to increase land yields, to reduce erosion, and to improve industrial efficiency.

> Now the simulated world is developing powerful technologies for pollution abatement, land yield enhancement, land protection, and conservation of nonrenewable resources all at once. All these technologies are assumed to cost capital and to take 20 years to be fully implemented. In combination they permit the simulated world to go on growing until 2050. What finally stops growth is the accumulated cost of the technologies.
>
> (Meadows et al. 1992, 174–175)

The world's population is growing at the exponential rate of 1.1 percent per year, and the world's industrial output per person is also growing at approximately the same exponential rate. The next simulation explores the consequence of a zero population growth rate and a zero industrial output per person growth rate.

> If the population adopts both a desired family size of two children and a deliberately moderated goal for industrial output per capita, it can maintain itself at a material standard of living 50 percent higher than the 1990 world average for almost 50 years. Pollution continues to rise, however, stressing agricultural land. Per capita food production declines, eventually carrying down life expectancy and population.
>
> (Meadows et al. 1992, 196–197)

Exponential growth rates will consume any amount of resources or technology improvements that are thrown in the way. Just stabilizing population and industrial output growth rates also does not create a society that can sustain itself indefinitely. However, a combination of zero population and zero industrial output growth rates, and technology improvements, can create a sustainable society (Figure 2.8).

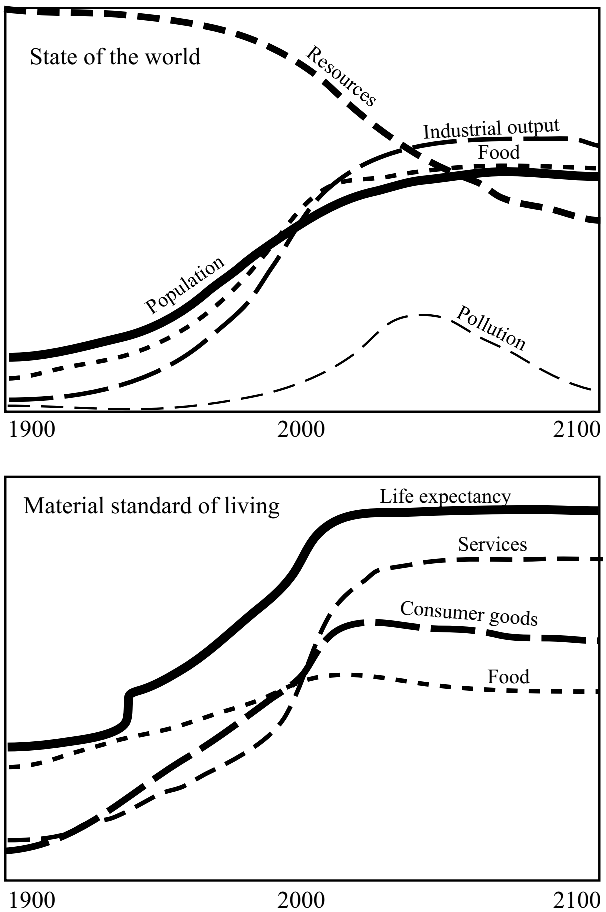


FIGURE 2.8 *Beyond the Limits* computer simulation results with control of population growth and green and efficient technologies.

Source: Reprinted from Meadows et al. 1992, with permission by Chelsea Green Publishing Company (www.chelseagreen.com).

> In this scenario population and industrial output per person are moderated as in the previous model run, and in addition technologies are developed to conserve resources, protect agricultural land, increase land yield, and abate pollution. The resulting society sustains 7.7 billion people at a comfortable standard of living with high life expectancy and declining pollution until at least the year 2100.
>
> (Meadows et al. 1992, 198–199)

3

OUR ECOLOGICAL FOOTPRINT

That our economy is embedded in Nature seems like an obvious statement until one looks at the consequences of this reality. The economy like any horse, lion, or fish has a metabolism. It needs to take in resources from the environment, which it uses for development and growth. The growth produces waste, which the environment needs to absorb. For an animal or an economy to prosper there needs to be enough resources to feed it and there needs to be enough environmental capacity to absorb its waste (Wackernagel and Rees 1996, 9–12).

The ecosphere is natural capital essential to our survival. Forests are an example of natural capital. There is a sustainable yield of wood that can be taken from the forests of the world that maintains the forests for future yields. This is an example of a renewable resource. A renewable resource grows at a certain rate. If we use the resource at or below this rate the resource will last forever. Forests provide benefits beyond wood products. They also create oxygen from carbon dioxide, they provide erosion and flood control, and they provide habitat for a wide variety of plants and animals. Fresh water, necessary for life, is created by moisture evaporation from the oceans being carried by winds over the land where it precipitates out, collecting in rivers and lakes. This is a replenishable process. The ozone layer that protects us from ultraviolet light is another example of replenishable natural capital. Though nonliving, these natural features of the ecosphere are replenished by interaction between solar energy and the ecosphere. Fossil fuels and minerals are examples of nonrenewable resources. There are finite amounts of these. Fossil fuel once used is gone forever. Minerals, like iron made into steel, can and should be recycled (Wackernagel and Rees 1996, 35).

Weak sustainability is the position of mainstream economists. Weak sustainability maintains that as long as the sum of the value of man-made and natural capital is non-declining the society is sustainable. This means that a forest can be completely cut down as long as the wood is used to create man made assets. This concept ignores the life support features the forest provides like oxygen production, flood control, and climate tempering. Strong sustainability values the life support functions of the ecosystem. Strong sustainability requires man made capital and natural capital to be maintained as separate entities. They are not interchangeable as traditional economics suggests (Wackernagel and Rees 1996, 37).

Carrying capacity is defined as the population of a species that can be maintained indefinitely in a given area of habitat (Wackernagel and Rees 1996, 48–49). An ecological footprint is defined as the amount of land that one person needs to sustain himself. A person's ecological footprint can be subdivided into four categories. Energy land is the land necessary to absorb the carbon dioxide produced by energy consumption. Consumed land is land that the built environment is on: home and office. Farm land is land necessary to produce the food one needs. Forest land is land necessary to provide forest products such as wood and paper (Wackernagel and Rees 1996, 51–55, 68).

If the ecologically productive land area of the Earth was divided equally among the current population of the Earth, each person would get about 1.8 hectares, which is 4.4 acres. One hectare is 100 meters by 100 meters, thus 10,000 square meters. One hectare is thus about the size of two football fields with their sideline areas side by side. A person's fair share of the Earth's productive land is approximately three and a half football fields. The average citizen of the United States has an ecological footprint of about 8 hectares, which is 4.4 times our fair earth share. Currently the population of the Earth uses about 2.7 hectares per person, which is 50 percent higher than the earth can maintain (Figure 3.1) (www.

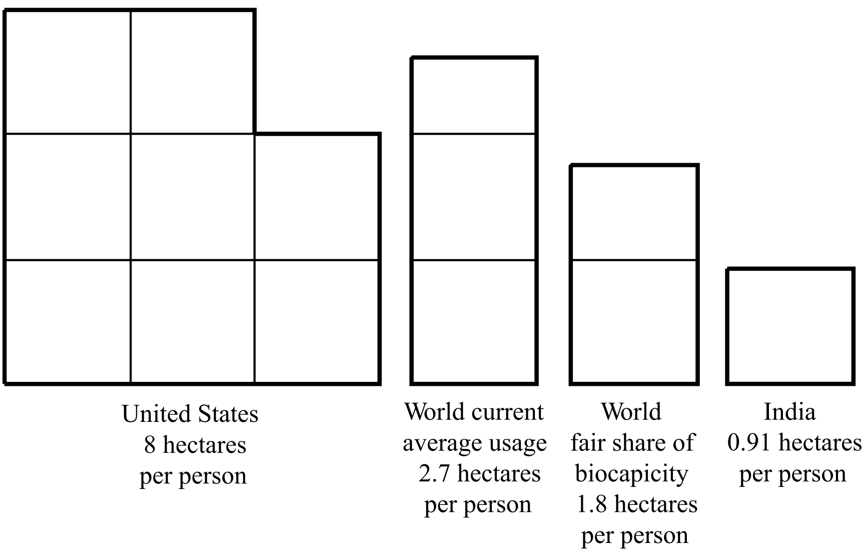


FIGURE 3.1 Comparative ecological footprints.

Source: Global Footprint Network, Footprint for Nations. www.footprintnetwork.org.

footprintnetwork.org). A little over half of the 2.7 hectares is land to soak up the carbon dioxide given off by energy production. That puts the non-carbon dioxide part of the footprint at 1.3 hectares. The energy part of the US footprint is close to two-thirds of the 8 hectare footprint. We have a problem, but a transition to an alternative energy society would go a long way toward a sustainable future (Freed et al. 2010, 12).

The ecosphere of the earth is more than just a source of materials for our use. The ecosphere creates and maintains the conditions that make life possible. The importance of the ecosphere's life support functions and its interconnected complexity suggests that we need to leave enough of the world's ecosystems alone in order to ensure our survival. This becomes more difficult as the population increases. Carl Folke, in Chapter 2 of *State of the World 2013*, "Respecting Planetary Boundaries and Reconnecting to the Biosphere", points out that currently agriculture uses 12 percent of the non-ice covered land area and should be kept below 15 percent to ensure ecosphere stability (Assadourian and Prugh 2013, 23).

4

GLOBAL WARMING AND CLIMATE CHANGE

On a global scale the earth is kept warmer than it would otherwise be by gases in the atmosphere that absorb heat that would otherwise reradiate out into space. The primary greenhouse gases are water vapor, carbon dioxide, and methane. Solar radiation hits the Earth and warms it up. The Earth then reradiates heat back toward space. The greenhouse gases intercept this heat causing the atmosphere to warm up. This has been a good thing for life on Earth and has been going on for 3 billion years or so. The carbon dioxide that humans are putting into the atmosphere did not start global warming; however, human produced carbon dioxide has intensified it (Mann and Kump 2008, 22–23).

Positive and negative feedback loops affect the temperature of the atmosphere. Adding carbon dioxide causes the atmosphere to warm up, which causes more water to be evaporated into the atmosphere. When water is in vapor form it absorbs heat that would otherwise radiate out into space. As the atmosphere gets warmer its capacity to hold water in vapor form increases, which means more heat will be absorbed. This is a positive feedback situation. However, as the atmosphere warms and evaporation off the oceans increases, there will be an increase in cloud cover, which reflects solar energy away from the earth, thus cooling the earth. This is a negative feedback situation (Mann and Kump 2008, 24–25).

The most important greenhouse gas is carbon dioxide, and it is the most difficult to deal with. Combustion, if it is complete, takes materials like coal, oil or natural gas, which are molecules made up of carbon, hydrogen, and other molecules, combining them with oxygen to produce energy. The important molecules for energy production are hydrogen and oxygen. The carbon and other molecules are just along for the ride. The combustion process produces heat that drives our engines, and the byproduct is a rearrangement of the carbon, hydrogen, and oxygen molecules. The output molecules from the process are carbon dioxide and water. When the combustion is not complete and there are impurities in the fuel, there

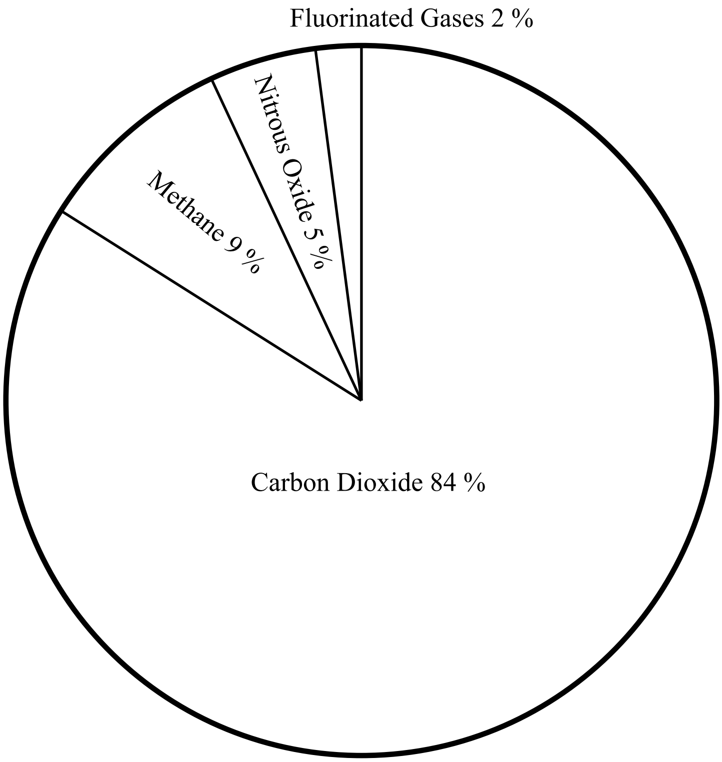


FIGURE 4.1 United States greenhouse gas emissions in 2011 were 6,702 million metric tons of CO_2 equivalent.

Source: United States Environmental Protection Agency, Greenhouse Gas Emissions/National. www.epa.gov/climatechange.

are also unburned hydrocarbons, nitrous oxides, and sulfur oxides emitted by the combustion process. These can be cleaned up from the combustion process by various means but there is no way to eliminate carbon dioxide as a result of combustion (Figure 4.1). Burning coal produces more carbon dioxide per amount of energy produced than burning natural gas because the ratio of carbon to hydrogen in coal is larger than the ratio of carbon to hydrogen in natural gas.

Methane is more potent as a greenhouse gas than carbon dioxide but there is much less of it. Methane is produced in nature by termites and bacteria as part of their metabolism. Rice production and livestock production has increased the methane content in the atmosphere (Mann and Kump 2008, 29).

Natural causes can warm and cool the earth. The Earth wobbles on its axis and the shape of its orbit changes, the Sun does vary in its intensity, and volcanos can erupt and put enough material high in the atmosphere to reflect solar energy (Mann and Kump 2008, 63).

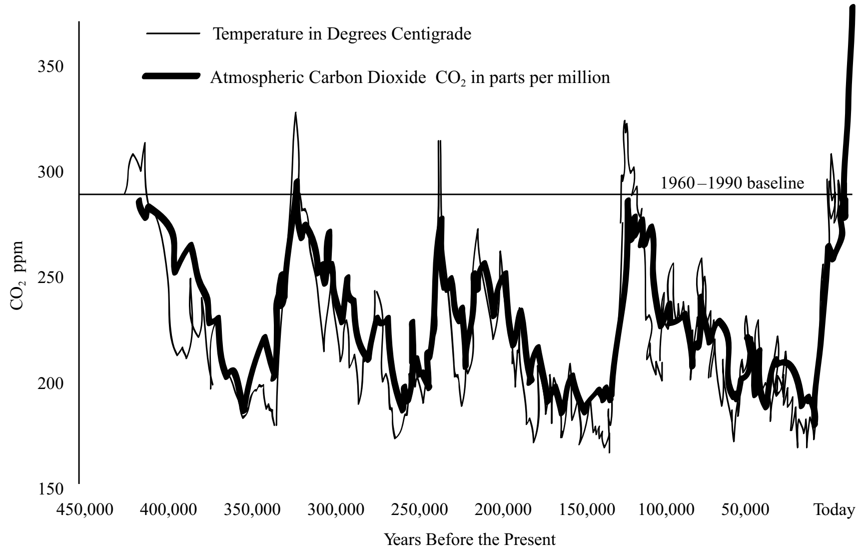


FIGURE 4.2 Temperature and carbon dioxide levels over the last 420,000 years.
Source: Pelit et al. 2001.

Plotting the relationship between carbon dioxide levels in the atmosphere and the temperature of the atmosphere over the last 420,000 years is eye opening (Figure 4.2). Note the close relationship between temperature and carbon dioxide levels. Also note that our current carbon dioxide levels are far out of range.

Computer models of global warming are very complex. The atmosphere has multiple interacting layers and important interactions with the oceans. These models are tested against historical data to determine how well they predict real variation (Figure 4.3). Observed atmospheric temperature can be compared with computer modeled atmospheric temperature including only natural causes like volcanos and solar variation, and computer modeled temperatures including natural and human-caused greenhouse gases. The computer models that included both the natural and the human caused greenhouse gases fit the actual atmospheric temperature measurements very closely. The predictions suggest that the earth's surface temperature could increase from 3 to 10 degrees Fahrenheit. The uncertainty is caused by the complex mix of positive and negative feedback loops. Another large uncertain input for the estimates is the human response to the problem. Thus an exact prediction is not possible (Soloman et al. 2007, 13).

To improve climate change prediction related to human response to the problem, multiple scenarios were investigated by the Intergovernmental Panel on Climate Change (IPCC) (Figure 4.4). The highest estimate assumes that we continue along with a fossil fuel dependent economy. The lower estimate assumes that a transition is made to non-fossil fuel clean energy economy. The middle estimate assumes a balanced approach part way between a fossil fuel and non-fossil

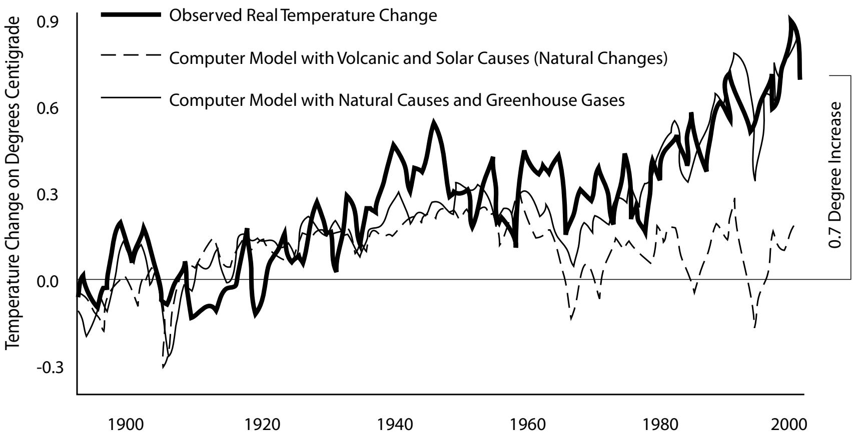


FIGURE 4.3 Observed temperature rise compared to human and natural causes.

Source: Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 9.5.

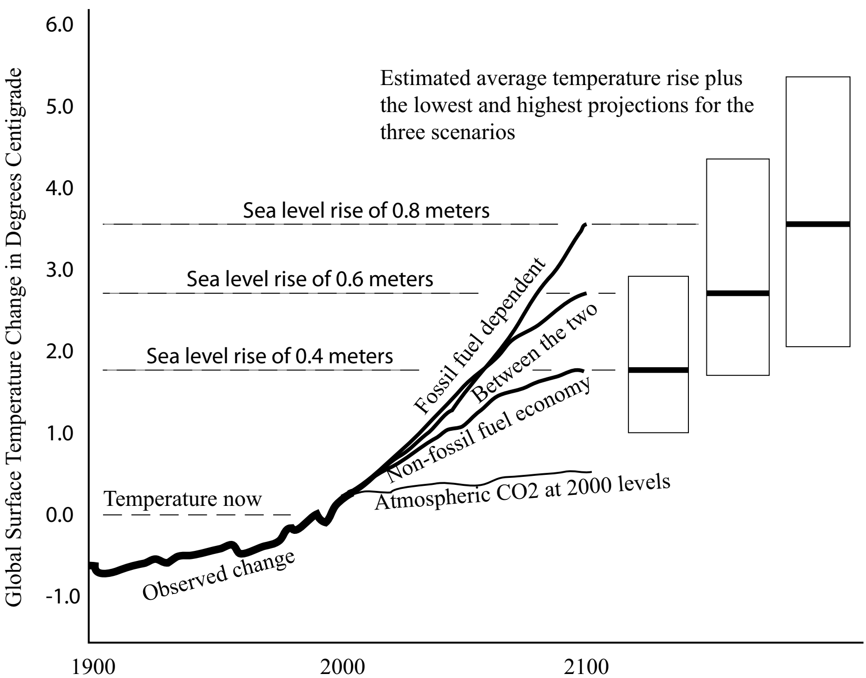


FIGURE 4.4 Three scenarios for global temperature rise with the range of uncertainty.

Source: Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPN.5.

fuel economy. Note that even the non-fossil fuel economy results in a temperature rise of 2 degrees Centigrade. The computer models suggest that temperature increase is not the only problem. The increase in global temperature is likely to cause modifications in rainfall patterns. More rain will fall in the tropics, and the subtropical desert zone will move northward; thus the precipitation that now falls on northern Europe and North America will move northward (Mann and Kump 2008, 88–89).

These precipitation changes are the result of the movement northward of the jet streams that form where the Hadley Cells meet. Air rises at the equator full of moisture. As it rises and moves north, rainfall occurs. In the low-latitudes, the air drops, increases in pressure and dries out resulting in desert areas like the Sahara. Over the temperate latitudes, air rises in the high latitudes losing moisture as it moves southward, descending in the low latitudes where the tropical air is descending. Over the polar regions, air rises over the high latitudes, losing moisture as it moves north to descend as dry cold air near the poles. A change in this circulation pattern will still move heat from the tropics toward the poles but it could cause droughts, flooding, and severe storms to occur in new regions of the globe that have the potential to cause large problems for the heavily populated temperate zones (Mann and Kump 2008, 89).

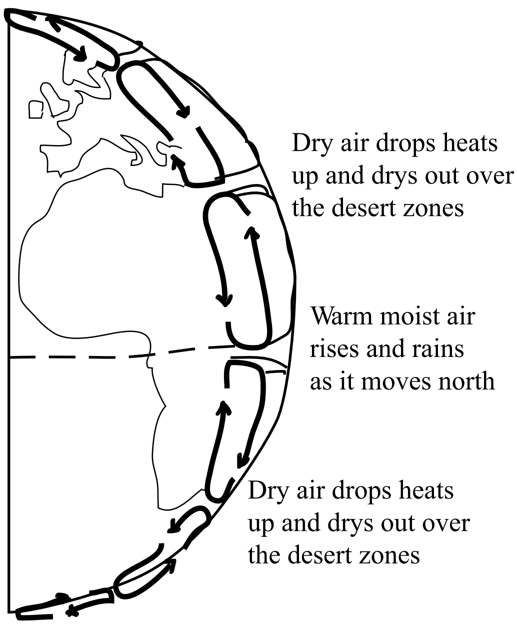


FIGURE 4.5 Hadley Cells moving heat from the equator toward the poles.

Source: Wikimedia Public Domain, Image created by NASA, uploaded October 29, 2009. http://en.wikipedia.org/wiki/Hadley_Cells (accessed August 20,2014).

Of the world's population, 10 percent lives in low lying coastal regions. Increasing sea levels caused by Greenland and Antarctic ice melting will cause coastal areas to be submerged, and threatened with more and more powerful tropical storms. Many areas of the world depend on water runoff from mountain snows and glaciers. Glaciers around the world are already in decline. Changes in the Hadley circulation cells will cause droughts to occur more frequently and last longer in the temperate regions where large populations live. The population is still expanding exponentially. More people with less water means less food (Mann and Kump 2008, 108–111).

Ecosystem loss could also be massive. Ecosystems are related to climate conditions; tropical rainforests in equatorial climates, desert ecosystems in the sub tropics, forests and grasslands in the temperate regions, and tundra near the poles. As the climate changes, ecosystems will have to migrate northward. Will they be able to move past our concrete civilization, and will the climate change be slow enough for them to migrate or will there be mass die offs (Mann and Kump 2008, 112–113)?

Coastal wetlands provide a good example of the difficulty of migration. Coastal wetlands provide protection from storms and wave action by acting as a large sponge. They also provide habitat for a wide diversity of plants and animals. Since we as a species have settled much of the shoreline, it will be almost impossible for a coastal wetland to migrate inland as the ocean level rises because our houses, offices, commercial buildings, and connecting infrastructure of roads are in the way (Horton and Eichbaum 1991, 149–158).

Coral reefs provide another example. Coral reefs create an ecosystem that supports a vast diversity of life. They provide food in the form of fish, and protection against storms. Coral reefs around the world are in decline caused by warming ocean temperatures and the acidification of the oceans. The oceans absorb some of the excess carbon dioxide that we put into the atmosphere. This increases the carbonic acid levels, which stunts coral growth. Studies project that if we do not severely limit carbon dioxide levels in the atmosphere coral will not be able to grow by the end of this century. Polar bears require sea ice to hunt for seals. As the Arctic sea ice decreases, their ability to survive will be threatened unless they can adapt to a new land based existence (Mann and Kump 2008, 114–118).

The *Washington Post*, on May 23, 2013 (Fears 2013), reported on the ongoing steep decline of amphibians: "The disappearance of amphibians is a global phenomenon. But in the United States, it adds to a disturbing trend of mass vanishing that includes honeybees and numerous species of bats along the Atlantic states and the Midwest."

There is no easy answer. The question is not can we solve the problem, but can we contain the problem. The primary human source of carbon dioxide is fossil fuel use to power our society (Figure 4.6). Throughout history transitions from one fuel source to another have been driven by economic considerations. Coal was a more economic fuel than wood, and oil and gas are more economical than coal. To make a transition to alternative fuels, an economic necessity needs to be

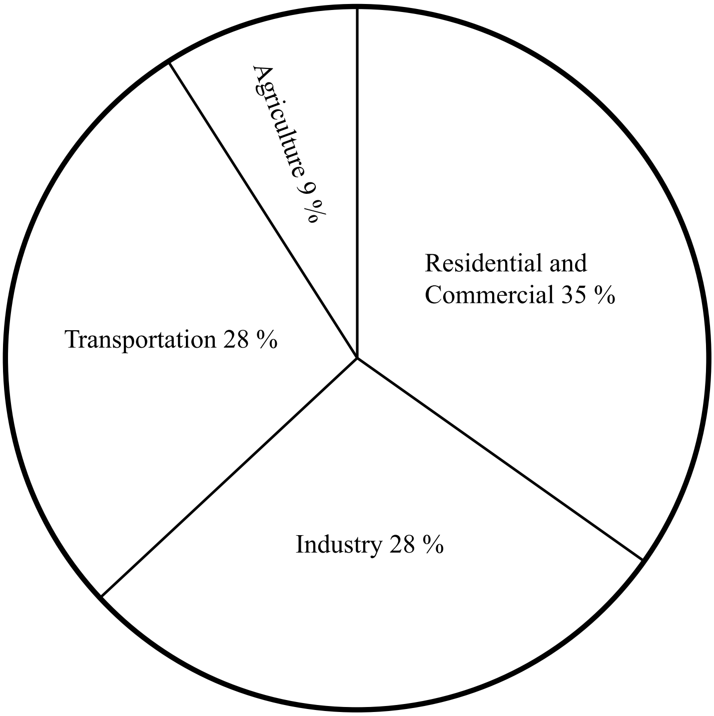


FIGURE 4.6 United States carbon dioxide emissions by industry.

Source: United States Environmental Protection Agency. Greenhouse Gas Emissions, National. www.epa.gov/climatechange.

created. Society needs to create the economic necessity because there is enough fossil fuel, especially coal, in the world to cause massive global warming. We also need to make a transition to alternative fuels before fossil fuels reach the point of scarcity and thus become too expensive (Mann and Kump 2008, 156–161).

One way to create the economic necessity to reduce the use of fossil fuels and increase the use of alternative fuels is to tax carbon emissions. Electricity generated by coal puts more carbon into the atmosphere than electricity produced by natural gas. Wind turbines, and photoelectric panels produce electricity with no carbon emissions into the atmosphere. The tax on carbon can be slowly raised to a level that would tip the economic decisions made by society away from fossil fuel and toward alternative energy sources. There is enough sun, wind, waves, tidal flows, and biomass to power our society given the right economic climate (Gore 2009, 120).

In the end the problem of global warming cannot be solved by technical means. No new technology or new economic construct can create climate stability if the population continues to grow exponentially and people continue to want more and more goods, thus causing economic activity to grow exponentially. We need to learn to live within our limits (Meadows et al. 1992, 198–199).

PART II

Ecology and the Environment

A basic knowledge of ecology is important to understanding how society can live in harmony with nature and harvest its resources without destroying the biodiversity and resilience that sustain it. A comparative study of ecology with architecture and urban design can demonstrate relationships that should be reinforced in a quest to create a more sustainable future. Another important part of creating a sustainable future is a clear understanding of how economic decisions are made in order to create an economic system that considers environmental quality in its decisions. To be an advocate for environmental quality requires a way of seeing nature that allows its complex multilayered interactions to be understood. A familiarity with fractal geometry provides a way of seeing that opens up new awareness of complex structures. The Chesapeake Bay provides a good example of a complex multilayered ecological system that interacts with a large human population.

5

ECOSYSTEM EXAMPLE

The Chesapeake Bay

The Chesapeake Bay borders on Maryland and Virginia and is about 190 miles long and from 4 to 30 miles across (Figure 5.1). There are approximately 50 rivers that drain into the Bay from New York State to the north through West Virginia to the west, Virginia to the south, Delaware to the east, and Maryland in the middle. The land area draining into the Bay is close to 64,000 square miles (cf. Figure 5.2). This large watershed drains into a very shallow bay. Before European settlement, this large drainage area created a bounty of life in the Bay by supplying the nutrients for marine life to grow and prosper in the Bay (Horton and Eichbaum 1991, 3).

The Bay is a complicated place for life. Fresh water flows down the rivers into the Bay and slowly flows down the Bay to the ocean. The tides bring in a surge of salt water twice a day with the high tide. The two flows mix in a complicated way affected by the winds (Figure 5.3). A wind blowing down the bay pushes water out of the Bay toward the ocean. A wind blowing up the bay pushes water up and into the Bay. Hurricane Isabel pushed so much water up the bay that downtown Annapolis was flooded. In general the less dense fresh water runs southward toward the ocean on the top, and the denser salt water runs northward up the bay on the bottom. The tides modify this flow twice a day. The tidal action causes a mixing of fresh and salt water. Rivers are fresh up stream and salty near the bay with a gradient of saltiness between and with the gradient changing with the tides and the seasons. In spring, with heaver rains, the water is fresher. In summer, with less rain, the water is saltier. It takes about six months for water to pass from the Susquehanna River to the ocean (Horton and Eichbaum 1991, 11–17).

Nitrogen and phosphorous are washed off the land into the bay. Before development this was a source of nutrients for the life in the bay. These nutrients are good for marine life in the bay in appropriate quantities. With human population growth around the bay, these nutrients washing off our urban developments and out of our sewage treatment plants are much too plentiful in the bay, causing

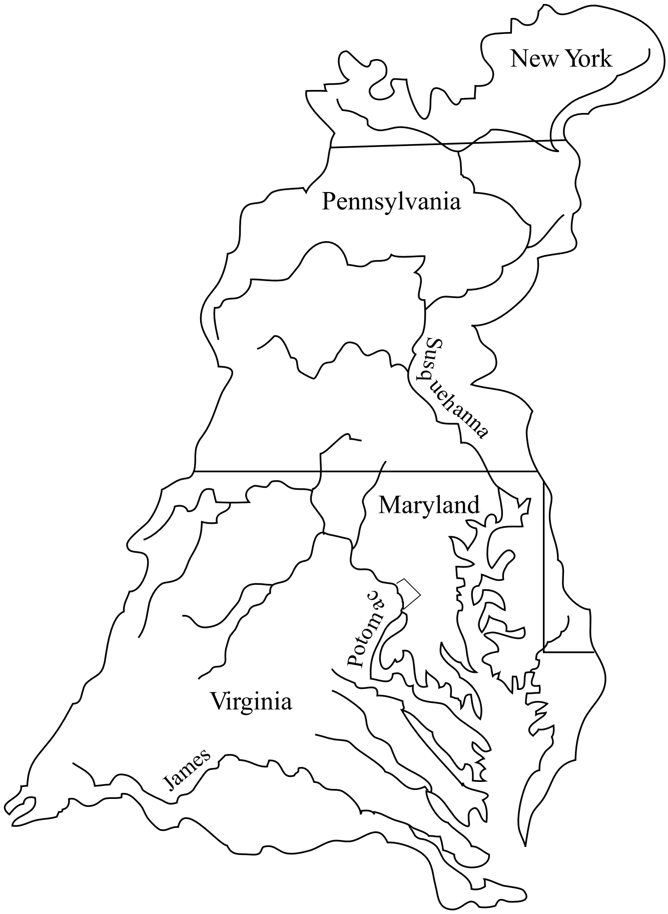


FIGURE 5.1 The Chesapeake Bay watershed.

Source: From *Turning the Tide* by Tom Horton and William M. Eichbaum. Copyright 1991 Chesapeake Bay Foundation. Reproduced by permission of Island Press, Washington, DC.

too much algae growth, which takes too much oxygen out of the water and reduces the penetration of sunlight into the water (Figure 5.4). The deep channels can end up with little or no oxygen. In wet years, more of these excess nutrients along with sediments run off into the bay causing a decrease in marine estuary growth (Horton and Eichbaum 1991, 17–19).

Oysters are more important to the ecosystem of the bay than as food for humans. Oysters are filter feeders. They suck in water from the bay and then deposit dense fecal matter on the bottom. The pre-1870 oyster population could filter a volume of water equal to the entire bay in a few days. The current population of oysters takes a year to filter a similar volume of water. The loss of the oyster population because of over harvesting creates a less resilient ecosystem (Horton and Eichbaum 1991, 27–29).

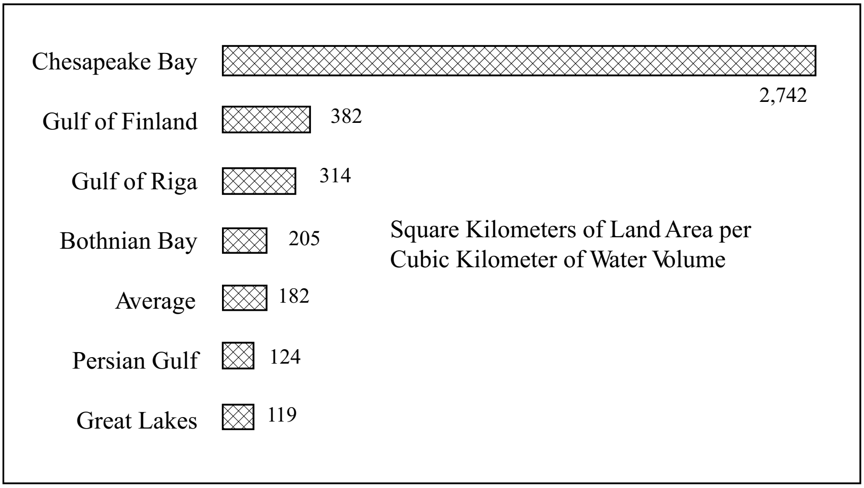


FIGURE 5.2 Area of land draining into the volume of water for seven major bays and lakes.

Source: From *Turning the Tide* by Tom Horton and William M. Eichbaum. Copyright 1991 Joseph Hutchinson. Reproduced by permission of Island Press, Washington, DC.

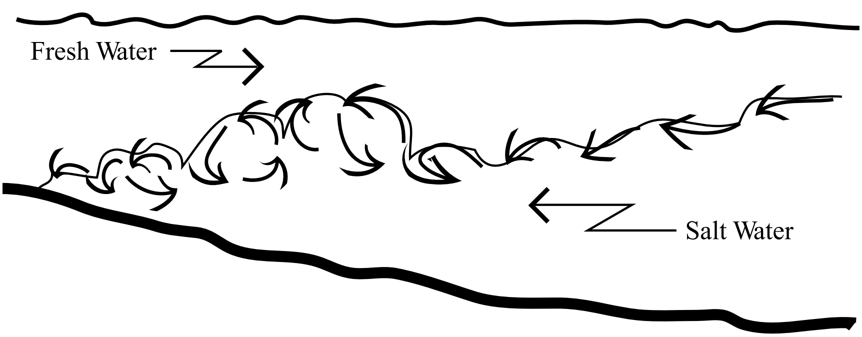


FIGURE 5.3 Fresh and salt water mix together in an estuary creating a complex ecosystem.

Source: From *Turning the Tide* by Tom Horton and William M. Eichbaum. Copyright 1991 Joseph Hutchinson. Reproduced by permission of Island Press, Washington, DC.

The state of the bay can be assessed by looking at three variables. The pollution we put into the bay, the harvest of crabs, oysters, and fish we take out of the bay, and the resilience of the bay to maintain a stable ecosystem into the future (Horton and Eichbaum 1991, 33–36).

Agriculture takes up a quarter of the Chesapeake Bay watershed and is a major source of excess nutrients from manure and fertilizers. Both of these sources contribute nitrogen and phosphorous into the bay, which causes excess algae growth.

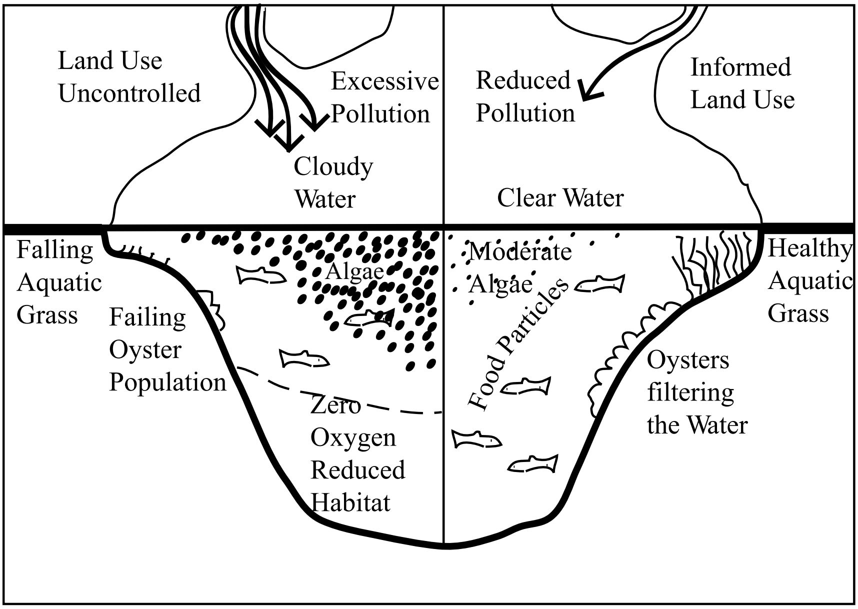


FIGURE 5.4 Oxygen depletion in the bottom of the Bay caused by excessive nutrients coming from the land.

Source: From *Turning the Tide* by Tom Horton and William M. Eichbaum. Copyright 1991 Joseph Hutchinson. Reproduced by permission of Island Press, Washington, DC.

Animal agriculture has grown considerably in the Susquehanna River watershed. From the 1950s to the 1990s, milk cows have increased 5 times, hog production has increased 10 times, and chicken production has increased 100 times. Animal waste and fertilizer adds 5 times the nitrogen, and 14 times the phosphorus that human waste adds to the bay through sewage treatment plants (Horton and Eichbaum 1991, 46). Some of the mitigation measures to address this excess nutrient problem are to only use the fertilizer that the land needs, to capture manure so that it can be spread over the land in a more controlled manner, and to maintain forest buffers around streams to slow down and filter runoff from agricultural fields. The forest buffers need to be 100 feet or more to do the job (Horton and Eichbaum 1991, 50–55). Remember the scenarios from the computer simulation of the World economy in Chapter 2. One of the causes of collapse was the pollution caused by food production for a rapidly growing population.

The Susquehanna River dominates most of the Chesapeake Bay. The Susquehanna drains half of the bay's watershed. The upper bay from the mouth of the Potomac River northward is really the tidal part of the Susquehanna River. Phosphorous levels in the Susquehanna are slightly down but nitrogen levels are up. The watershed of the Susquehanna River is mostly in Pennsylvania and New York, neither of which have any direct frontage on the bay. This means that efforts by Maryland and Virginia to improve the bay they share will not be successful unless Pennsylvania and New York are also part of the clean up (Horton and Eichbaum 1991, 54–58).

Controlling storm water runoff is an important component of any clean up of the bay. Storm water runs off developed areas much faster than off forested undeveloped areas. Storm water running off developed areas carries with it fertilizer from lawns, oil and rubber from roads, and sediment from construction zones. Forests and non-tidal wetlands slow down and filter this runoff. With increasing population growth, development is increasing. As development increases the forested and wetland areas are being lost to paved roads, parking lots, lawns, and golf courses (Horton and Eichbaum 1991, 61–66). The water quality of the bay depends on our ability to slow down and filter the runoff from our development, which means leaving enough nature in place to do the job. However, if the population and resulting development continue to grow exponentially, the bay will eventually die.

Sewage treatment has improved over the years, and along with a ban on the use of phosphate in laundry detergents, has resulted in a significant reduction of phosphorous in sewage runoff. Nitrogen is much harder to control. However, the reduction in phosphorous in the Potomac River has resulted in a comeback of aquatic life in the river. Properly sited and maintained septic tanks and drain fields can be an appropriate way to treat human waste where enough site area is available and streams, rivers, or the bay are not too close to the septic systems. Sewage treatment has been a success story and can be improved, but eventually the technical ability to clean up sewage will run up against population growth. Even the most expensive, highest quality sewage treatment system lets some nutrients through to the bay. As the population increases the small amount of sewage let through becomes larger and larger (Horton and Eichbaum 1991, 66–75).

The excess nutrients from sewage treatment plants and agriculture cause algae growth, which reduces oxygen levels in the water. In addition, excess nutrients cause species like the fish killing microbe Pfiesteria to grow. Laws proposed by the Maryland General Assembly to reduce nutrient runoff were opposed by farmers from the Eastern Shore (Marsh, 1998). The land and the Bay are connected:

> There is a story told by Ed Ricketts, the eccentric marine biologist immortalized in John Steinbeck's Cannery Row. After listening for days at a conference to theories of what caused the crash of the West Coast's sardine fishery, Ricketts stood up, a shiny object half concealed in one hand. "You want to know where all the sardines went" he said. "I'll show you." We put them all in these little tins.
>
> (Horton and Eichbaum 1991, 104)

As mentioned earlier, the bay, in its pristine state because of its large watershed and shallow waters, was an ecosystem full of life. As development began, the bay was an important source of food. But, over the last 100 years, one after another of the once abundant species of marine life have been overfished. Striped bass, shad, and herring have all been harvested almost to extinction. The blue crab population appears to be stable. Signs of decline have been reversed by harvest restrictions. The Capitol reported on April 14, 2010, "Gov. Martin O'Malley, held a news conference at Fisherman's Inn in Kent Narrows this morning to announce a nearly 60 percent increase in the crab population. He attributed the increase to harvest restrictions enacted in both Maryland and Virginia two years ago" (Wood 2010).

The poster child of overharvesting is the oyster. The Chesapeake Bay was brimming with oysters when the Europeans arrived. "Chesapeake, or Chesepioc, is the Indian name for Great Shellfish Bay" (Horton and Eichbaum 1991, 115). Starting in the 1880s, the oysters were stripmined out of the Bay at 10 million bushels per year. The harvest declined steadily to 2 million bushels per year by 1930, and the current harvest is only a few hundred thousand bushels per year (Horton and Eichbaum 1991, 115–118).

Overfishing is a problem when a resource is owned in common. It is not in the best interest of any given fisherman to limit his catch, since no one owns the fish. So all the fisherman catch as many fish as possible. The end result is that the fish or oysters are driven to the brink of extinction (Turner et al. 1993, 205–210).

The pristine Bay was home to a diverse population of waterfowl. Only 3 of the 20 varieties of ducks have survived the changes the Bay has experienced. This decline is a result of the loss of underwater grasses and tidal and non-tidal wetlands. These habitats provided food and shelter. The geese population has increased because the geese were able to adapt to feeding on the leftovers of corn harvests. The net result is that the total water fowl population is stable, but not very diverse. Harvesting of waterfowl is primarily by sport hunters, which lends itself to regulation. (Horton and Eichbaum 1991, 121–127). The lack of diversity creates a less resilient ecosystem.

Resilience is the ability of an ecosystem to withstand a disturbance without too much harm and then bounce back. The primary features of the Chesapeake Bay's resilience are the forests and non-tidal wetlands on the land and the tidal wetlands, underwater grasses, and oysters in the water. All of these features act as buffers and filters and stabilizers and regulators (Horton and Eichbaum 1991, 128–130).

Horton and Eichbaum, in *Turning the Tide* (1991), describe a forest from the standpoint of various entities. The timber man sees an oak tree of about 80 years as prime wood material because it no longer adds wood very rapidly. The squirrel sees the 150 year old oak as just coming into its prime acorn production. The birds see oaks of 200 to 300 years old as prime complex habitats with multiple niches to live and nest in. The forest values all of these and the dead oak fallen to the forest floor that provides food for decomposers and new opportunities for young trees to grow. Finally the Bay sees the forest as the filter that consistently delivers clean filtered water (Horton and Eichbaum 1991, 130–131).

Forests once covered the vast majority of the Bay watershed. Development has reduced the forested area by half. Where these forests are located is as important as how much forest there is. Ideally the forests would be located in wide strips surrounding the Bay and its rivers and streams. This would provide an excellent filter system for runoff from developed areas and farmland. This is not the case. The forested areas are scattered around the watershed in large and small patches, and the high pollution areas have the least forest cover (Horton and Eichbaum 1991, 133–140).

Non-tidal wetlands make up about 3 percent of the watershed and are the places where water sits and filters into the ground. They are the swampy areas after rains. They provide habitat for numerous species from frogs to ducks. As development expands these inland wetlands are seen as problem areas to be drained so progress can move over them. The creation of water retention areas as part of new developments is an unproven substitute for leaving the wetlands alone (Horton and Eichbaum 1991, 141–146).

Most of the life of the Bay is along its edges. The edge of the Bay is a complex fractal made up of many interacting overlapping inlet sizes from large to small. This expands the length of the edge beyond measurement.

Estuaries like Chesapeake Bay are the most productive ecosystems on earth, and the edges of the estuary are the most productive area of the estuary (Figure 5.5). There are about 250,000 acres of tidal wetlands in the Bay ecosystem. Over the last century, Maryland and Virginia have lost about half of their tidal wetlands. The loss is due to development and to rising sea levels as the land subsides. Since most of the edge of the Bay is developed, the wetlands cannot migrate inland as the sea rises, so they disappear and are replaced by riprap edges. Osprey, bald eagles, oysters, crabs, and soft shell clams all live along the edges of the Bay. Our sewage treatment plants are also along the edge of the Bay (Horton and Eichbaum 1991, 147–150).

Maryland's Critical Area Act put zoning restrictions on a 1,000 foot strip along the edge of the Bay. The act preserves forests near the edge and requires a vegetated buffer from 100 to 300 feet at the edge. The concept was that human development, no matter how good, causes problems. Leaving enough nature near the edge is the best way to protect the Bay edge from damage. Virginia has a similar act. Both have problems but the concept is correct (Horton and Eichbaum 1991, 158–167).

Shoreline erosion was controlled in the pristine Bay by underwater grasses that reduced wave action and caught sediment near the shore rather than letting it spread further into the Bay. Excess nutrients cause algae growth, which clouds the water and creates a coating on the grasses. Excess sediments also cloud the water. The cloudy water and coated grasses reduce photosynthesis, which causes the grasses to die. Restoring the grasses would go a long way toward protecting the shoreline. There have been some success stories. As the phosphorous was controlled in the Potomac River, the grasses have come back, not completely but substantially (Horton and Eichbaum 1991, 169–174).

Most of the major rivers flowing into the Bay have dams on them. The dams cause two problems. The first is that they cut off migration of fish that want to go up stream to spawn, which puts stress on future populations of fish. The second

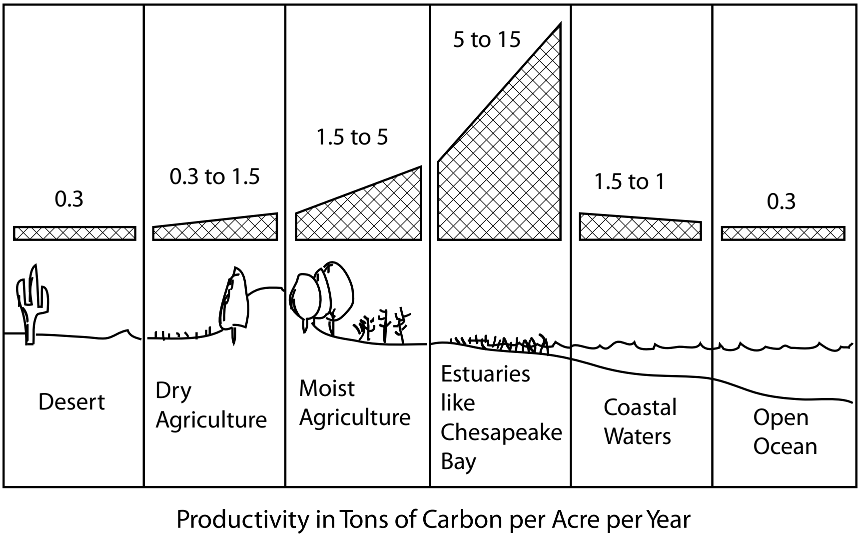


FIGURE 5.5 Productivity levels in tons of carbon per acre per year.

Source: From *Turning the Tide* by Tom Horton and William M. Eichbaum. Copyright 1991 Chesapeake Bay Foundation. Reproduced by permission of Island Press, Washington, DC.

is the use of fresh water for human purposes like agriculture, drinking, and bathing. These uses tend to reduce the amount of fresh water flow into the Bay. The Bay is an estuary. It needs a balance between fresh and salt water flows (Horton and Eichbaum 1991, 181–187).

The exponential growth of population in any ecosystem will eventually outstrip the resources and sinks. In addition the exponential growth of goods per person will also outstrip the ecosystem's ability to support human society. Combined together the problem is compounded. We need to rethink what we mean by progress and economic growth. Ecosystem resilience is a function of the complex layers of interacting living systems with the physical environment across scales from large to small. Development replaces complex ecosystem interactions with unstable simplicity. If we desire ecosystem resilience we need to limit development and leave enough of nature untouched.

6

ECOLOGY AND ARCHITECTURE

Ecology is the study of the totality of living systems and the geologic, atmospheric, and hydrological systems that come together to support the living systems. Thus, ecology as a science is surrounded and intersects with many other scientific disciplines. A subset of these disciplines includes physiology, genetics, hydrology, atmospheric science, geology, behavior, biochemistry, and biology (Smith and Smith 1998, 3–5). Ecological systems and the animals and plants that make up the system maintain stability by a combination of positive and negative feedback. Positive feedback accelerates a response. Negative feedback retards a response. The combination of multiple positive and negative feedback loops creates a nonlinear system. Nonlinear systems are stable within limits, which is a very important characteristic. A linear system will grow or decline along its linear path when perturbed, and thus cannot create a stable environment (Smith and Smith 1998, 10–13).

Architecture at its core is a puzzle where the pieces change shape as the architect brings the order of the design together. Architecture like ecology is surrounded and supported by multiple disciplines. The architectural puzzle includes parts of each of the supporting disciplines. The decision to expose or hide the HVAC ducts, the decision to expose or hide the structure and which direction the structure runs, the location and design of the elevator lobby, and the orientation and type of light fixtures are examples of architectural decisions that are then followed up by engineering calculations to fill in the details of the design. As all these pieces of the puzzle come together they affect each other and the larger design concept, causing nonlinear interactions that eventually create a stable solution (Figure 6.1).

Living systems embedded in an ecosystem inhabit niches along environmental gradients or around feeding and or breeding areas. Far from the center of the niche, survival is not possible. Moving toward the center of the niche is an area where growth is possible and inside that is an area where reproduction is also possible.

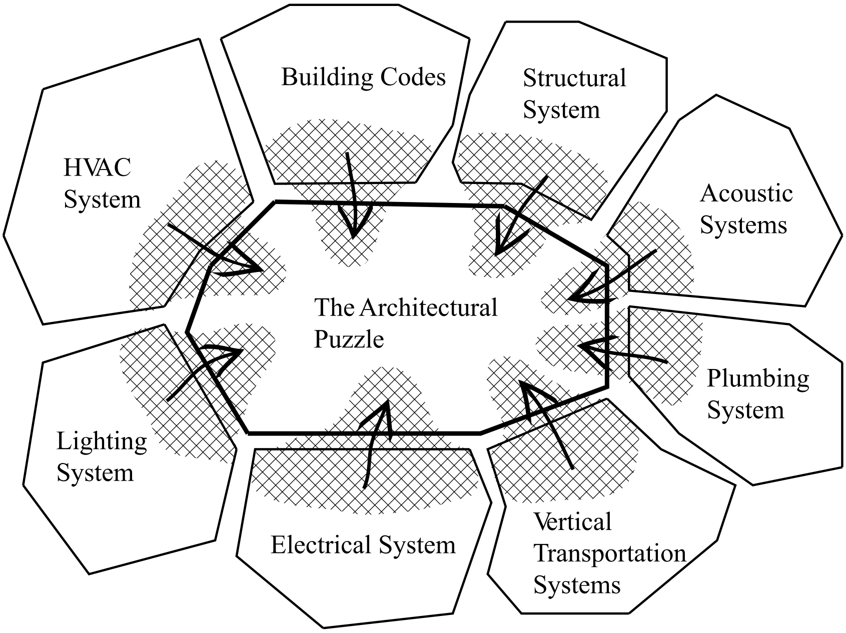


FIGURE 6.1 The architectural puzzle includes engineering information from many disciplines.

At the center of the niche is the optimum point for the organism (Smith and Smith 1998, 12).

Architecture and urban design also have their niches. The siting of houses in different climates is an example. In warm humid environments, a location high on a hill would allow for better cross ventilation whereas in a hot arid environment a house would be better off low in a valley near water elements and in the cold night air pool. In a temperate environment, a site part way up a south slope provides a balance between solar access and wind protection in winter and access to cross ventilation in summer (Brown and DeKay 2001, 88). On a commercial scale niches exist around transit stops for service related businesses, and in downtown business districts for office buildings. In downtown areas there is often a vertical niche structure with stores and restaurants at the ground level and offices above. An urban plan for a region creates niches for industry, residences, schools, shopping, downtown business, and historic districts. Planned unit developments and New Urbanism place uses closer together so that people can live, shop, and work without traveling great distances.

Almost all life on earth depends on photosynthesis. Photosynthesis takes in carbon dioxide and solar energy and uses these and water to create sugars, which then are made into carbohydrates and proteins used by the plant. In the process the plant gives off oxygen and water. Animals eat plants for their carbohydrates and proteins, and they breathe the oxygen the plants created exhaling the carbon dioxide that the plants need (Smith and Smith 1998, 21).

In dry climates there is a modification to the photosynthesis process. Water is scarce, so the process is divided into two parts. The leaf opens up at night to take in the carbon dioxide. The carbon dioxide is stored chemically as malate and asparate for later use. This process limits the amount of water that is exhausted since it is cooler at night. Then during the day the carbon dioxide is reconstituted and combined with solar energy to create the sugars that then become the carbohydrates and proteins needed by the plant for growth (Smith and Smith 1998, 23).

The architectural response to a warm humid climate, where water is not a problem, is to open the design as wide as possible for cross ventilation while limiting direct solar penetration. Bounced solar is used for illumination. In hot arid climates, houses are built with high thermal mass and ventilated at night to cool the thermal mass down. During the day, the house is closed to the outside to hold on to the cool stored from the night before. Windows are small to let in a minimum amount of solar heat during the day.

The conditions for life are driven by the Sun's energy interacting with the oceans and atmosphere of the earth. More solar energy reaches the equatorial regions than the polar regions. The atmosphere is warmed at the equator and water is evaporated into the warm air, which rises and travels north. As the air rises and moves north it cools and thus cannot hold as much water in vapor form resulting in rain

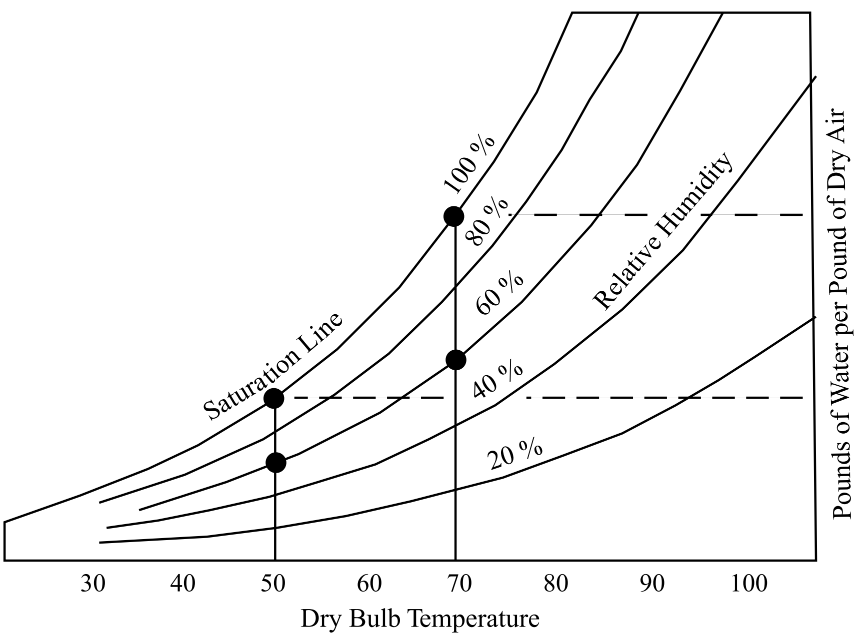


FIGURE 6.2 The psychrometric chart maps the air water vapor thermodynamic mixture. Warmer temperatures can hold more water in vapor form than colder temperatures.

(Smith and Smith 1998, 31–32). The psychrometric chart (Figure 6.2) illustrates how air at higher temperatures can hold more water in vapor form than air at colder temperatures.

When the air descends in the middle latitudes it warms up, which dries the air out creating a strip of deserts around the world above and below the equator. The rotation of the earth deflects these air currents creating the easterly trade winds in the low latitudes and westerly trade winds in the higher latitudes. These are called trade winds because sailing ships used them to move goods around the world before steam ships. The oceans also move heat from the tropics to the poles. The Gulf Stream is part of this elaborate ocean current system. The Gulf Stream moves warm water near the surface from the tropics up the east coast of the United States and then over toward the UK. The warm water of the Gulf Stream makes northern Europe much warmer than it should be at its latitude. The Gulf Stream cools in the north Atlantic between England, Iceland, and Norway and descends and returns cold water in a deep water current back toward the poles. These ocean currents generally flow in a westerly direction near the equator and in an easterly direction in higher latitudes because of the rotation of the earth (Smith and Smith 1998, 33–38).

At a more local level, as moist air comes against a mountain range it is forced to rise, which causes it to cool, which causes the moisture in the air to rain or snow out. As the air moves down the back side of the mountain range, the air has lost most of its moisture and it descends, which causes it to warm up and dry out further. Thus the windward side of a mountain range is wet and the leeward side of a mountain range tends to be dry. This is an example of two microclimates created by a mountain range. Nature lives in the general climate and the micro-climate (Smith and Smith 1998, 41).

Plants need sunlight for photosynthesis. Plants have adapted to different levels of light. Sun plants need larger amounts of sunlight to achieve an optimum amount of photosynthesis while shade plants have adapted to need lesser amounts of sunlight to achieve optimum growth (Smith and Smith 1998, 50).

Buildings also respond to the amount and intensity of available light. Alto's libraries located in Finland have extensive skylight systems to bring in large amounts of light in an overcast environment (Figure 6.3). In contrast the Kimbell Art Museum in Fort Worth, Texas, located at a lower latitude and in a clear sky intensive sunlight area, is illuminated by a modest to small slot along the top of its vaulted ceilings that is then reflected back onto the concrete vaults. Another example is Luis Sullivan's Auditorium Building in Chicago, Illinois. The auditorium has no need for daylighting so it is placed in the center of an office block surrounded by office space that does need daylighting.

Plant growth, driven by photosynthesis has an optimum temperature range where growth is maximized. Animals also have temperature ranges. Cold blooded animals have to use their environment to create their optimum temperature. Warm blooded animals use their metabolism to maintain their temperature (Smith and Smith 1998, 59).

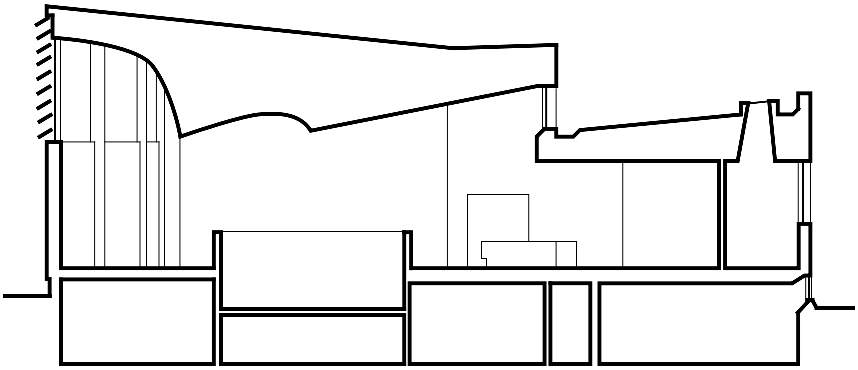


FIGURE 6.3 Alvar Alto's libraries are designed to bring in a large amount of daylight in a climate where daylight is scarce half the year.

Source: Moore 1993.

Humans have an optimum temperature and humidity range where we are comfortable without elaborate intervention. The bioclimatic chart (Figure 6.4) illustrates this range. Humans will be thermally comfortable in light clothes in the shade over a temperature range from about 70 to 80 degrees Fahrenheit, and over a humidity range of 20 to 70 percent. Note that at humidities above 50 percent, the temperature comfort range gets narrower. Comfort can be extended to slightly warmer temperatures by introducing air motion, usually by cross ventilation but also by ceiling fans. Comfort can also be extended to slightly lower temperatures by the addition of an increase in the mean radiant temperature. This is what passive solar heating does. The sun heats up thermal mass inside a space that holds on to the heat to create an elevation of the mean radiant temperature above the air temperature. In the hot dry area above the comfort range, air motion can be combined with the addition of water droplets into the air. The water droplets evaporate taking energy out of the air thus cooling the air at the expense of a slightly higher relative humidity.

Whales and dolphins have a blood distribution system in their flippers that surrounds warm arterial blood with returning veins. The result is that the returning blood is heated before returning to the body core (Smith and Smith 1998, 67–68). This is a cross flow heat exchanger. Exhaust air heat recovery systems, like an energy transfer wheel, operate on the same principle. Heat from air being exhausted is passed through a heat exchanger to warm the incoming air in winter. In summer, the incoming air is cooled by the exhaust air.

Plants draw water into their roots and up into the plant by osmotic pressure difference. The leaves transpire moisture into the air because the moisture level of the atmosphere is less than that of the leaves. This process provides the water that the plant needs for growth. In wet climates the ratio of above ground plant to below ground root structure is large. The plant does not need an extensive root system to supply water. In dry climates this is reversed. An extensive root system

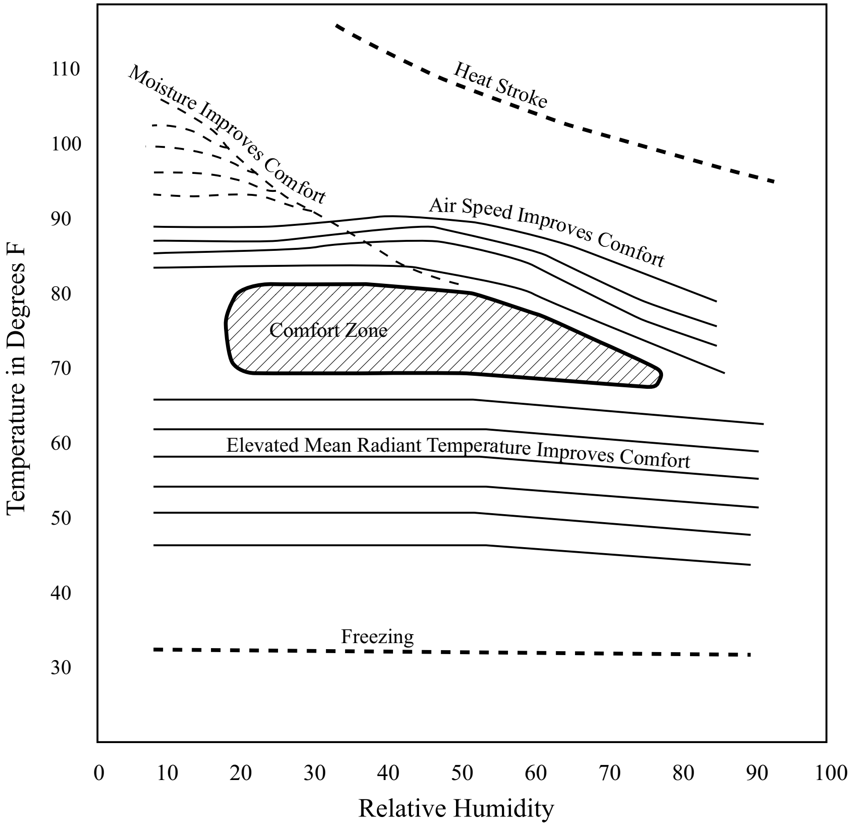


FIGURE 6.4 The bioclimatic chart maps human comfort in relation to temperature, humidity, mean radiant temperature, and wind speed.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

is necessary to supply water and less above ground leaf structure is necessary for transpiration (Smith and Smith 1998, 76–78).

Buildings in warm humid climates tend to sit up off the ground to get out of the moisture and into the free air stream for cross ventilation. Buildings in hot dry climates can achieve advantage by connecting to the earth, which a few feet down is colder than the air. In addition, fine water droplets introduced into the air flowing through a building can reduce the air temperature while increasing the relative humidity. This can be done mechanically or through the use of cool towers.

Cool towers spray water into the top of a stack of air. The water is evaporatively cooled and drops into the space below cooling it. The air needs to exhaust through low openings in the cooled space for the air flow to happen (Brown and DeKay 2001, 194).

All inhabited buildings need a supply of water for drinking, bathing, washing, and toilet flushing. At a residential scale, the utility supplied water is under enough

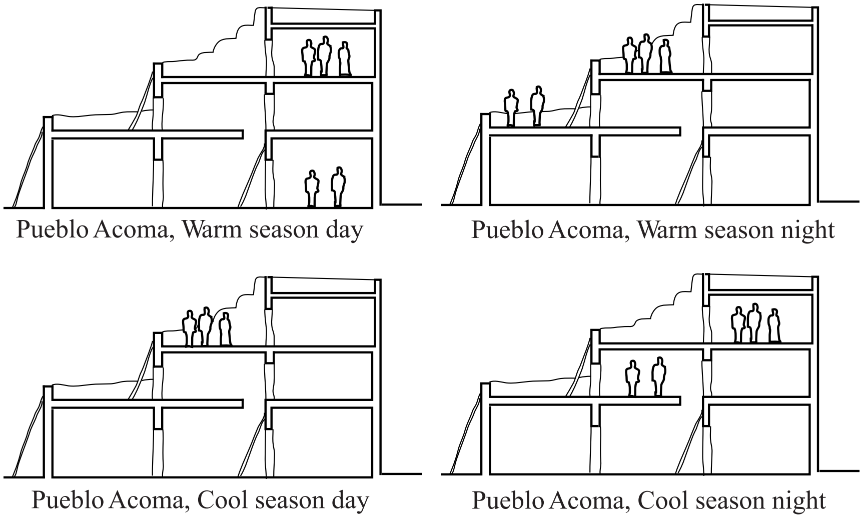


FIGURE 6.5 Pueblo Acoma demonstrates settlement structures designed for human movement in response to seasons.

Source: Brown and DeKay 2001.

pressure to lift it two to three stories. In taller buildings, it is necessary to pump water pressure up into the building. As with plants, water is necessary for the organism, people in the building, to survive.

Animals and plants display periodic behavior. Plants flower in spring and go to seed in summer. Male deer grow antlers in summer, that are displays of male strength in the late fall, and then are shed as winter comes on. Crabs relate their activity to the tides. Birds migrate north in the summer and south in the winter (Smith and Smith 1998, 88–94).

Pueblo Acoma (Figure 6.5) is one example of human movement related to seasons. In summer it is cooler inside the thermal mass of the pueblo rooms during the day but at night it is cooler outside on the terrace of the pueblo. In winter this situation reverses. A similar diurnal migration happens in the traditional Iraq house. During summer days the thermal mass of the house, cooled from night ventilation and additionally cooled by evaporative cooling, makes the interior the location of choice. At night the outside cools down quickly making it more comfortable to inhabit the roof, which may or may not have a light weight covering for some protection from weather (Brown and DeKay 2001, 136).

In nature there is no waste. Plants use minerals and water from the soil and carbon dioxide from the air to create growth giving off oxygen as a waste product. Animals use plants for food and oxygen from the air to oxidize the food to create growth giving off carbon dioxide as a waste product. Both plants and animals return nutrients to the forest floor in the form of dead organic matter. Decomposer plants and animals use the dead organic matter as food and excrete minerals as waste, which the plants then use as food. There is no waste. Waste is food. The ecosystem is in balance (Smith and Smith 1998, 97–100).

Human economy is not well-balanced. We extract minerals from the earth and organic matter from plants and animals and use it to produce material things and food. When we are done with the material things we throw them away in trash heaps. We have been doing this for thousands of years. We consume food then dispose of the waste from our consumption through the sanitary sewer system slightly treated into rivers and oceans. Somehow we need to learn to create industrial ecologies that use the waste from one process as food for another process. We also need to reuse materials rather than throwing them away. Once steel or aluminum has been produced it needs to stay as steel and aluminum, recycled forever.

There can be an industrial ecology surrounding a coal fired power plant. Fly ash scrubbed from the exhaust gases can be used as a substitute for cement in concrete production. Sulfur dioxide also scrubbed from the exhaust gases can be combined with limestone to make calcium sulfate, synthetic gypsum. Both of these products are coming from what was previously the waste stream of the flue gases. However, we are still left with the carbon dioxide exhausting into the atmosphere.

Populations can be dispersed in a uniform, random, or clustered way. Different species have different population growth patterns. Some species like fish produce a vast number of young with only a few surviving to adulthood. Birds and mammals create a modest number of offspring with deaths spread over all ages. Humans, before stable food production and modern public health and medicine, were like other mammals with deaths spread out over all ages. There were lots of births and lots of deaths resulting in a very small population growth rate (Smith and Smith 1998, 127–133).

Industrial development provides improved public health and a more stable food supply. In addition modern medicine reduces deaths, but it takes a while for births to decrease. The population of the developing world is expanding quickly as a result, and will continue expanding in the near term future as the large number of young people reach reproductive age. The population distribution diagram has a wide base and a narrow top. Most of the population is young and approaching reproductive age. The population distribution of the United States and other developed countries illustrates how a zero population distribution has equal amounts of people in all age groups until old age tapers off the top of the distribution (Figure 6.6). Zero population growth is a necessary condition for the sustainability of human society. The earth cannot support an ever growing population. There are problems with this transition that are not solved yet. In developed countries like the United States social security is based on the younger workers paying for the retirement security of the older workers. This system was set up when the population distribution looked more like the developing world's population distribution. As a society approaches and attains zero population growth, the number of younger workers available to help support the retirement security of the older workers decreases, which causes a funding problem. A solution other

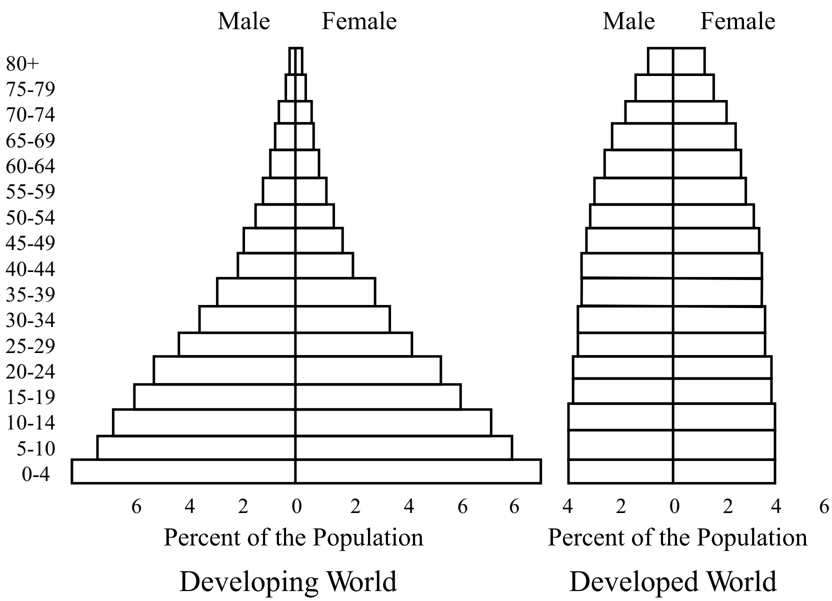


FIGURE 6.6 Population distributions by age comparing developing countries with developed countries.

Source: United States Census Bureau, Global Population Profile, 2002.

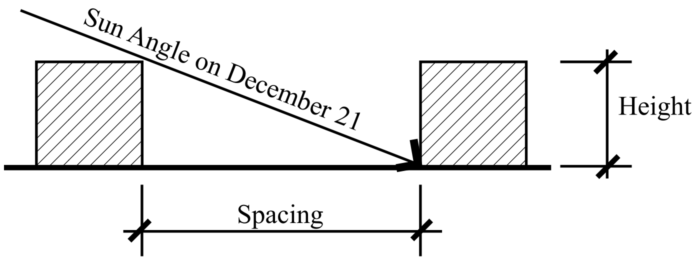
than an increasing population needs to be found. The consequences of over population are catastrophic.

On St. Paul Island off Alaska 4 male and 22 female reindeer were introduced to the island in 1910. The herd grew exponentially, eventually overgrazing the island so badly that a population collapse left only eight animals. This exponential growth beyond the limits of the environment followed by collapse is a typical response to populations exceeding resources. Population controls are necessary. One way nature controls population is through predators. As the grazer population expands the predator population expands thinning out the grazer population, which results in preserving the plant population that the grazers need for food (Smith and Smith 1998, 157–162).

Another way nature controls population takes the form of defended territories. Animals, usually the males, define and defend territories that are theirs to forage in and breed in (Smith and Smith 1998, 171–174).

The distribution of buildings can be controlled in various ways with planning restrictions defining lot size, lot coverage, floor area ratios, and height limits. A more restrictive and more natural method of controlling building distribution is by requiring solar access. Solar access constrains buildings so as not to cast shadows beyond their site lines over the middle 4 to 6 hours of the day (Figure 6.7).

Access to water could limit the growth of cities before modern technology which allows water to be brought in from a wide ranging area. Los Angeles is an example



Latitude	9am - 3pm	Noon
24	1.5(H)	1.1(H)
32	2.0(H)	1.5(H)
40	3.0(H)	2.0(H)
48	5.4(H)	3.0(H)
56	8.4(H)	4.0(H)

FIGURE 6.7 Solar access.

Source: Brown and DeKay 2001.

of this. It draws water from all over California through the California water system, and from all over the Rocky Mountains through the Colorado River.

Ecosystems are very complex overlapping structures. Animals and plants find niches to survive in that interact with other animals and plants. The complex overlapping and interacting provide a stable nonlinear system. If one piece of the system fails the whole system has resilience to maintain stability. Nature can withstand major stresses on it because even when almost all of an ecosystem is wiped out by a cataclysm like Mount Saint Helens exploding, plants and animals use the situation as an opportunity to move in, and thus repopulate the area. Dynamic change is built into natural systems.

Stuart Brand in his book, *How Buildings Learn*, looks at buildings over time and shows that they go through many lives, with parts of the building being renewed over and over while other parts last for a longer period of time. The structure and basic form of the building will last the longest. The skin and the heating and cooling systems will be changed multiple times. The interior space plan will change very often and the furniture will change very rapidly (Brand 1994, 13). Architects need to consider this long view when they are designing. A building designed too tightly for a single use, may not have the necessary flexibility to last through time.

As human settlements spread over more area, there is a problem with the amount of nature that is left over. Nature needs large enough patch sizes so that species that require interior forest conditions as well as species that require edge conditions can both exist. It is also important that the patches are interconnected or at least close together. Plants and animals need to migrate to new areas to maintain the dynamic balance of ecosystems. Isolated islands result in less diversity, which translates into less resilience. This will become very important as climate change causes plants and animals to migrate north to new more favorable territories. If they cannot move they will die off (Smith and Smith 1998, 283–287).

Ecosystems go through a succession when they are starting over after a cataclysm. First grasses and small animals move in followed by larger plants and animals. The early migrants create the nutrients and microclimate conditions for the next succession of plants and animals. The soil, moisture, and temperature conditions determine what the mature condition will be. Warm temperatures and wet conditions create a tropical rainforest. Moderate moisture and mild temperatures create a deciduous forest. Dryer conditions create a savanna in warm temperatures, a prairie in mild temperatures, and a coniferous forest in colder temperatures. Low moisture conditions create deserts in high temperatures and tundra in cold temperatures (Smith and Smith 1998, 290–298).

As an example, a pine forest creates a shade condition where oak and hickory saplings and seedlings have an advantage over pine saplings and seedlings, resulting in the eventual succession from a pine forest to an oak and hickory forest (Smith and Smith 1998, 309).

Human settlements also go through a succession as the need to handle larger populations presents itself. Cities start as small settlements in advantageous physical areas. As the population increases, the central areas of the settlements grow into commercial centers with more significant buildings. At some point along this path a basic city plan gets laid out that ends up being the infrastructure for all future growth. The driving force in urban succession is economic. As the center of the city becomes more important to commerce, the value of the land increases, which requires larger buildings on the land to create a return on the investment in the land.

Boston is an example of this succession. A street pattern laid out early in Boston's history has remained fairly constant as building size has dramatically increased. The street pattern maintains itself over time. This reinforces the concept that urban design is more important to successful, vibrant, walkable cities than individual buildings.

7
ENVIRONMENTAL ECONOMICS

Economic theory was developed based on the first law of thermodynamics, which is conservation of energy and matter (Beinhocker 2006, 66–68). A basic assumption of economics is that when any source of material or energy becomes scarce, the price will increase which will cause new sources of material and energy to be developed. This assumption was reasonably valid in an earlier age when society was not perched on the edge of sustainability. Standard economic theory assumes an infinite amount of earth ecology to provide materials and energy, and to dispose of wastes (Beinhocker 2006, 68–74).

The central idea of economic theory is that supply and demand will create a fair price for goods and services used by the economy. The demand curve represents the fact that, as the price of a product decreases, consumers will buy more of that product. The cost or supply curve represents the fact that, as the price of the product increases, the producer has an incentive to produce more of the product.

The price of a product is determined by where the demand curve crosses the cost curve (Figure 7.1). The curve ignores where the materials and energy come from to make the product and where the waste products from making the product are disposed. This information is compressed into the cost of production. There is no direct way for economic theory to consider the environmental cost of the production. The curve also ignores time. It represents an instant in time. The way economic theory represents time in its calculations is through interest rates. A given quantity of money is worth more today than a year from now because the money could be invested and earn interest in a bank or a return on an investment. This is a correct and valid concept. However, from an environmental point of view the time value of money causes materials and energy to be more valuable used today, in a business venture, rather than being conserved for later use. This brings up the need to define various forms of sustainability.

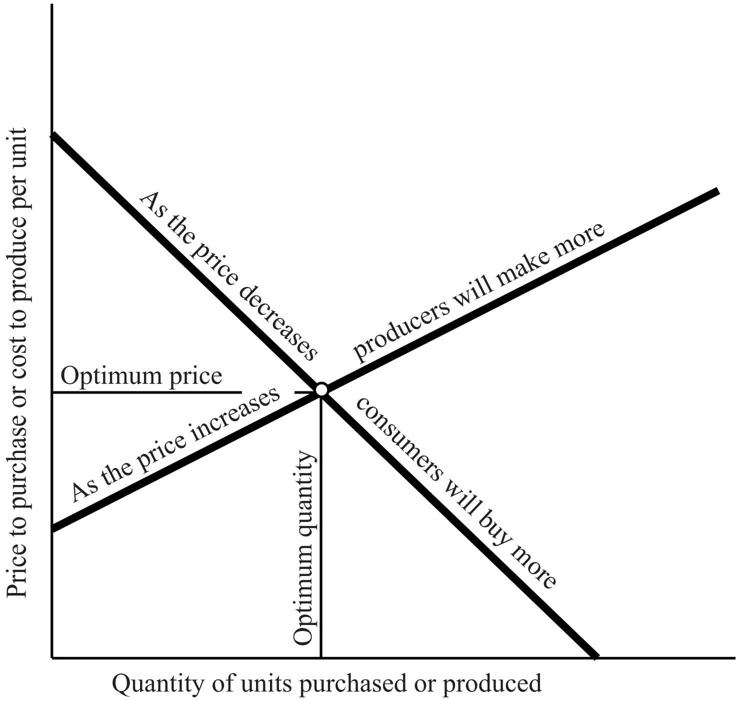


FIGURE 7.1 Supply and demand curves determine optimum production.

Source: EPA 2010.

In a weak version of sustainability, which is in alignment with economic theory, human made goods can substitute for natural capital. With this concept of sustainability it is acceptable to clear cut a forest as long as the wood is used to create houses that can be passed down to future generations. There is no concern for the intrinsic value of the forest to create oxygen and shelter a diverse population of animals. There is also no concern that the forest will not be there to build houses in the future. A slightly stronger version of sustainability requires that the value of natural capital be maintained into the future. The problem with this is that, as natural capital is used up, its value will increase because of scarcity (Wackernagel and Rees 1996, 37).

The strongest form of sustainability requires that natural capital; forests, rivers, oceans, and so on, be maintained into the future as a separate entity from human made capital. Forests provide oxygen, slow and filter storm water runoff, provide habitat for animals, moderate climate extremes, and, when sustainably harvested, supply wood for future generations. This stronger form of sustainability calls for the actual service flows from the environment to be maintained over time, rather than the value of the service flows not declining (Wackernagel and Rees 1996, 37).

Natural capital takes on three forms. Renewable natural capital includes living things like forests, animals, fish, and, in general, all living, reproducing ecosystems. Replenishable natural capital includes the features of the earth like fresh water, and the ozone layer that replenish through solar energy processes. Non-renewable natural capital includes fossil fuels that when used are gone, and resources like metals mined from the earth (Wackernagel and Rees 1996, 35).

Most industries have a waste flow from their industrial processes. As an example, consider a paper mill located on a river. The waste stream can be dumped into the river at no cost to the paper producer. The waste stream will cause pollution in the river. The demand and cost curve diagram can illustrate the economics of the situation, by including a cost curve that includes the social costs of the pollution (Figure 7.2).

The method that society uses to modify this situation and enforce the social cost on the industry in question is to create regulations that control the amount of pollutant that can be dumped into the environment. The business environment generally resists regulations. They claim that it increases costs, and thus reduces competiveness and potential job growth. The question is, *Why resist regulations if the costs can be passed on to the consumer in higher prices?* Regulations that require a business to reduce its dumping of pollution into the environment incur an increase in their marginal cost. Demand for the product being produced generally does not change with the imposition of the new regulation. The result is that only part of the cost of the regulation can be passed on to the consumer. The remaining cost is borne by the business, which will reduce profits (Turner et al. 1993, 243).

The supply and demand curves showing the difference between the private cost curve and the social cost curve that includes the cost of pollution can also be used to explore the consequences to society of only considering private costs. There is too much of the product produced. More pollution is produced. The price of the product is not high enough. Since the cost of the pollution is external to the private economic decision there is no incentive to improve the situation. And finally, reuse or recycling of the pollutant is not considered because there is no cost to dumping the pollutant in the environment (Tietenberg 1996, 48).

When a resource is owned privately the owner has a strong incentive to conserve the resource since a decline in the value of the resource is a personal loss. When a resource is owned in common there is a tendency for multiple parties to harvest as much of the resource as they can.

Renewable common property resources, such as fish in the sea, provide an opportunity for a sustainable source of food year after year, if they are managed properly. Consider how a fish population grows. Starting from a small population, the fish growth rate will increase as more fish are available to reproduce. The growth rate will reach a maximum and then decline, as the population of fish reaches the quantity that the environment can maintain. Now consider what happens as a fisherman who owns the fishery catches fish from this population. The population will decline, which will result in an increase in fish reproduction to replace the fish lost to the fisherman. There will be a maximum quantity of fish that the

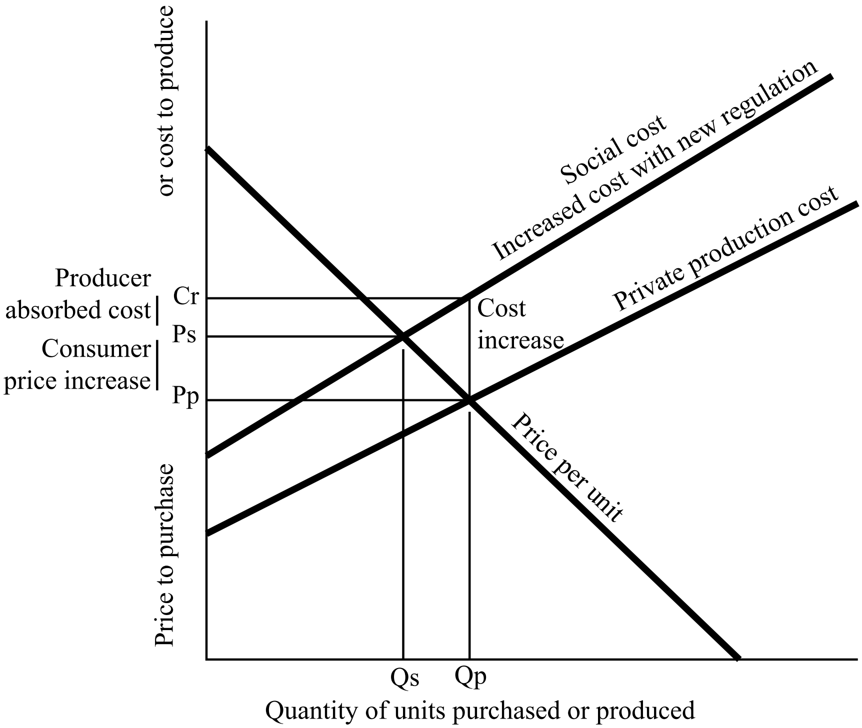


FIGURE 7.2 Including the social cost of an industry's pollution with regulations causes changes in price and quantity produced.

Source: EPA 2010.

fisherman can take out of the fishery year after year that leaves enough fish uncaught so that they can reproduce to replace the fish taken away by the fisherman. This is the maximum sustainable yield. An owner of the fishery would have an incentive to never go beyond the sustainable yield because he would be concerned with future yields, and since he owns the fishery he would be rewarded with the future yields. Actually, the most profitable yield of fish is less than the sustainable yield because it takes effort to catch the fish and profit is revenue from the catch minus effort. Profit is maximized at yields less than the sustainable yield where, since there are more fish available, they are easier to catch (Tietenberg 1996, 272–276).

When the fishery is owned in common, problems arise. No one fisherman can be assured that his maintaining fish catches at or below the sustainable limit will reward him with future fish catches year after year. So every fisherman in his self-interest catches as many fish as possible. This drives the catch beyond the sustainable limit, and, as the technology of catching fish improves, the fish population can be driven close to extinction (Tietenberg 1996, 280).

Society produces waste in various forms. Economic theory can help determine the optimal amount of effort to apply. The cost of processing waste so that it does

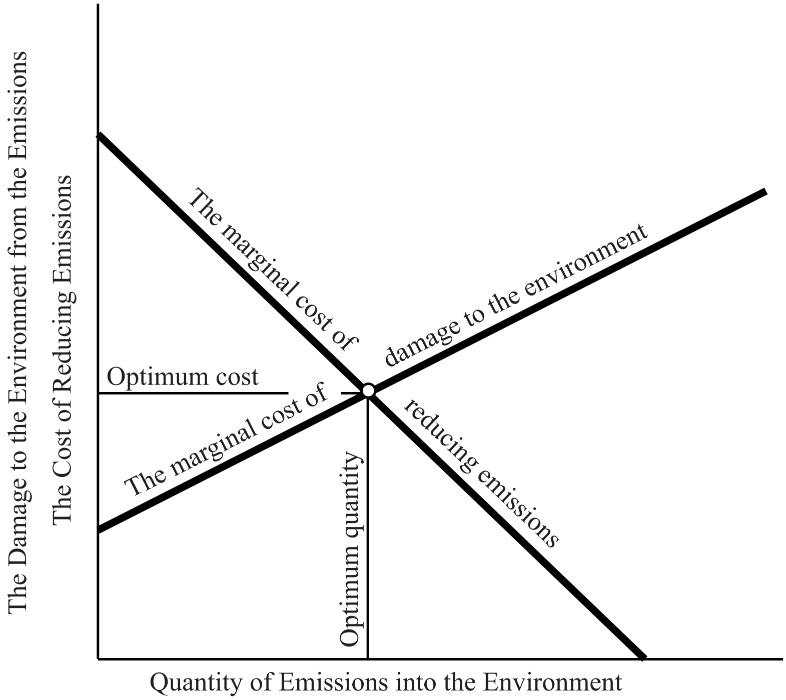


FIGURE 7.3 The economics of determining optimum waste disposal into the environment doesn't consider how much waste the environment can handle.

Source: EPA 2010.

not reach the environment increases exponentially as the process approaches the point of allowing no waste. The cost of the marginal damage to the environment increases exponentially as more waste is allowed to be dumped into the environment. Where these two curves cross is the optimal amount of waste processing (Figure 7.3) (Turner et al. 1993, 254).

This analysis is purely economic. There are two problems. The first is, *Can the environment handle this amount of waste?* The second is, *How do we set a value on damage from waste disposal into the environment?* A strong sustainability response to this problem would be to determine the amount of waste that the environment in question can process naturally. And in addition, strong sustainability would try to find an industrial process that could use the waste in question as an input. Waste is food in a natural ecosystem.

The use of paper in the newspaper industry provides an example of decisions about waste streams The cost of using virgin pulp to make new paper starts high at zero recycling and curves down to no cost at 100 percent recycling. The cost of using recycled paper starts at zero when no recycling is used and increases to a high amount when all recycled paper is used. Adding these two curves together produces a private optimum cost curve resulting in a decision to use a mix of virgin

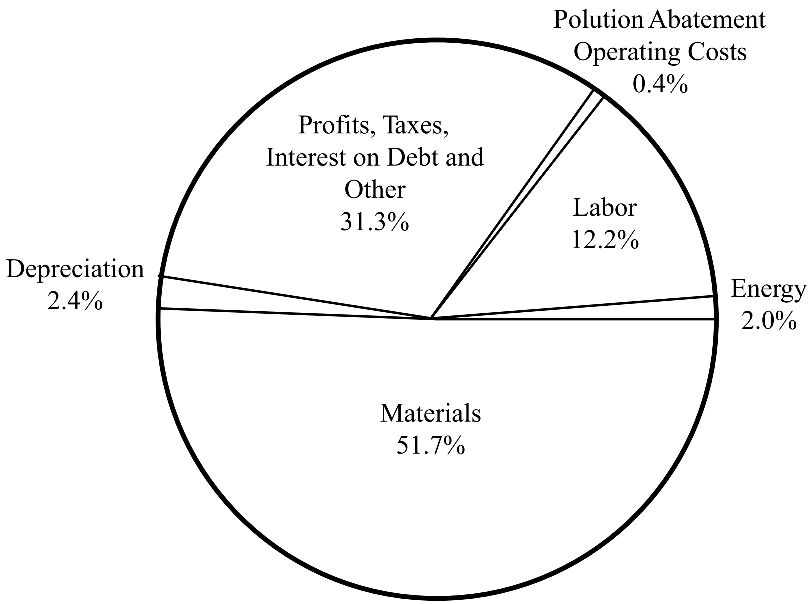


FIGURE 7.4 Pollution abatement costs are a small percentage of total manufacturing costs.

Source: EPA 2010.

and recycled paper that minimizes costs. There are social costs related to the disposal of the paper that is not recycled. There is a cost to the environment caused by the waste stream degrading it. The cost to the environment starts high, with no recycling of paper, and decreases as recycling increases. The social optimum recycling is the sum of the private cost curves and the social cost curves. The social optimum calls for the recycling of significantly more paper than the private optimum (Tietenberg 1996, 187–189).

Since the social costs are external to the private economic decision, it is difficult to achieve the social optimum recycling amount. The traditional answer to this kind of problem is a government regulation that requires the social optimum recycling. But, as we saw earlier, only part of the cost of the regulation can be passed on to the consumer as a price increase so businesses resist regulations. However, the average pollution abatement cost of manufacturing companies in the United States is only 0.4 percent of operating costs, and only 1.2 percent of operating costs in the paper industry, which has the highest pollution abatement costs (EPA 2010, 9–7).

Economics can be applied to the optimum harvesting of wood from a forest. When a forest starts growing the volume of wood produced increases rapidly. This is followed by a period of constant growth in the volume of wood produced. Finally, as the forest matures the volume of wood produced begins to decrease, reaching a point where the mature forest has no increase in wood volume. From an economic standpoint, there are two points where harvest is considered. The first harvest point is at the point where the rapid increase in volume of wood levels off to steady growth. After this point incremental growth is declining. The second harvest point is at the end of the steady growth period before the declining growth of the maturing forest begins. After this point there is a decreasing volume of wood produced each year (Tietenberg 1996, 248–254).

None of this decision making considers the ecological value of the forest to produce oxygen, and provide habitat for a diverse population of flora and fauna, some of which could turn out to be very valuable to society.

Large oil spills cause damage to the environment, which causes economic damage to the people who live in the area of the spill and create their living from the environment. As the amount of precaution is increased the expected penalty payout decreases and the cost of the precaution increases. The intersection of these two cost curves would represent the optimum amount of precaution. However, the oil companies are large and wealthy so they can afford armies of lawyers to defend themselves against payouts. The end result of this is that decades can go by before payouts are made. Because the time value of money reduces the penalty payout amount, the penalty amount is less than it would have been, resulting in a reduction of the optimum amount of precaution taken by the oil companies (Tietenberg 1996, 448–450).

The economy of the United States and the world needs to grow at a rate of 3 to 4 percent per year to be considered healthy. This is a problem. The material resources of the Earth are limited, and the ability of the Earth to absorb the waste products of economic growth is also limited. A 3 percent per year growth rate results in a doubling in 23 years. A 4 percent per year growth rate results in a doubling in 18 years. To envision the consequences of exponential growth consider as an example a suburban county outside a large city. Only 25 percent of its land area is covered with subdivisions and strip malls, which leaves plenty of open space for quality of life. If this county has a growth rate in land use of 4 percent per year, 18 years from now the county will be 50 percent covered with subdivisions and strip malls, and in 36 years all of the land area of the county will be covered with subdivisions and strip malls. If the county council initiates Smart Growth concepts and can reduce the land use growth rate to 2 percent per year, the county will be half covered in 35 years and completely covered in 70 years. Even modest growth, if it is exponential, causes explosive results.

Herman Daly's and John Cobb's book, *For the Common Good,* tries to address the problem of growth. One issue they present is that the gross domestic product (GDP) does an incorrect job of measuring the real gross domestic product. The following two examples illustrate the measurement problem. The GDP counts as a positive number the oil we take out of the ground and burn up to fuel our society. This would be equivalent to a person spending part of his savings in a year but considering it current income for that year. A related problem is oil spills. When a large oil spill happens, such as the Exxon Valdez, the cost of the cleanup is considered a positive addition to the GDP. This would be equivalent to a person spilling oil or something else on their living room carpet and then considering the cost of cleaning up or replacing the carpet as positive income for that year (Daly and Cobb 1994, 62–84).

Herman Daly has produced a per capita index of sustainable welfare. The sustainable index, which corrects for the issues mentioned above, is relatively flat. It shows a slight growth in the mid-1960s and a slight decline in the late 1970s, with a slow rise after that (Daly and Cobb 1994, 464).

We need to discover how to create an economy that grows qualitatively, not quantitatively. At some point we will all have to decide that there are limits on the amount of goods we can produce and own. Quality of life will have to outweigh having three more and bigger wide screen TVs.

It seems clear that depending on economic theory alone to guide society's decisions about the environment is a mistake. As an example, consider that

> a complete loss of expected world GNP 100 years from now, at current interest rates, would have a present value of about one million dollars. This is trivial in comparison to the present value of potential loss of controlling the greenhouse effect because clean up monies would be spent in the near future.
>
> (Tietenberg 1996, 394)

There are two approaches to this problem and we may need to use both of them. One approach is to admit that we can never know enough to manage the entire ecosystem of the earth. The result of this admission would be to leave enough wild ecosystems alone so they can provide important natural services like oxygen production to keep the human race alive. The second approach would be to research how the ecosystems of the world work so that we can live in a non-destructive relationship with nature. Ecosystems are complex and self-affine across many scales. This diverse complexity creates stability. A failure of one or even many individual components doesn't cause collapse. Unfortunately our current economic system tends to find easy feeding in focused areas like the financial sector feeding on mortgage securities and their related derivatives. The result of this monoculture is boom and bust. The human economy needs to mimic the natural world and become more diverse, complex, and layered across size, from large to small.

8

NATURE'S GEOMETRY

Fractal geometry is the study of irregular shapes. Nature is full of these irregular shapes from trees and leaves, through mountains and rocks, to weather patterns and clouds. However these irregular shapes display a self-similarity across multiple scales that can be identified and used to inform our understanding. Nature's self-similarity has a randomness to it. As an example, oak trees branch like oak trees and maple trees branch like maple trees from first branches to twigs, but all the branchings are not identical. Mathematics calls this self-affinity. The study of nature's self-affinity was first presented by Benoit Mandelbrot in *The Fractal Geometry of Nature*. On the first page of the first chapter Mandelbrot asks the question,

> Why is geometry often described as cold and dry? One reason lies in its inability to describe the shape of a cloud, a mountain, a coastline, or a tree. Clouds are not spheres, mountains are not cones, and coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line.
>
> (Mandelbrot 1983, 1)

The fractal dimension is a measure of the irregularity of a shape. A prime mathematical example of an irregular self-similar entity is the Koch curve (Figure 8.1). The Koch curve is constructed through an iterative process. First a line segment is divided into thirds. Then the middle third of the curve is taken out and replaced with a triangular blip with sides equal in length to the thirds of the original line; thus the line is now four segments long. This procedure is then repeated on each of the now four line segments. The iterative process goes on to infinity in mathematical concept. In real world drawing of the Koch curve there is a limit to the iterations due to line width used to draw the curve. The fractal dimension as defined by Mandelbrot can be calculated as:

$$a = (1/s)^D$$

where a is the number of pieces and s is the reduction factor.

$$4 = (1/(1/3))^D$$

$$4 = 3^D$$

$$\log(4) = D \log(3)$$

$$D = \log(4)/\log(3)$$

$$D = 1.26$$

The dimension of the Koch curve tells us that it is more than a one-dimensional line and less than a two-dimensional plane. Other fractal curves have different fractal dimensions. The Cantor set, where a line is divided into thirds and then the middle third is taken out, has a fractal dimension of ($D = \log(2)/\log(3) = 0.63$). The Cantor set after many iterations reduces to a cluster of clusters of points. The Minkowski curve divides the original line into fourths and then constructs a line with eight segments. The fractal dimension of the Minkowski curve is ($D = \log(8)/\log(4) = 1.5$). The Peano curve divides the line into thirds and then creates a curve with nine segments creating a curve with the dimension

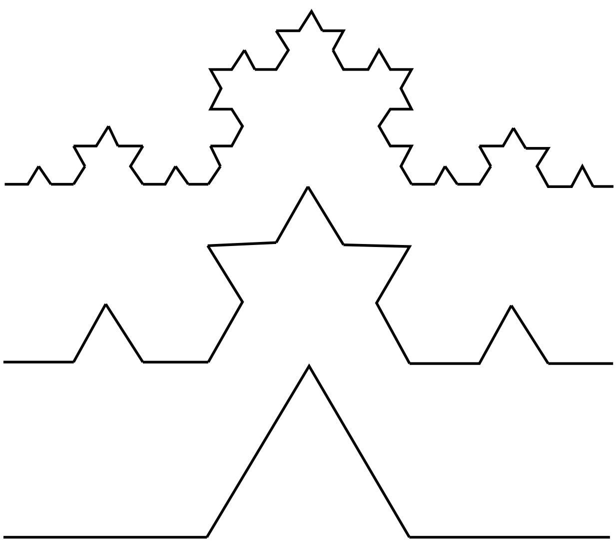


FIGURE 8.1 The Koch curve illustrates the construction of a fractal.

Source: Bovill 1996.

(D = log (9)/log (3) = 2.0); thus the Peano curve is a line that, when iterated to infinity, will fill the two dimensional plane. As a comparison, a straight line divided into three segments that maintains the three segments has a dimension of (D = log (3)/log (3) = 1) (Bovill 1996, 23–27).

Mandelbrot asks the question, "How long is the coast of Britain?" (Mandelbrot 1983, 25). He comes to the conclusion that the length is undefinable because, as one uses a smaller and smaller measuring unit, the length gets longer and longer as more inlets and points are included in the measurement (Figure 8.2). However, a fractal dimension can be calculated for the coastline by measuring its length with shorter and shorter measuring units. Graphing the Log(coastline length) versus the log(1/length of the measuring unit) produces a straight line. The slope of the line is the measured dimension (d = 0.26). The fractal dimension is (D = 1 + d). Thus the fractal dimension of the coast of Britain is (D = 1.26). This is the same

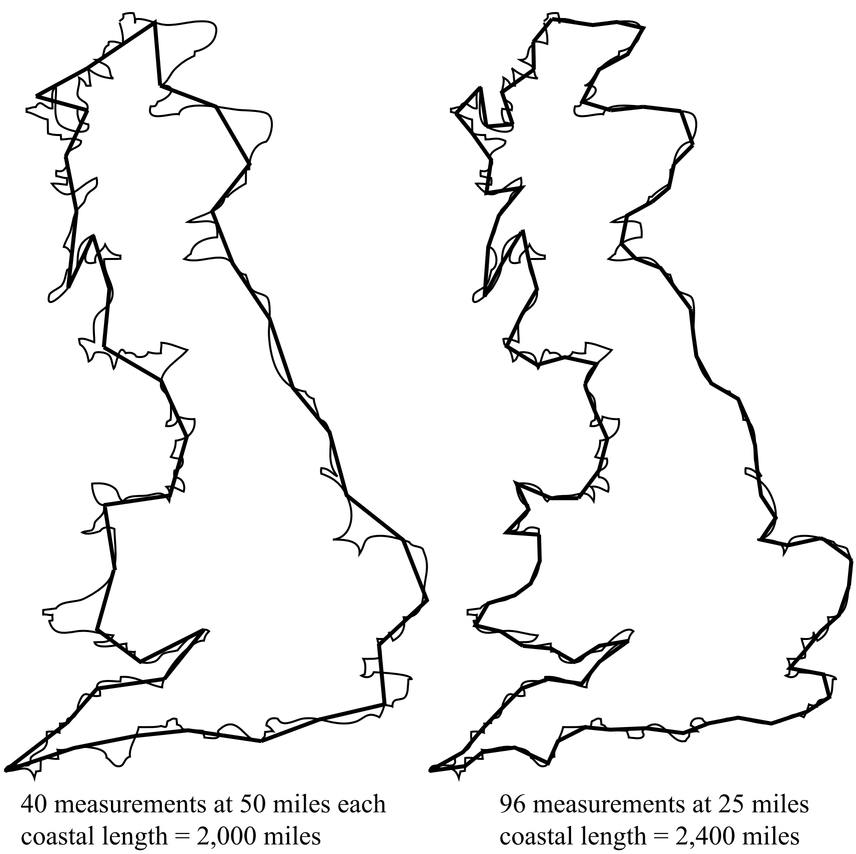


FIGURE 8.2 Measuring the length of the coast of England with smaller and smaller surveying distances produces longer and longer coastline lengths.

Source: Bovill 1996.

FIGURE 8.3 Measuring the fractal dimension of the coast line at Shell Beach, Sea Ranch, California with the box counting method.

Source: Bovill 1996.

dimension as the Koch curve. Mandelbrot thus shows that nature is fractal (Bovill 1996, 27–38).

Another slightly more flexible method of determining the fractal dimension of a shoreline is the box counting method. In this method a grid of boxes is drawn over the map of the coastline edge. Then a smaller grid of boxes is drawn over the same coastline. The number of boxes that the coastline runs through is counted in both cases. As an example, the fractal dimension of a short section of the coastline at the Sea Ranch in northern California can be determined by using a grid 400 feet square and a grid 200 feet square (Figure 8.3). At 400 feet there are 26 boxes with coastline in them. At 200 feet there are 65 boxes with coastline in them. The 400 foot box grid has 13 boxes across its long dimension. The 200 foot box grid has 26 boxes across its long dimension. The fractal dimension is determined by dividing the difference between the logs of the number of boxes across the long dimension of the box grids into the difference between the logs of the number of boxes with line in them. The fractal dimension of this coastline is equal to 1.32 (Bovill 1996, 41–42).

In constructing the Koch curve a line segment was divided into thirds, the middle third was erased, and a triangular blip was placed in the opening. Then this process was repeated for the four line segments to create blips on all four of them. This process is conceptually repeated to infinity. This is called iteration. A slightly different iterative process uses rectangular shapes that are reduced and mapped onto all of the original shapes. Four rectangles placed in the shape of a Koch curve, when iterated, creates the Koch curve. Michael Barnsley (1998) showed that the same four rectangles that could be used to produce a Koch curve, rearranged a different way, can create an iterated image of a life like fern with multiple self-similar leaves. The importance of Barnsley's fern is that a natural looking fern can be produced with the same iterative procedures that produced the Koch curve and other fractal constructions. It also showed that complex natural forms can be produced with minimal starting information through iteration (Peitgen et al. 1992, 255–260).

Another form of iteration involves the use of simple equations in the complex plane. Complex numbers have a real number part and an imaginary number part. Imaginary numbers come from the fact that there is no solution to the square root of −1. No number multiplied by itself can result in −1. Mathematics solves this problem by using i to represent the square root of −1. Then i is used to indicate the imaginary part of a complex number $z = x + yi$. The complex plane is two dimensional. The horizontal axis is the real number scale, and the vertical axis is the imaginary number scale. Julia sets, named after Gaston Julia, are derived by iterating a simple equation $z(n + 1) = z(n)^2 + c$, where c is a complex number. The iteration creates two sets. One set of results is unbounded so the numbers get very large. The other set is bounded. The Julia set is the boundary between these two sets of results. Julia sets are fractal in that structures repeat at different scales but not in an identical self-similar manner. They are self-affine; thus they are like natural fractals. Trees, coastlines, and mountain ridges display self-affine repetitions (Bovill 1996, 60–67).

Julia sets come in two varieties. Some Julia sets are all connected together, and some Julia sets are disconnected into a collection of separate components. Every Julia set has a complex number $(x + yi)$ as its seed. Benoit Mandelbrot plotted on the complex plane the locations of the Julia sets that are and are not connected.

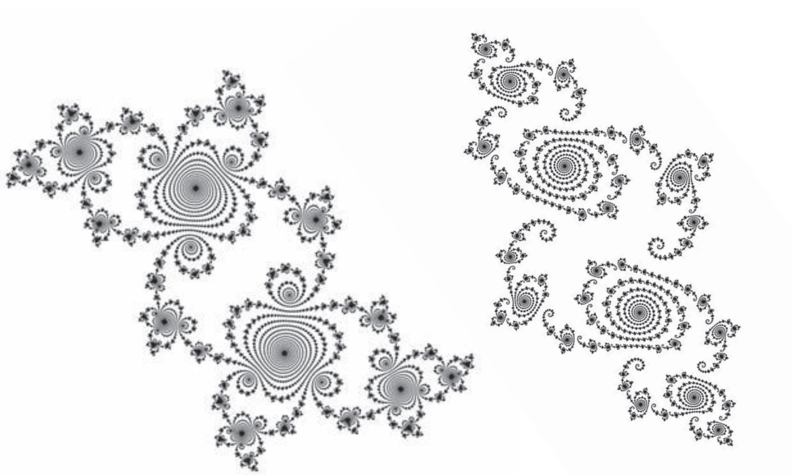


FIGURE 8.4 A connected Julia set and a disconnected Julia set.

Source: Wikimedia Commons, Attribution-Share Alike 3.0. Author Adam Majewski. Uploaded June 26, 2011. Wikipedia, Julia Set. http://en.wikipedia.org/wiki/Julia_Set.

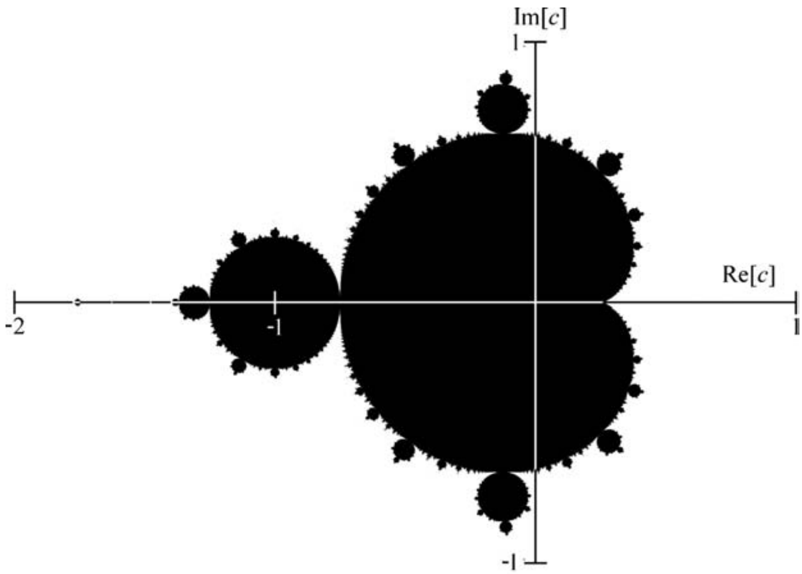


FIGURE 8.5 The Mandelbrot set is the intersection of the connected and disconnected Julia sets.

Source: Wikimedia Commons, Public Domain. Author Yourmomblah. Uploaded June 2, 2013. Wikipedia, Mandelbrot set. http://en.wikipedia.org/wiki/Mandelbrot_Set.

The result is the Mandelbrot set (Figure 8.5). The colored-in area represents the area of the complex plane that produces connected Julia sets. The area outside the colored-in area is the area of the complex plane that produces disconnected Julia sets. The edge between these two areas is infinitely complex. Using a computer to zoom in on the edge of the Mandelbrot set at any point produces a never ending display of Julia set like forms, including small replicas of the Mandelbrot set (Bovill 1996, 68–70). YouTube has many videos zooming into the complex edges of the Mandelbrot Set. Search for "Mandelbrot set" or "Mandelbrot set zoom". The infinitely complex boundary of the Mandelbrot set provides a good analogy for nature. Nature is infinitely complex, which gives it stability. Take a close look at the structure of trees (Figure 8.6). The upper branches are self-affine replicas of the whole tree. This cascade continues through about five levels of branching.

Edward Lorenz, experimenting with a set of three equations that represented a simplified model of the thermal functions that drive weather patterns in the atmosphere, inputted some rounded off numbers to start a computer run and discovered that the results were completely different from the original simulation. This is the chaos problem of sensitivity to initial conditions. Iterating the equations produces a strange attractor named the Lorenz attractor (Figure 8.7). The tiniest modification of the initial conditions produces wildly different solutions after a few iterations. The solutions loop around the attractor in very different ways after a

FIGURE 8.6 Zooming in on a stand of trees produces self-affine images.

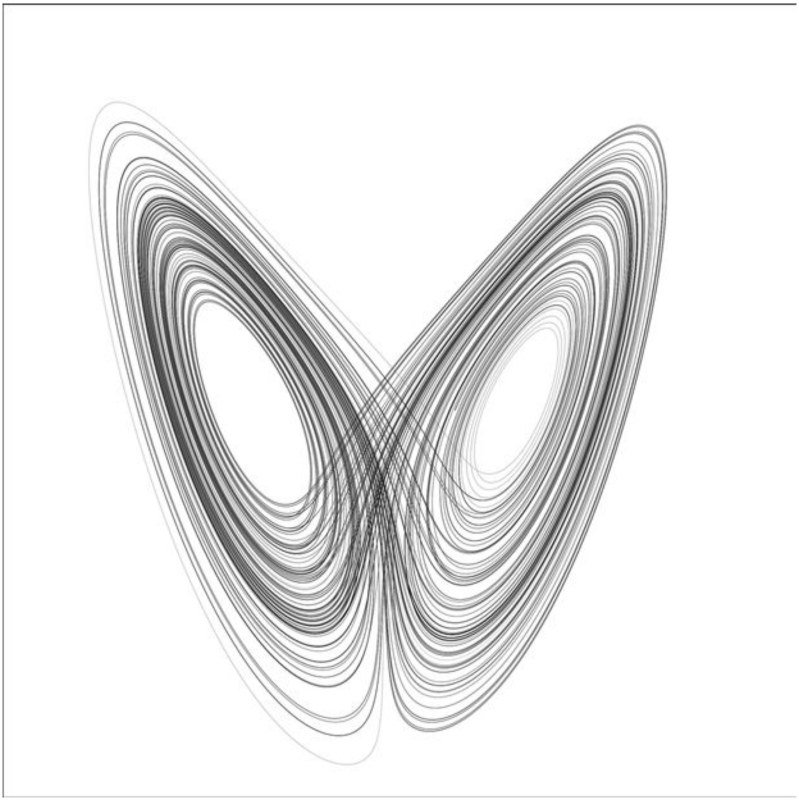


FIGURE 8.7 The Lorenz attractor.

Source: Wikimedia Commons, Attribution-Share Alike 3.0. Author Wikimol and Dshwin. Uploaded on January 4, 2006. Wikipedia, Chaos Theory. http://en.wikipedia.org/wiki/chaos_theory.

few initial loops, even though the initial conditions were almost identical. This has a real world implication. Weather forecasting has limits. Even with improved data collection and improved computer simulations it is not possible to forecast the weather accurately beyond 5 to 10 days into the future. The atmosphere is a chaotic system (Peitgen et al. 1992, 697–708). If we cannot predict the weather even with a large number of accurate data points, how can we expect to manage the ecosystems of the earth?

Another look into chaos can be seen by iterating the simple equation: ($x_{n+1} = rx_n(1 - x_n)$). When this equation is iterated, with the parameter r set between 1 and 4, the results display the doubling route from stability to chaos. The Feigenbaum diagram, named after Michael Feigenbaum, shows how the solution to the equation bifurcates into two solutions, then four solutions, then eight solutions, and finally into a chaotic region where there are large numbers of solutions (Figure 8.8). But surprisingly there are windows of order in the chaotic region. Feigenbaum discovered that the ratio of the distances along the horizontal axis from one doubling point to the next doubling point is a constant across the whole diagram and is equal to 4.6692 . . ., referred to as the Feigenbaum constant. Years after the mathematical discovery of period doubling leading to chaos, experiments in fluid flows arrived at the same constant (Peitgen et al. 1992, 585–591).

Chaos theory demonstrates that there are limits to what is knowable. Natural systems are complex, and indeterminate. Human culture needs to accept this and tread lightly on nature. The bright side of chaos and its sensitive dependence on

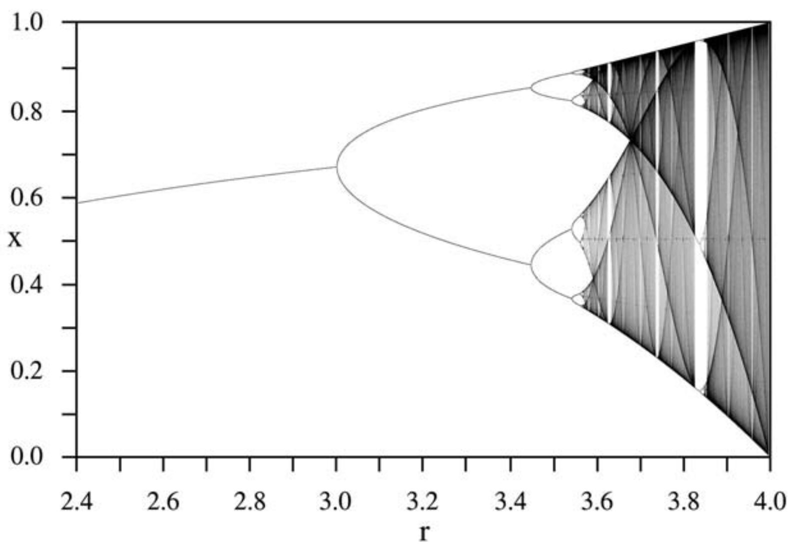


FIGURE 8.8 The Feigenbaum diagram shows the doubling cascade into chaos and the windows of order that can form in the chaotic region.

Source: Wikimedia Commons, Public Domain. Author PAR. Uploaded September 14, 2005. Wikipedia, Bifurcation Diagram. http://en.wikipedia.gov/wiki/Bifurcation_diagram.

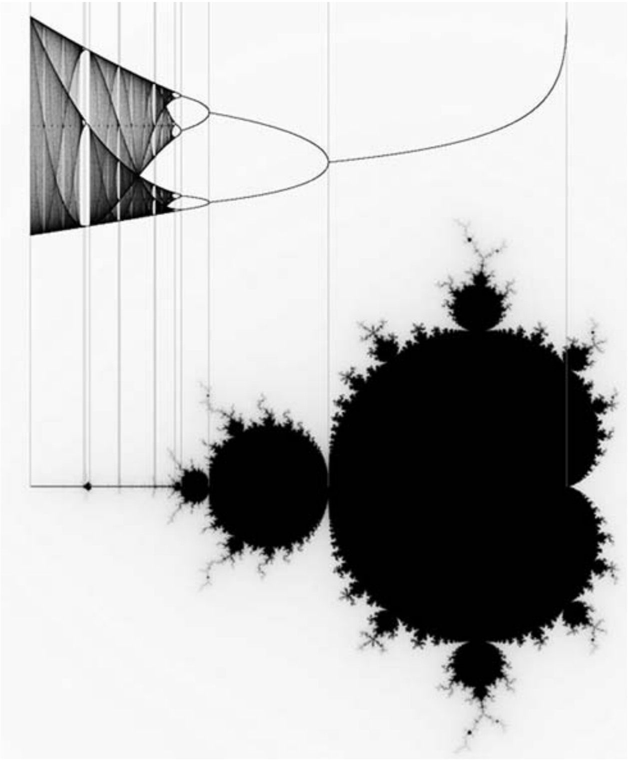


FIGURE 8.9 The relationship between the Feigenbaum diagram and the Mandelbrot set.

Source: Wikimedia, Public Domain, Author Georg-Johann Lay. Uploaded April 7, 2008. Wikipedia, Mandelbrot Set. http://en.wikipedia.org/wiki/Mandelbrot_Set.

initial conditions is that small changes applied at the right time can create large modifications in future outcomes. This is sometimes called the butterfly effect (Gordon et al. 2006, 63).

In conclusion, a basic understanding of fractals and chaos can open up a new way of seeing the world (see Figure 8.10). Michael Barnsley, in the first chapter of his book *Fractals Everywhere* (1988), gives the following warning,

> Fractal geometry will make you see everything differently. There is danger in reading further. You risk the loss of your childhood visions of clouds, forests, galaxies, leaves, flowers, rocks, mountains, torrents of water, carpets, bricks, and much else besides. Never again will your interpretation of these things be quite the same.
>
> (Barnsley 1988, 1)

This statement applies equally to individuals and to human society as a whole.

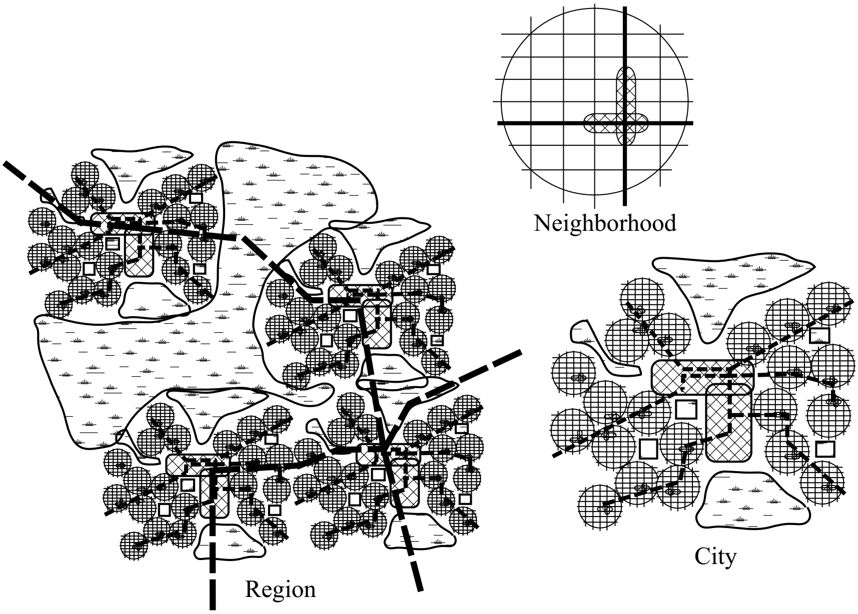


FIGURE 8.10 Urban environments show fractal characteristics. Walkable neighborhoods are connected into cities with local transportation systems, and the cities are connected into urban regions with regional transportation systems.

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PART III

The Residential Scale

The energy use of residential scale buildings is driven by their interaction with the outside climate. The United States Green Building Council's Leadership in Energy and Environmental Design (LEED) rating system for residential buildings provides a good overview of the important features to consider in a residential design. Bioclimatic design offers a design procedure that starts with raw climate data, organizes it on the bioclimatic chart to suggest design responses, and finally provides a logical approach to optimum building orientation. Passive solar heating and cooling depend on controlling when to let the Sun in and when to block the Sun. Sun charts define where the Sun is in the sky by month and time of day, which provides a manifold to test the shading benefits of overhangs and fins. Passive solar heating and cooling require a delicate balance between window area, thermal mass, and insulation levels. In winter, it is about letting the Sun in and keeping the wind out. In summer, it is about keeping the Sun out and letting the wind in. Thermal mass and insulation have embodied energy, which can be compared to the heating energy their deployment saves to determine optimum amounts of each. Overlaid on energy efficiency decisions is the choice of all the materials the house will be built, finished, and furnished with. Where do the materials come from, do they outgas volatile organic compounds, and where do they go when their use is no longer needed? The WaterShed House is a good example of energy efficient green design at the residential scale. The WaterShed House was awarded first place in the 2011 Department of Energy Solar Decathlon competition.

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9

BUILDING EXAMPLE

WaterShed House

The WaterShed design project was a collaboration of 200 students and their faculty mentors at the University of Maryland to design, build, and operate a demonstration house for the 2011 U. S. Department of Energy Solar Decathlon. WaterShed won first prize in the competition.

The house uses both passive and active heating and cooling techniques. South glass collects solar heat to warm the interior. Cross ventilation provides cooling when the weather conditions are appropriate. An array of evacuated tube solar collectors actively collects solar heat. The heat is used for domestic solar hot water, as a boost to solar heating, and as a heat source to regenerate a liquid desiccant used to dehumidify the interior. The active part of the space heating and cooling is provided with mini split heating and cooling units. Electrical power for the house is provided by 42 solar panels mounted on one of the shed roofs.

WaterShed is a configuration of two shed roofed modules connected by a small flat roofed section. The bathroom spans over a constructed wetland to make gray water collection easier. The front shed contains the public living spaces. The rear shed contains the bedroom and office area. All the living spaces have ample operable windows for light, ventilation, and solar heat. The sheds slope to the center to facilitate rainwater collection. Outdoor areas are provided off both sheds and are surrounded by plantings providing shading, privacy, and food. The design team also created adaptable furniture for more flexible use of space (WaterShed 2012, 52).

The energy use of the house was greatly reduced by the highly insulated envelope. The walls are wood frame construction where triple studs were spaced 4 feet on center and then sheathed with tongue and groove engineered wood decking. A liquid applied self-sealing water and air barrier was applied to the outside of the sheathing. The wall cavity was filled with five and a half inches of open cell spray foam insulation. This, combined with 2 inches of rigid insulation on the

FIGURE 9.1 WaterShed House.

Source: United States Department of Energy Solar Decathlon 2011. Photo by Stefano Palterra.

FIGURE 9.2 WaterShed House living room.

Source: United States Department of Energy Solar Decathlon 2011. Photo by Tim Tetro.

FIGURE 9.3 WaterShed House kitchen.

Source: United States Department of Energy Solar Decathlon 2011. Photo by Tim Tetro.

FIGURE 9.4 WaterShed House bathroom.

Source: United States Department of Energy Solar Decathlon 2011. Photo by Tim Tetro.

exterior, adds up to an R-45 wall. A typical residential 2 × 4 wall has an R-value of 12 to 15. The floors and ceiling received similar superinsulation treatment. This highly insulated envelope reduces the size of the necessary heating and cooling equipment (WaterShed 2012, 26).

The house has a liquid desiccant waterfall that absorbs water vapor out of the interior air. The reduction in relative humidity reduces demand on the air conditioning system. The clear liquid desiccant becomes saturated with water from the house. It is pumped to a regeneration unit where solar heated glycol from the evacuated tube solar collectors heats the desiccant. The heated desiccant is then sprayed from the top of air chimneys where the water is drawn out of the desiccant (WaterShed 2012, 22). Dryer air is more comfortable than more humid air because it is easier for us to evaporate sweat off our skin if the air is dryer. When sweat is evaporated off a person's skin the process takes energy out of the skin causing a cooling sensation. In summer this is pleasant. In winter it is wind chill.

Water flows are an important feature in the design of the WaterShed House. Rainwater is collected from the inward sloping roofs for irrigation uses. The green roof on one of the sloping roofs slows down runoff, and provides for a cooler roof in summer. The bathroom is located between the two sloping roofs, which makes collection of gray water from sinks and showers easier. The gray water flows into a constructed wetland that filters the water for irrigation and thus release to the environment (WaterShed 2012, 30). The constructed wetlands bring together plants and microorganisms. This combination cleans the gray water and rainwater of pollutants and nutrients. Using this combination of gray water and rainwater collection for irrigation can reduce potable water use by up to 50 percent (WaterShed 2012, 33).

The house has 87 square feet of garden beds as well as a vertical garden wall generating 15 varieties of produce. After being consumed, the leftovers are combined with garden waste in a compost bin. Time and heat produce rich garden soil, which fertilizes the produce being produced (WaterShed 2012, 46).

Maryland Governor Martin O'Malley observed,

> The WaterShed team's entry serves as a model for future development. By analyzing the challenge and harnessing each member's creativity and knowledge toward a shared vision, the team created a home that manages storm water, minimizes water use, and harnesses green energy to reduce the need for fossil fuels.
>
> (WaterShed 2012, 3)

10

LEED FOR RESIDENTIAL BUILDINGS

LEED is a rating system developed by the United States Green Building Council. The rating system outlines important sustainable design features that residential buildings should incorporate, and provides a scoring system to rank success. The rating system is available on the USGBC website, (www.usgbc.org/leed/rating-systems). The LEED rating system for residential buildings provides a guideline process for architects and builders to produce a more sustainable product.

The LEED for homes checklist is extensive. It starts with innovation in the design process, and then proceeds through site issues, water issues, energy and atmosphere issues, material issues, indoor environment issues, and finally awareness for the owner and the public. A detailed checklist is available on the USGBC website at new.usgbc.org/leed/rating-systems. The following is a summary of the main sections of this rating system.

The innovation and design process section has a total of 11 points and includes integrated project planning, durability management, and innovative or regional design opportunities. This section reinforces the importance of including all the design professionals early in the design process so innovation can happen.

The location and linkages section has a total of 12 points and includes site selection, preferred locations, infrastructure, community resources, and access to open spaces. These criteria are echoes of New Urbanism concepts of walkable communities linked by mass transit.

The sustainable sites section has a total of 22 points and includes site stewardship, landscaping, local heat island effects, surface water, nontoxic pest control, and compact development. This section is focused on responsible landscaping with plants that can survive in the location without extensive watering and also awards points to dense development that uses up less land per house.

The water efficiency section has a total of 15 points and includes water reuse, irrigation systems, and indoor water use. Here the focus is minimizing water use through efficient fixtures, efficient irrigation, and possible gray water reuse.

The energy and atmosphere section has a total of 38 points and includes sections on insulation, air infiltration, windows, the heating and cooling equipment and distribution, the water heater, lighting, appliances, renewable energy, and refrigerant management. This section has the highest point total because reducing energy use is very important. A review of the list above indicates that reducing energy use requires extensive attention to detail across many areas of the home design.

The material and resources section has a total of 16 points and includes material efficient framing, environmentally preferable products, and waste management. This section addresses the material choices to be incorporated in the home and the environmental efficiency of the construction process.

The indoor environmental quality section has a total of 21 points and includes combustion venting, moisture control, outdoor air ventilation, local exhaust, distribution of heating and cooling, air filtration, contaminant control, radon protection, and garage pollutant protection. Indoor environmental quality is an increasingly important issue as homes are designed to be more air tight to reduce energy use. This section addresses this problem with an extensive list of requirements and a significant number of points to be gained.

The final section is awareness and education, which has a total of 3 points and includes education of the home owner and or tenant, and education of the building manager. The final section only has 3 points but it is very important that the users of a high performance home or multifamily building understand what they have and how to appropriately use the features provided.

This list is extensive and all of it is good practice. Even if it is only used as a guideline to good practice with no intention of applying for the formal rating from the USGBC, the architect, builder and eventual homeowner, tenant, building manager, and or building owner will be well served.

11

THE ENERGY DESIGN PROCESS

There are three ways to use computer energy simulation software. The simplest is scorekeeping, which involves a single energy simulation run yielding the energy use for the current building design. The next level of analysis is problem solving. Problem solving points designers toward a proper course of action. This requires multiple energy simulation runs to determine optimum design features. At the highest level is attention directing. Attention directing is about guidance in knowing what questions to ask or what problems should be solved and in what order (Mason and Swanson 1981, 14).

If a search space is envisioned as a mountain range with peaks and valleys with the valleys representing low energy designs, the object of design is to find the lowest valley (Figure 11.1). Scorekeeping, a single run of an energy analysis computer program provides almost no usable design information. The single run's main usefulness is after the design is finished to show compliance with energy codes and to claim LEED energy and atmosphere points. Problem solving can find a local optimum point but it is not capable of jumping out of the valley it is located in to search for better lower valleys. Attention directing is designed to look at a wider range to find lower valleys and better overall solutions.

Multiple runs of a computer program each looking at an individual energy design option provide an overview of what features save the most energy (Figure 11.2). This information can then be combined with cost estimate information to point the designer at the most cost effective energy design features (Figure 11.3). Attention is directed to the most effective way to lower energy use.

A classic example of problem solving is determining what area of south glass a passive solar design should employ. The rules of thumb suggest a south glass area of about 20 percent of the floor area, and thermal mass of 4 to 5 times the window area 4 inches thick. Multiple computer runs slowly increasing the glass area can find an optimum glass area (Figure 11.4). For a house in Sterling, Virginia, in a

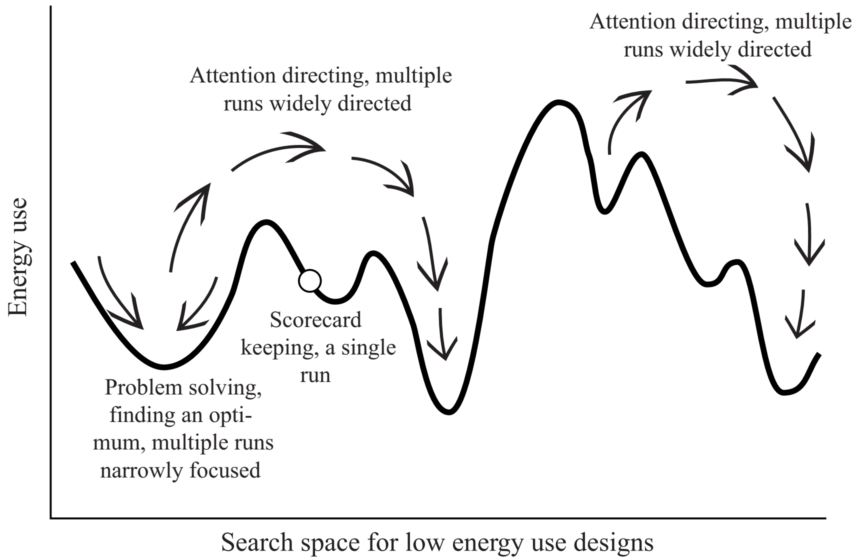

FIGURE 11.1 Attention directing needs to take a broad view of the energy design process to discover the best strategic approach.

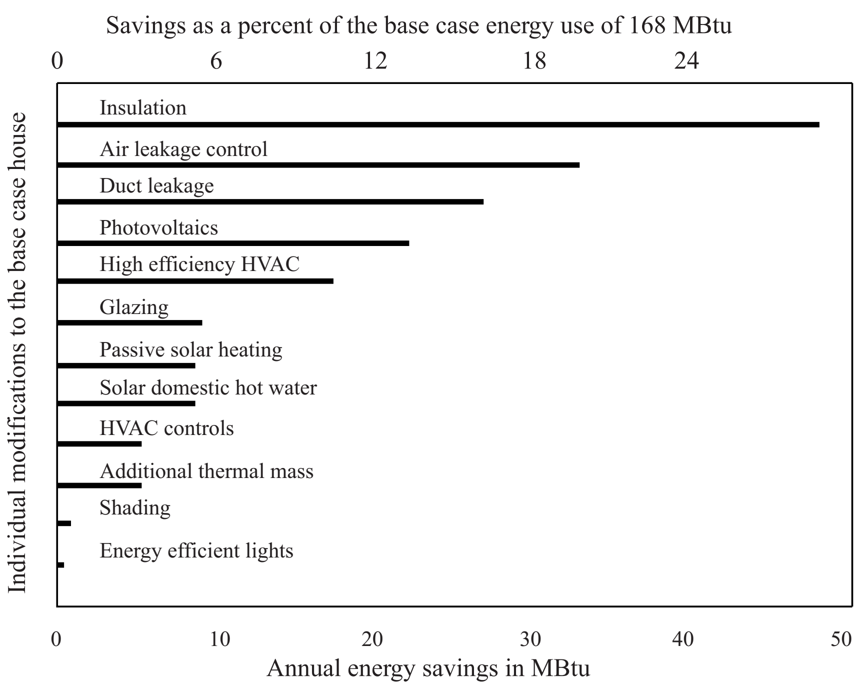

FIGURE 11.2 Annual energy savings for each individually applied energy design feature of a residential design.

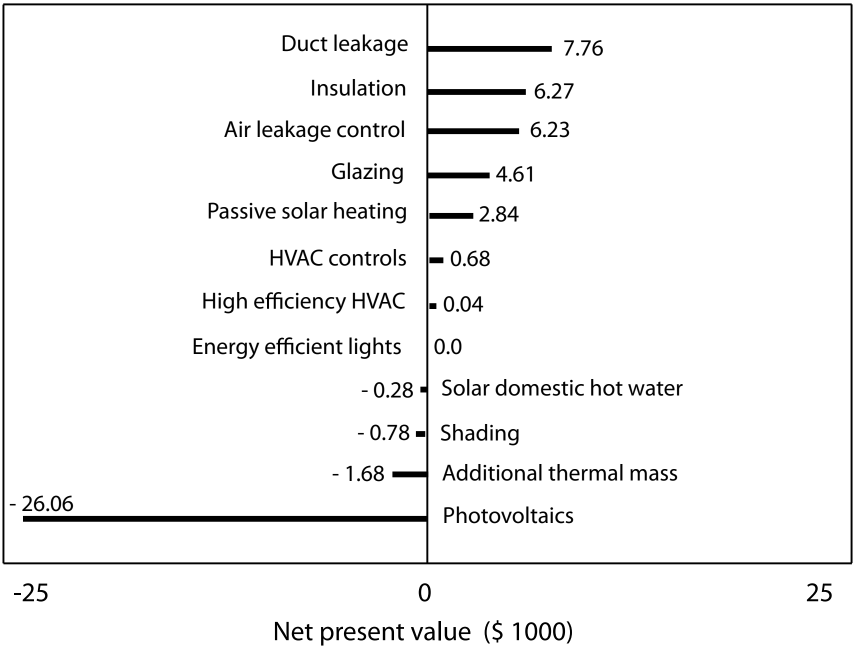

FIGURE 11.3 The net present value combines the cost of the energy design feature with the savings per year from the energy design feature over 20 years.

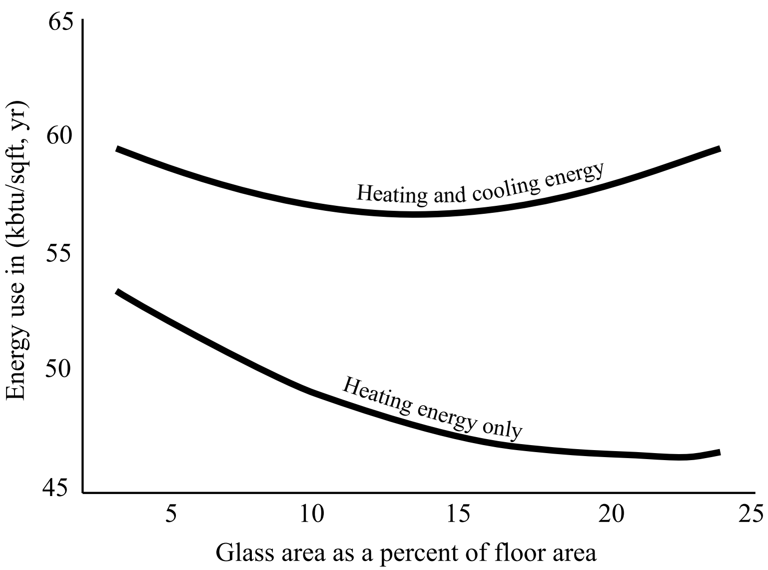

FIGURE 11.4 Multiple computer program runs slowly increasing the south window area can determine the optimum south glass area.

heating only situation, the optimum south glass area is 21 percent of floor area. Note however that the bottom of the optimum curve is very flat so there is a range of glass areas from 19 to 24 percent of floor area that will result in almost identical heating energy use. In a heating and cooling situation the optimum south glass area is 12 percent of floor area with a flat bottom range of 9 to 14 percent of floor area.

It should be clear from the examples above that deriving useful energy design information requires multiple computer runs, and there is a difference between attention directing which is a strategic overview to determine what design questions deserve attention, and problem solving which is a tactical exploration of local optimal solutions. A single run of an energy analysis computer program is only useful as the final documentation of the design for LEED or energy code reasons.

12

BIOCLIMATIC DESIGN

Victor Olgyay, in his book *Design With Climate* (1963), lays out a clear analytic procedure to guide the decisions necessary to create comfortable and energy efficient houses. The procedure begins with information about the range of temperature that humans consider comfortable.

This is followed by a discussion of heat gains and losses. People gain heat from metabolism, through conduction and convection, through their skin from the air temperature, and from everything around them that is warmer than their skin radiating energy toward them. People lose heat by conduction and convection through their skin to the air temperature, to all the materials that surround them that are cooler than their skin radiating energy away from them, and by evaporation of moisture off of their skin. Comfort ranges for various groups of people versus effective temperature can be experimentally determined (Figure 12.1). The effective temperature is calculated using a complicated equation that includes air temperature, humidity, mean radiant temperature, and air motion (Olgyay 1963, 14–18).

Victor Olgyay combined the information contained in the effective temperature into a chart of temperature versus humidity with overlays for mean radiant temperature, air speed, and added moisture in the air. He called the chart the bioclimatic chart (Figure 12.2). The bioclimatic chart transforms a complex equation for the effective temperature into an easy to read chart (Olgyay 1963, 19–22).

The cigar shaped area in the center of the bioclimatic chart represents the comfort range where most people would be thermally comfortable in the shade with light clothes on. This comfort range is roughly between 70 and 80 degrees Fahrenheit, and from about 20 to 75 percent relative humidity. If the air temperature is below this range an increase in the mean radiant temperature will provide the sensation of thermal comfort. If the air temperature is above the comfort range an addition of air motion can cause a cooling sensation by evaporating moisture off a person's

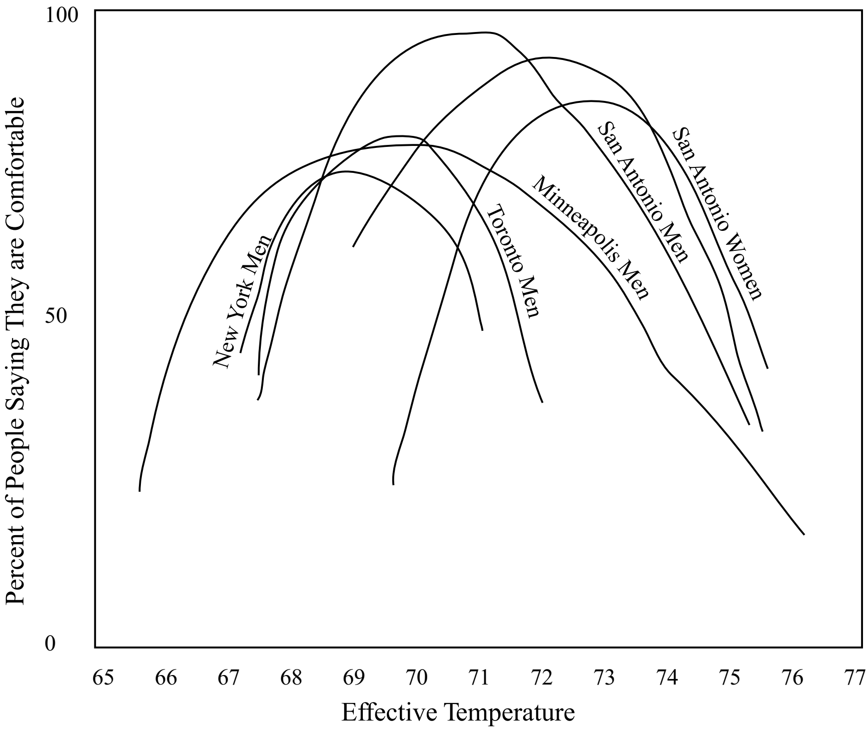

FIGURE 12.1 Effective temperature comfort ranges for men and women in different cities demonstrates that there is a range of comfortable temperatures.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

skin. If the air temperature is above the comfort range and the humidity is very low, the addition of moisture into the air can actually lower the air temperature at the expense of raising the relative humidity. Note that the comfortable temperature range gets narrower as the humidity level rises from 50 to 80 percent. This happens because, as humidity increases, it is more difficult for people to cool their skin via the evaporation of sweat.

Brown and DeKay in their book *Sun, Wind, and Light* (2001) provide a version of the bioclimatic chart that relates areas of the bioclimatic chart to passive solar strategies for heating and cooling a building. This form of the bioclimatic chart is easier to use in a design environment (Brown and Dekay 2001, 54–55).

The National Oceanic and Atmospheric Administration (NOAA) measures and publishes weather data for numerous locations around the United States. Using the monthly maximum and minimum temperature and the maximum and minimum relative humidity, the local weather conditions can be plotted on the bioclimatic chart. To do this it is necessary to understand the relationship between temperature and humidity on a typical day.

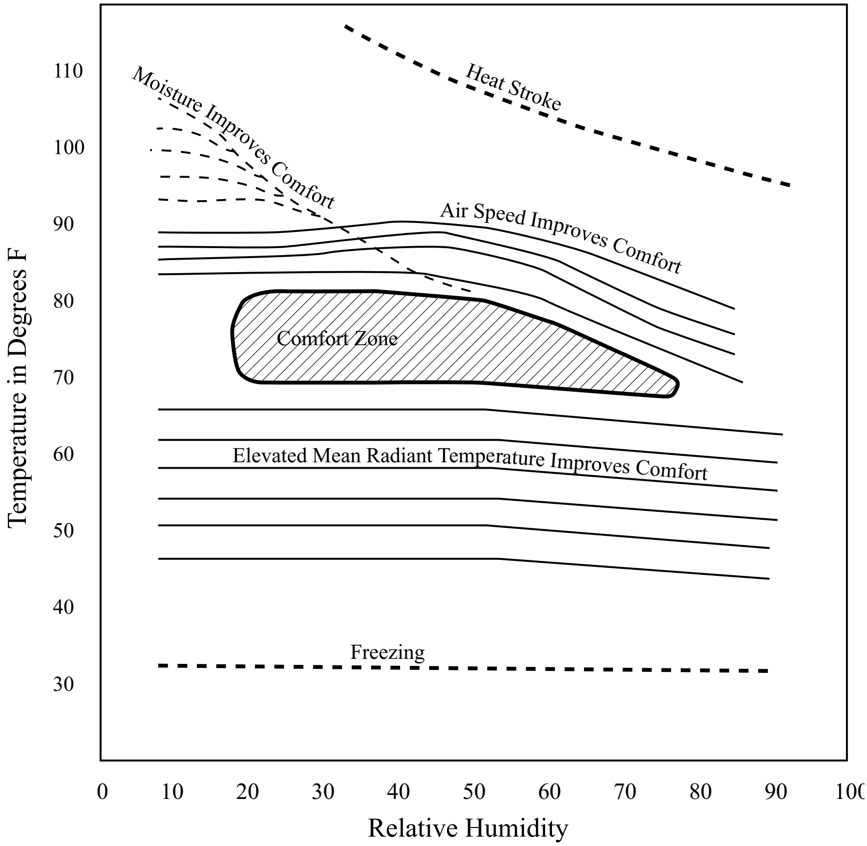

FIGURE 12.2 The bioclimatic chart maps human comfort in relation to temperature, humidity, mean radiant temperature, and wind speed.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

On a typical day the amount of moisture in the air doesn't change very much. As air gets warmer, it can hold more water in the form of vapor than it can when air is colder. The relative humidity is a measure of the amount of water in the air in vapor form compared to the maximum amount of water that can be in the air at that temperature. The result of this physical relationship is that the relative humidity decreases during the day reaching its lowest level when the air temperature is highest in early afternoon. The relative humidity increases during the night reaching its highest value when the air temperature is lowest during the night. Using this information one can take the monthly maximum and minimum temperature and humidity data and plot the local climate on the bioclimatic chart.

The average high temperature for a month is plotted with the average low relative humidity. The average low temperature for the month is plotted with the average high relative humidity. A line drawn between these two points is a good

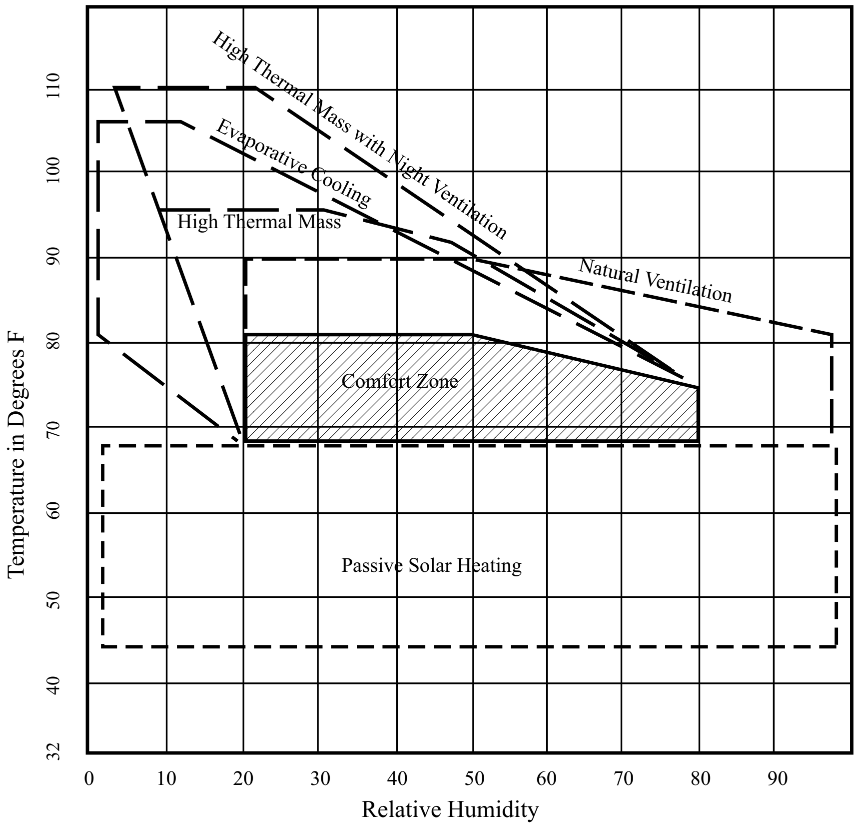

FIGURE 12.3 The bioclimatic chart from *Sun, Wind, and Light* (2001) maps the comfort range in relationship to architectural approaches to comfort design.

Source: Brown and DeKay 2001.

representation of how the temperature and humidity fluctuate through an average day for that month. Where the lines sit on the bioclimatic chart then provide design guidance. Thus, the bioclimatic chart provides useful design information from otherwise abstract weather data numbers.

Plotting Baltimore's weather on the bioclimatic plot indicates a climate that is warm and humid in the summer, comfortable in the spring and fall, and cold but not overly so in the winter (Table 12.1 and Figure 12.4). Comfort conditions can be extended in the summer through ventilation cooling, and can be extended in the winter with passive solar heating.

The plot for Tucson, Arizona, (Figure 12.5) shows a mild winter with low temperatures in the 40s and high temperatures in the 60s. The winter months all plot in the area of the chart that indicates the relatively easy use of passive solar heating. The summer months indicate hot dry conditions where a combination of evaporative cooling and night ventilation cooling will be necessary. In contrast,

TABLE 12.1 Baltimore, Maryland, temperature (°F) and relative humidity

	T (max)	*T (min)*	*RH (max)*	*RH (min)*
Jan	41	24	71	57
Mar	53	33	71	50
May	74	52	77	52
Jul	87	66	80	53
Aug	85	65	84	55
Sep	79	59	85	55
Nov	56	37	78	55

Source: National Oceanic and Atmospheric Administration, National Climate Data Center. www.ncdc.noaa.gov.

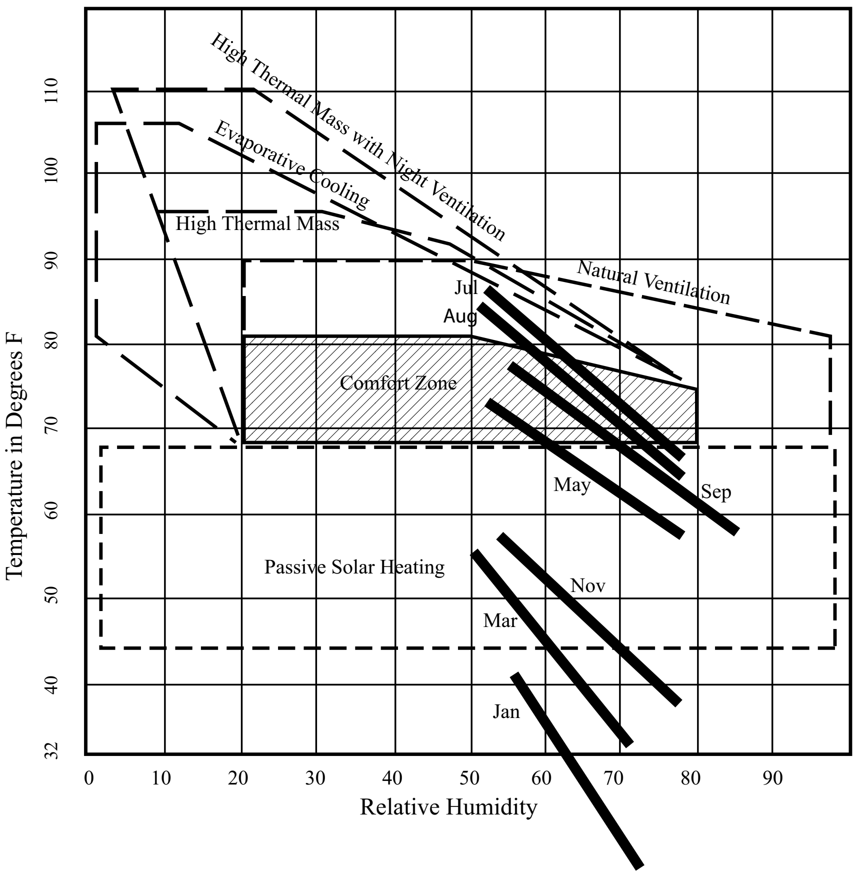

FIGURE 12.4 Baltimore, Maryland, weather data plotted on the bioclimatic chart.

Source: Bioclimatic chart, Brown and DeKay 2001. Climate plot, Carl Bovill.

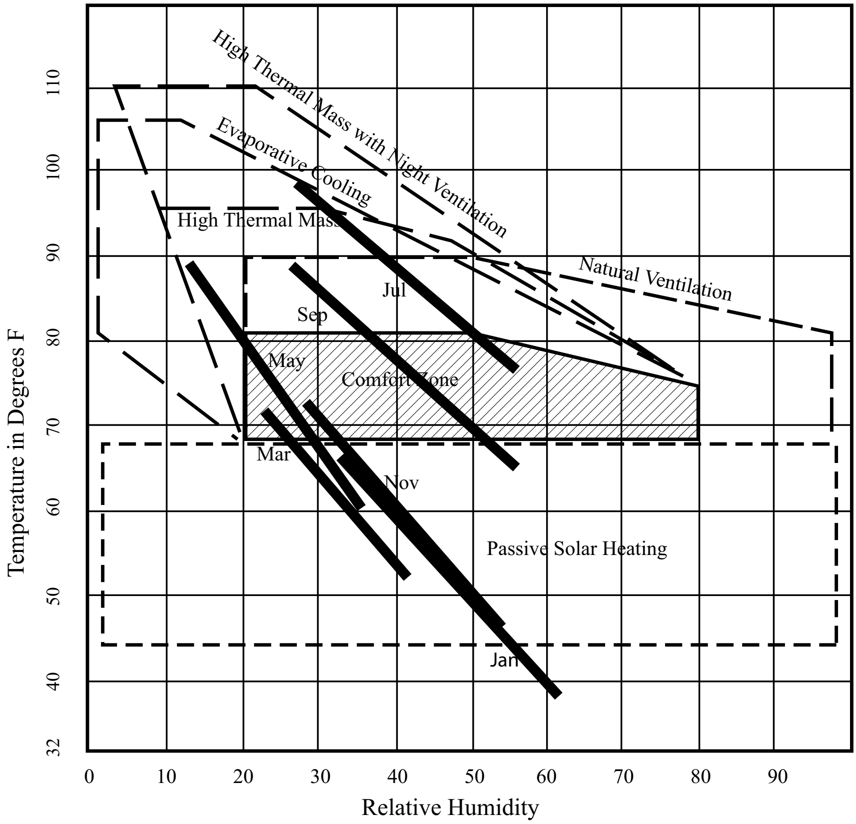

FIGURE 12.5 Tucson, Arizona, weather data plotted on the bioclimatic chart.

Source: Bioclimatic chart, Brown and DeKay 2001. Climate plot, Carl Bovill.

Burlington, Vermont, is dominated by its cold winter with a summer primarily in the comfort zone (Figure 12.6).

Honolulu provides an example of a cooling only problem. Plotting the monthly temperature and humidity conditions on the bioclimatic chart (Figure 12.7) shows all the months clustered at the humid end of the comfort zone with the daytime peak temperatures in the warmer months ascending into the cross ventilation area and the nighttime minimum temperatures descending into the mean radiant temperature zone. Comfort design in Honolulu calls for shelter from the sun and openness to the trade winds for comfort most of the year. In the colder months closing the windows and using a light blanket on the bed holds in enough body heat to provide thermal comfort.

Victor Olgyay (1963) also studied the heat loss and gain of houses in various climates. Then he correlated when, and from what direction solar gain arrives, with the cold and warm periods of the year. He used this information to provide

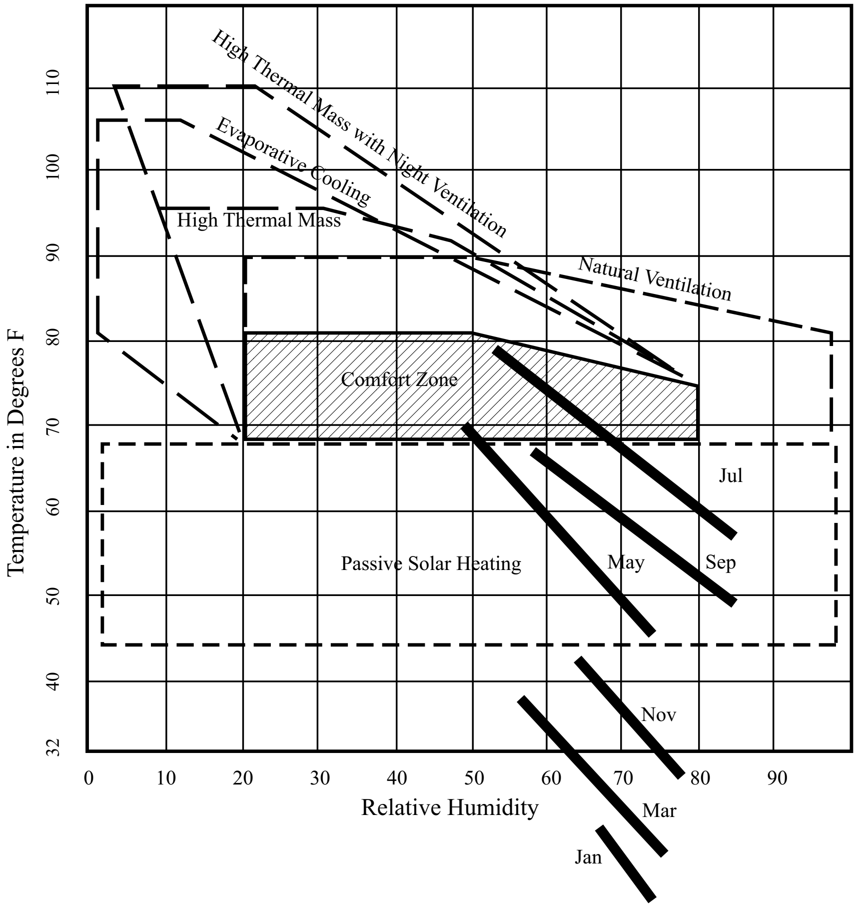

FIGURE 12.6 Burlington, Vermont, weather data plotted on the bioclimatic chart.
Source: Bioclimatic chart, Brown and DeKay 2001. Climate plot, Carl Bovill.

guidance on the orientation of a house to maximize heat gain in winter and minimize heat gain in summer.

In the northeast, with New York as the example of a temperate climate (Figure 12.8), the center of where the sun comes from during the cold times of the year is 17 degrees east of south. The center of where the sun comes from in the warm times of the year is perpendicular, at 17 degrees south of west. Given this information a designer should aim the major side and windows of a house 17 degrees east of south into the solar gain coming during the under heated part of the year. One should also minimize the exposure of the house to solar gain coming during the overheated part of the year. The result is a rectangular shaped house oriented slightly east of south with the primary window area on this elevation and minimum window areas on the east, west, and north elevations. In cold regions, Minneapolis

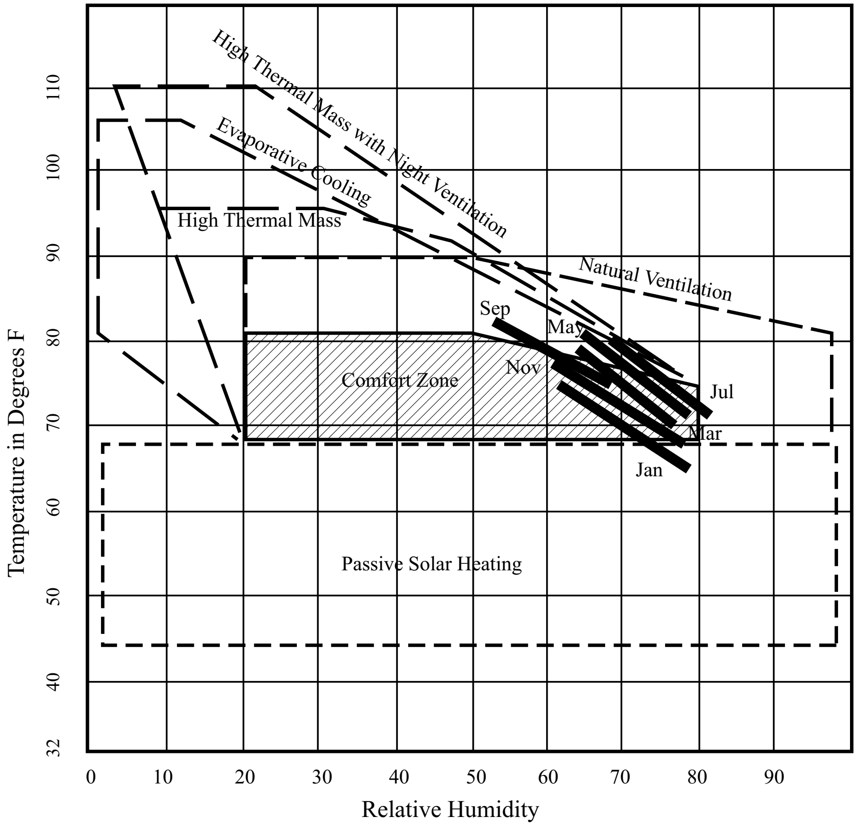

FIGURE 12.7 Honolulu, Hawaii, weather data plotted on the bioclimatic chart.

Source: Bioclimatic chart, Brown and DeKay 2001. Climate plot, Carl Bovill.

being the example, the recommendation is 12 degrees east of south. In hot dry regions, such as Phoenix, the recommendation is 25 degrees east of south. And in warm humid regions, such as Miami, the recommendation is 5 degrees east of south (Olgyay 1963, 58–62).

Olgyay also studied heat loss and gain in relation to shape. The balance is between a square shape having minimum exterior surface area, and thus minimum heat loss or gain, with the ability of a rectangular shape to provide more window area on the slightly east of south side with lesser windows on the east, west, and north sides. He proposed optimum shapes for cool, temperate, hot arid, and hot humid climates. They are all rectangular shapes, 1 to 1.11–1.3 for cold climates, 1 to 1.6–2.4 for temperate climates, 1 to 1.3–1.6 for hot arid climates, and 1 to 1.7–3.0 for hot humid climates (Olgyay 1963, 88–90).

I have included the numbers that Olgyay calculated for orientation and rectangular shapes to be complete and to provide context. The actual orientation angle and the shape of the rectangle is dependent on the choice of how much

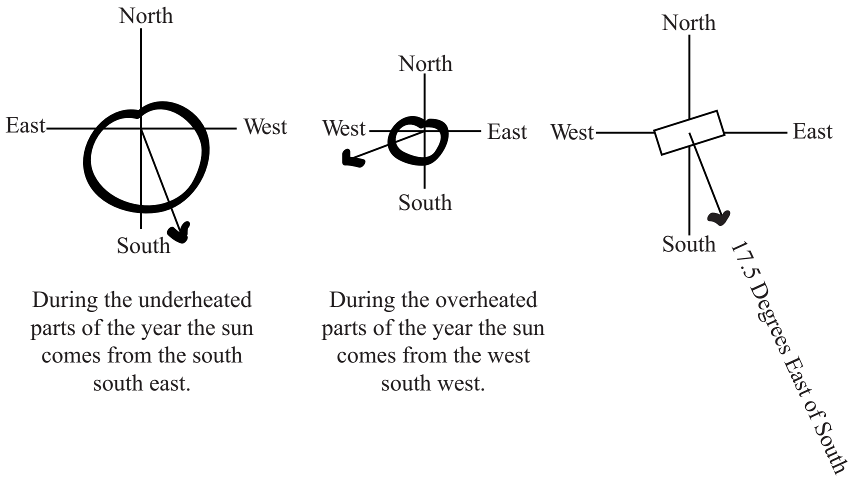

FIGURE 12.8 Deriving the optimum orientation for a house in a temperate climate as represented by New York.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

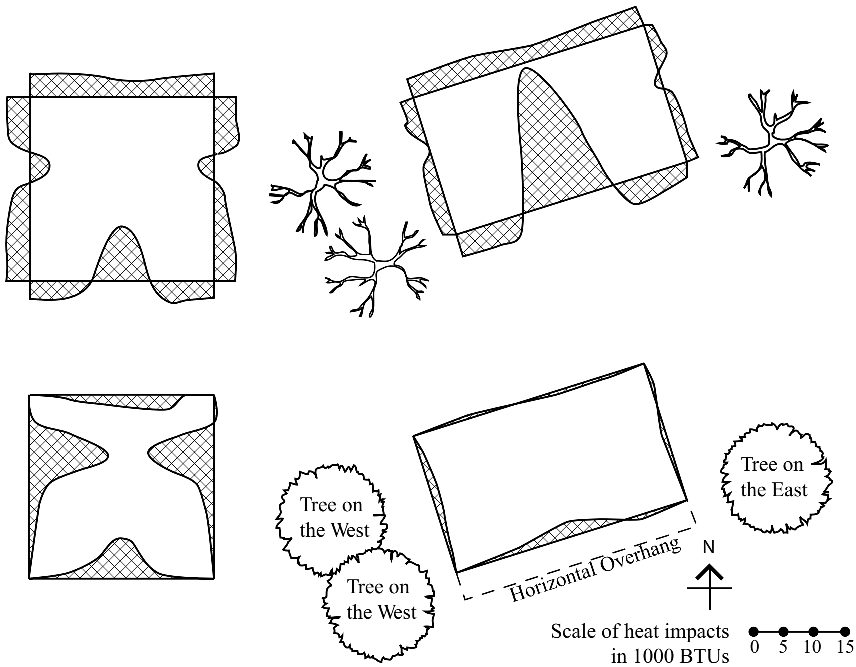

FIGURE 12.9 Comparing the thermal advantage of a bioclimatic designed house with a traditionally designed house in winter and summer.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

window area is on the dominant side and how much window area is distributed on the other orientations. The important point to remember is to orient a rectangular shaped house slightly east of south (17 to 22 degrees east of south) with the primary window area on the slightly east of south elevation.

To demonstrate the benefit of optimum bioclimatic design, Olgyay made calculations to compare a square house with equal window areas on all sides with a bioclimatic house oriented 17 degrees east of south with most of its windows on the slightly east of south elevation (Figure 12.9). The curves on each of the elevations show heat gain when the curve is inside the house and heat loss when the curve is outside the house. In winter the sun is low in the southern sky, which provides a larger heating benefit for the bioclimatic house with more windows aimed south. In summer, the sun rises north of east, rising high in the southern sky, and sets north of west, resulting in large solar gains through east and west windows during the summer. The bioclimatic house with minimum window area on the east and west minimizes solar heat gain in the summer (Olgyay 1963, 132–137).

An additional benefit gained from bioclimatic design beyond minimizing annual energy use is solar penetration early in the morning. On any typical day during the year, the air temperature is cooler in the morning and warmer in the afternoon. A house oriented slightly east of south receives solar penetration early in the morning and avoids solar penetration in the afternoon. Orienting the kitchen, breakfast area, and master bedroom at the east end of a house maximizes the perceptual benefit of this early morning pick me up.

13

SOLAR CONTROL AND SHADING

Orienting a house to the south or slightly east of south opens south windows to accept solar gain in the winter when the sun is low in the southern sky (Figure 13.1). A southern orientation also helps to exclude solar gain in the summer when the sun is high in the southern sky. An understanding of where the sun is in the sky and how to construct shading devices to allow winter sun to penetrate while excluding summer sun is central to passive solar design.

To properly design solar shading devices it is necessary to understand solar diagrams and how to plot the performance of shading devices in diagrams. The path of the sun across the sky dome can be projected onto a horizontal surface (Figure 13.2). The horizon is represented by the circumference of the circular diagram. The concentric rings represent 10 degree increases in altitude, from 0 degrees at the horizon on the outer ring of the diagram, to 90 degrees at the center of the diagram. These angles are referred to as altitude angles. The lines that form spokes on the diagram count out 10 degree increments along the ground plane. These angles are referred to as azimuth angles. The path of the Sun is plotted on top of this polar diagram by month and time of day. The time markings on the chart are solar time not standard or daylight savings times. Solar time is defined by positioning noon at the point where the Sun is halfway across the sky. As an example of how to read the time lines look at December on the 40 degree north latitude Sun chart. The Sun rises 59 degrees east of south at about 7:30am, at noon the Sun is due south and at an altitude angle of 27 degrees, and the Sun sets 59 degrees west of south at about 4:30pm.

The parts of the sky that shading devices cover up can be plotted on the sun path diagram (Figure 13.3). The area of the sky that is covered by a shading device represents the times of the year when the Sun does not strike the window because the shading device is blocking the sun. The Sun path diagram represents the view of the sky that the entire window sees. To get a feeling for this idea consider your

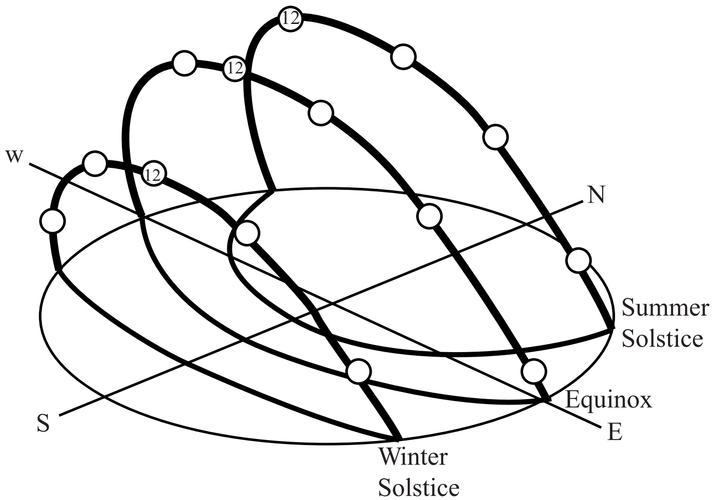

FIGURE 13.1 Creating a flat map of the position of the Sun in the sky vault.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

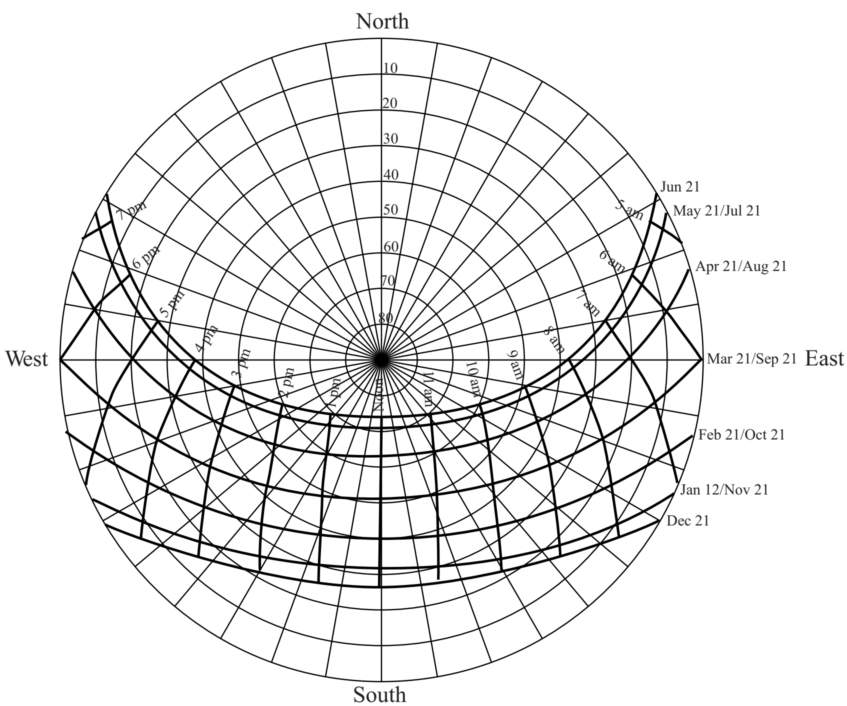

FIGURE 13.2 The Sun path diagram for 40 degrees north latitude.

Source: Moore 1993.

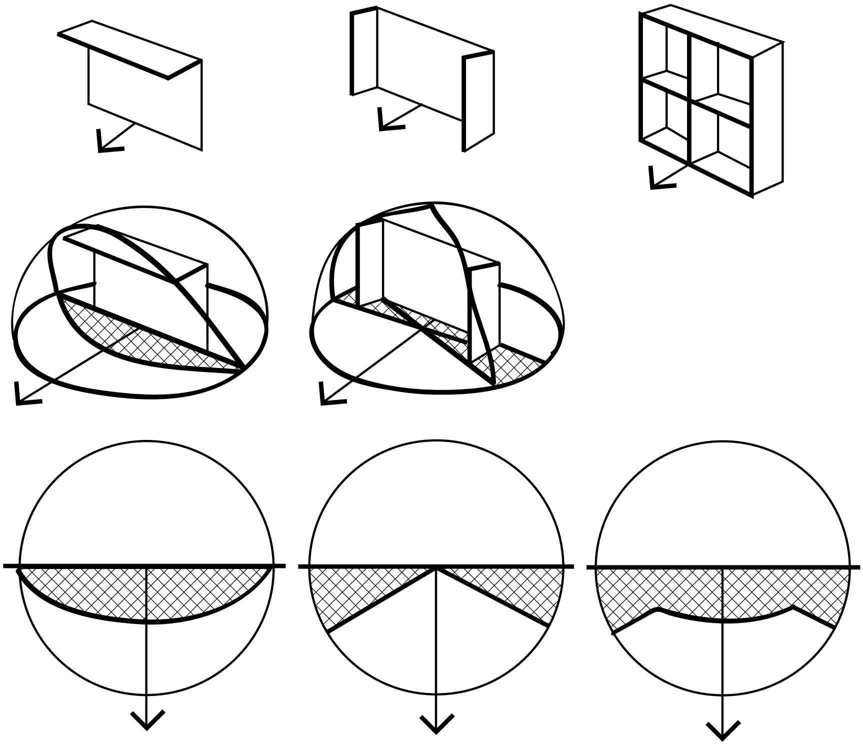

FIGURE 13.3 A conceptual diagram of how shading devices map onto the Sun path diagram.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

eyes to be a window. If you put your hand above your eyes you cannot see the part of the sky your hand blocks out. Whenever the sun is in that part of the sky your eyes, or the window, will be in shade. If you hold your hands up on either side of your eyes there will be parts of the sky on either side of you that you cannot see.

Any time of day when any monthly sun path is located in the blocked out part of the sky the window is completely shaded. No sunlight strikes anywhere on the window.

A section through a window can illustrate how a horizontal overhang protects the window from the summer Sun, which is high in the southern sky (Figure 13.4). The overhang blocks out the sky from the zenith through 25 degrees. When the Sun is in this part of the sky, no sunlight hits the window. When the Sun is lower than this in the sky, some sunlight hits the window. When the Sun is very low in the sky, the entire window is exposed to the Sun.

The part of the sky that is blocked out by a horizontal overhang can be plotted on the sun path diagram (Figure 13.5). First draw an arrow from the zenith, the

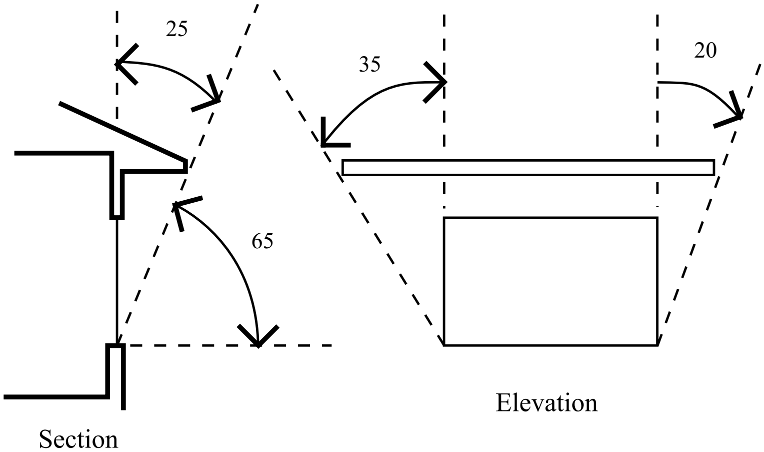

FIGURE 13.4 The parts of the sky that are blocked out by a horizontal overhang can be defined with cutoff angles.

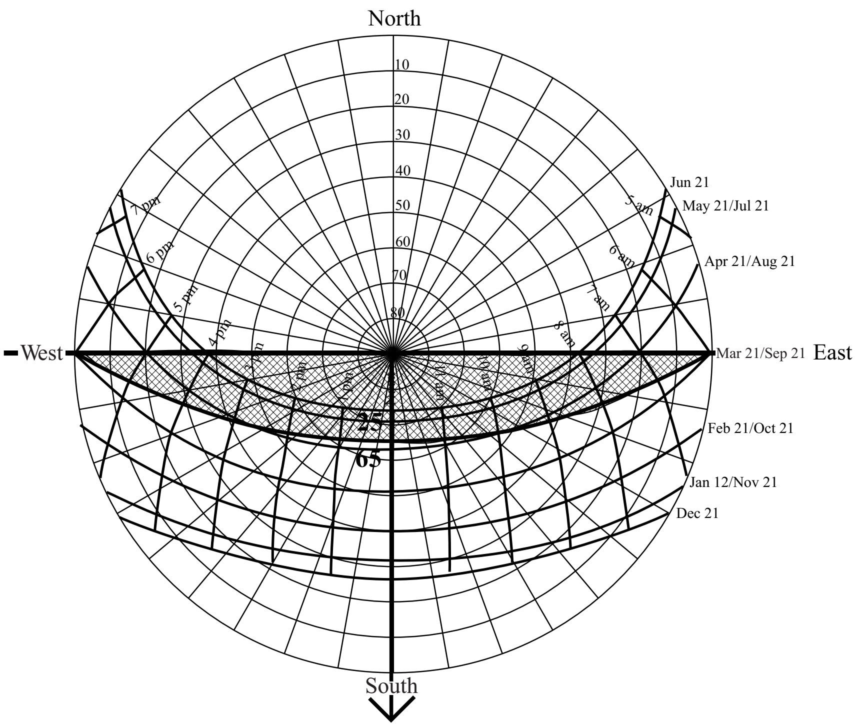

FIGURE 13.5 Plotting the 100 percent shading mask for a horizontal overhang with a 25 degree cutoff angle and an infinite extent on either side of the window.

center of the sky, to the horizon indicating the direction the window is facing. Then draw a line perpendicular to the arrow through the center of the sky to both horizons. This represents the wall the window is in. Anytime the Sun is behind this line the Sun is not hitting this wall. Then for an overhang that cuts out 25 degrees of the sky, count down from the center of the sky along the arrow line 25 degrees, or count up along the arrow line from the horizon 65 degrees. Then draw a curve through this point that starts and ends where the wall line meets the horizon line. This curve is a segment of a circle. If this horizontal overhang extends very far out in both directions from the window, the area between the curved line and the wall line represents the part of the sky completely blocked out. Any time the Sun is in this part of the sky the window will be in 100 percent shade. When the Sun is near this part of the sky the window will be in partial shade. When the Sun is far away from this part of the sky the window will be exposed to significant solar gain.

Most horizontal overhangs do not extend to infinity on either side of a window. To plot the 100 percent shaded area, measure the angles in elevation from the bottom edge of the window to the horizontal extent of the overhang. These angles are plotted from the center of the sky outward along the wall line (Figure 13.6). Then a curve is drawn from these points down to the point on the horizon where

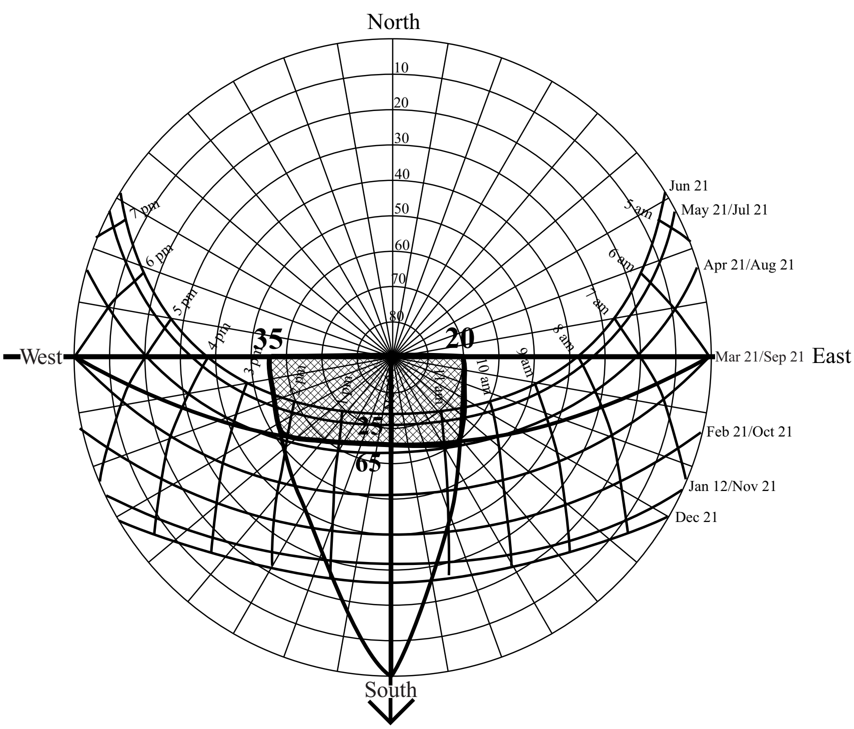

FIGURE 13.6 Plotting the 100 percent shading mask for a horizontal overhang with a 25 degree cutoff angle that extends beyond the window by a limited amount.

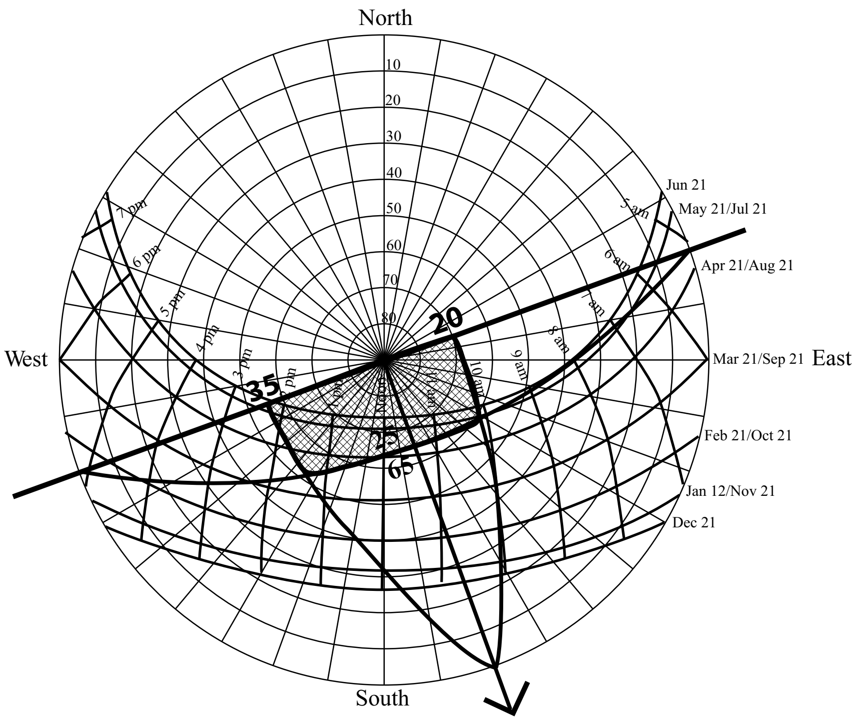

FIGURE 13.7 For a window facing 20 degrees east of south, the whole shading mask armature is rotated 20 degrees.

the arrow line meets the horizon. These curves are also segments of a circle. The 100 percent shade part of the sky is now only the area bounded by these curves and the horizontal overhang curve. At other times where the Sun paths are near this area, the window will be partially shaded.

If a house is oriented 20 degrees east of south, as bioclimatic design would suggest, the entire shading diagram rotates 20 degrees to the east (Figure 13.7). The arrow line goes from the center of the sky to the horizon at 20 degrees east of south. The wall line, perpendicular to the arrow line, starts 20 degrees south of west, runs through the center of the sky, and ends 20 degrees north of east. All the plotting described above is then overlayed on this rotated manifold.

Vertical fins are another shading device for windows. Fins block out part of the sky on either side of the window. If you hold your hands up on either side of your face your vision to either side is obstructed.

To determine how much of the sky is blocked out, measure the angle in plan from the far side of the window past the outside edge of the fin (Figure 13.8). This angle is plotted on the Sun chart along the horizon line from the back line representing the orientation of the wall toward the south (Figure 13.9). Then a line is drawn from this point to the center of the sky resulting in a wedge shape.

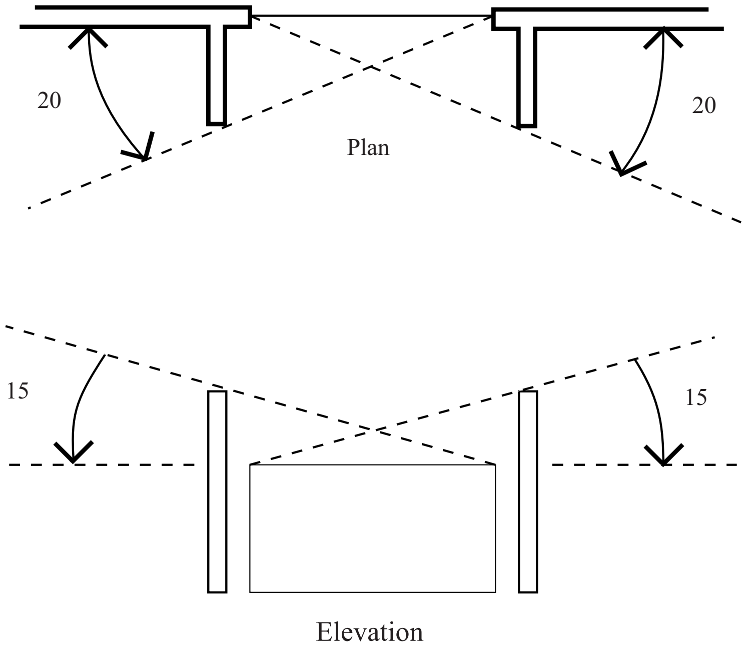

FIGURE 13.8 The parts of the sky that are blocked out by a vertical fin can be defined with cutoff angles.

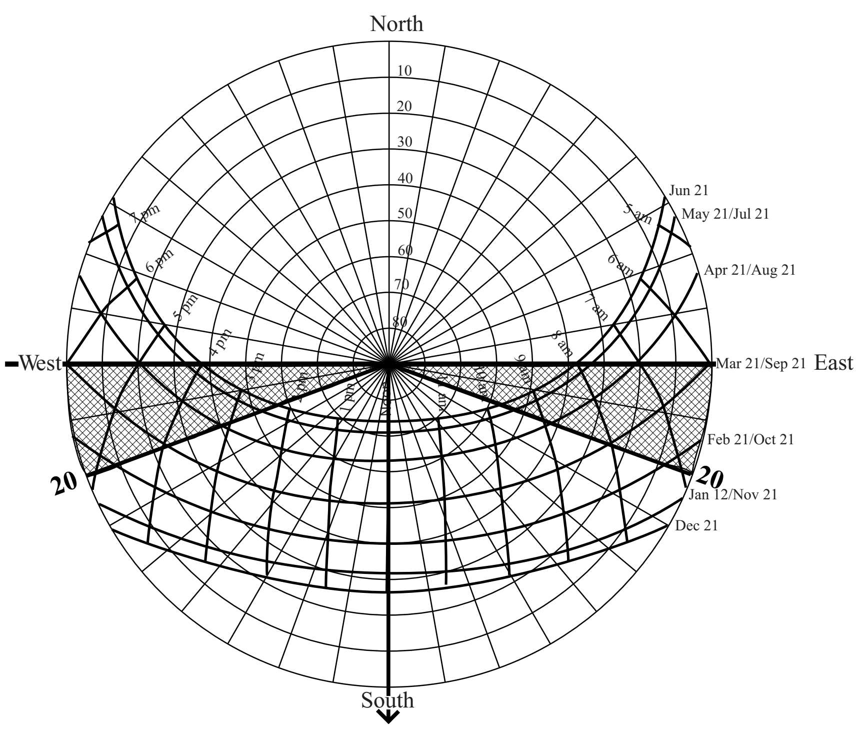

FIGURE 13.9 Plotting the 100 percent shading mask for fins with a 20 degree cutoff angle that extend an infinite amount above the window.

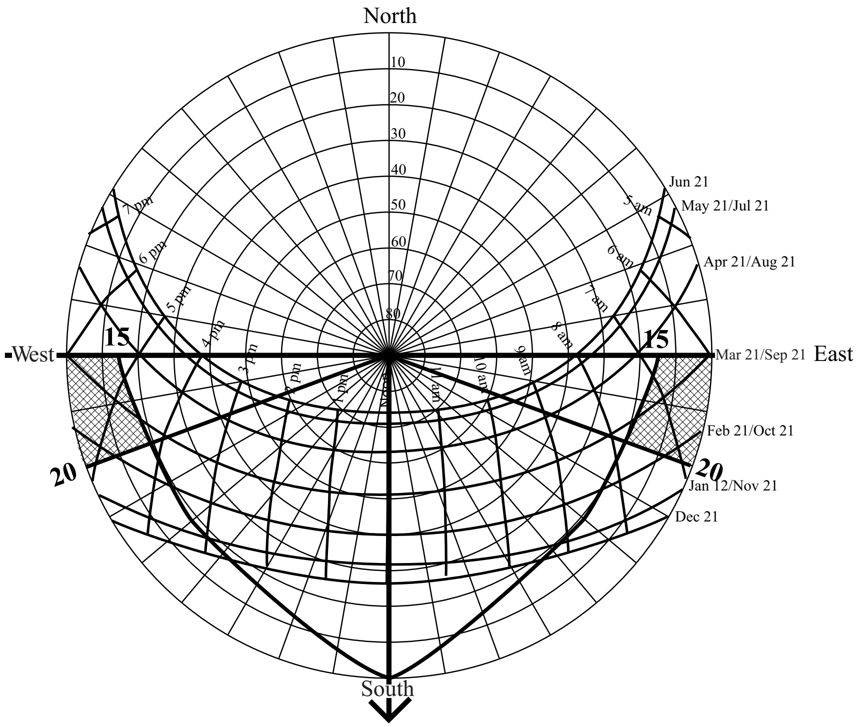

FIGURE 13.10 Plotting the 100 percent shading mask for fins with a 20 degree cutoff angle that extend a modest amount above the window.

The shaded-in area is only in complete shade if the fins extend upward to infinity above the window. Otherwise only part of the wedge shape will be in complete shade.

For fins that extend above the window, measure in elevation the angle from the far side of the top of the window to the top edge of the fin extending above the window. This determines the altitude angle of the Sun below which the Sun will not strike the window. Mark this altitude angle measurement from the horizontal line along the wall line toward the center of the sky (Figure 13.10). Then draw a curve from that point down to the point where the arrow line meets the horizon. Only the area in the wedge that lies between the horizon line and this new curve will be in complete shade. As with a horizontal overhang, areas near the 100 percent shade area will have significant shading, and areas far away from the 100 percent shade area will have very little shading.

Combining a horizontal overhang with vertical fins provides a potent shading device (Figure 13.11). The fins complete the horizontal overhang to infinity and the horizontal overhang completes the fins to infinity. The shaded area shows the times of the year where the Sun does not strike the window (Figure 13.12). Times near to this complete shading area will have partial shading. Times far away from the complete shade area will have little shading.

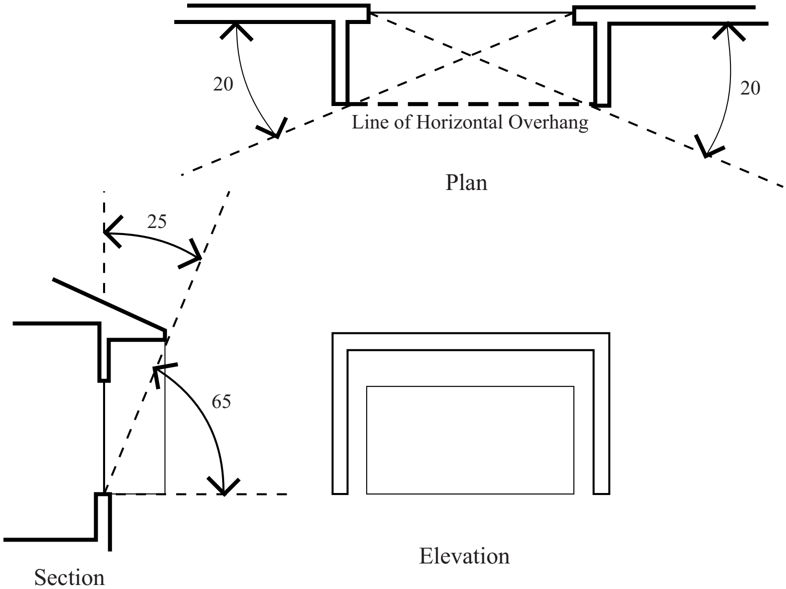

FIGURE 13.11 The parts of the sky that are blocked out by a combination of a horizontal overhang with vertical fin can be defined with cutoff angles.

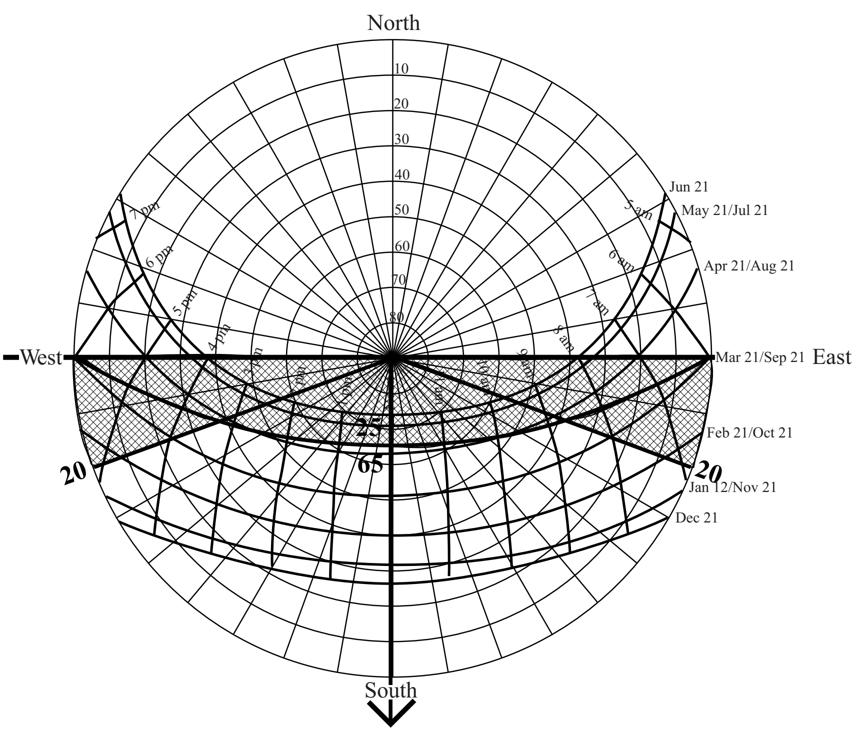

FIGURE 13.12 Plotting the 100 percent shading mask for the combination of an overhang and fins.

This procedure of mapping the shaded area on the Sun chart only makes sense if it can be used as a design tool. If the overheated period of the year, the hot summer months, can be plotted on the Sun chart, then a specification for a shading device can be determined. The time of day and months of the year that are overheated can be determined from a climate plot on the bioclimatic chart.

The comfort zone is defined as providing comfort for a person in light clothes in the shade. The shading specification is defined to provide complete shade for the times when the air temperature is above the comfort zone, rather than also including the comfort zone, because to include the comfort zone in the complete shading specification would over shade the window (see Figure 13.13). The desire is to shade the window during the summer months but to allow solar penetration during the winter months. Setting the shading specification at the top of the comfort range provides this balance between summer shade and winter penetration.

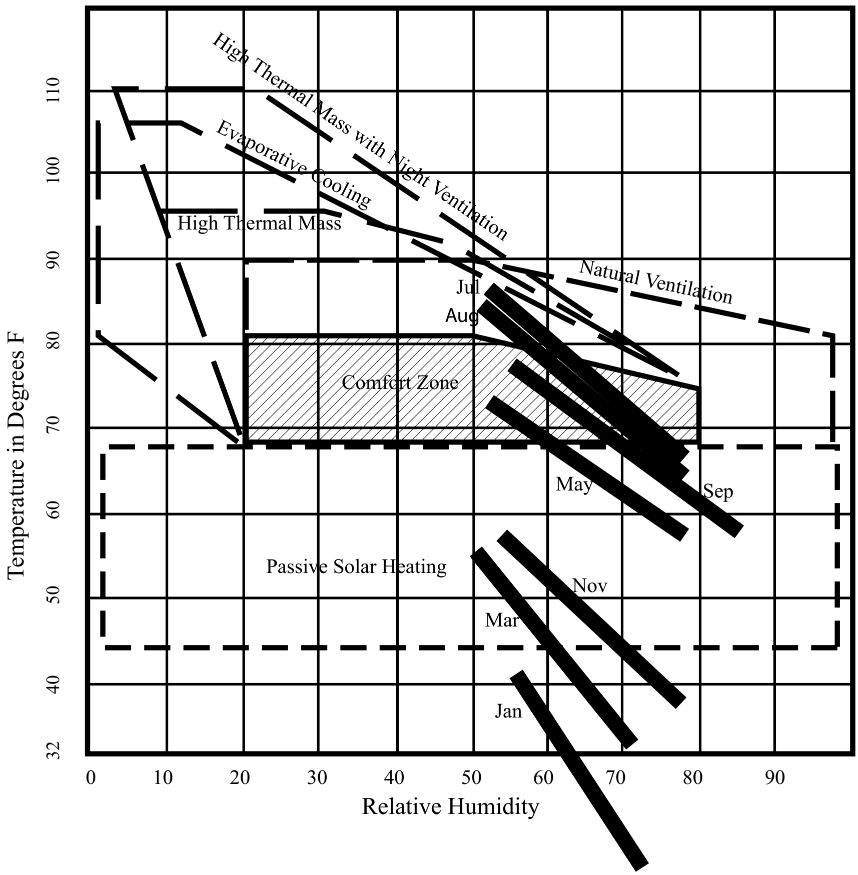

FIGURE 13.13 Weather data for Baltimore, Maryland, plotted on the bioclimatic chart can be used to define the overheated months of the year.

Source: Bioclimatic chart, Brown and DeKay 2001. Climate plot, Carl Bovill.

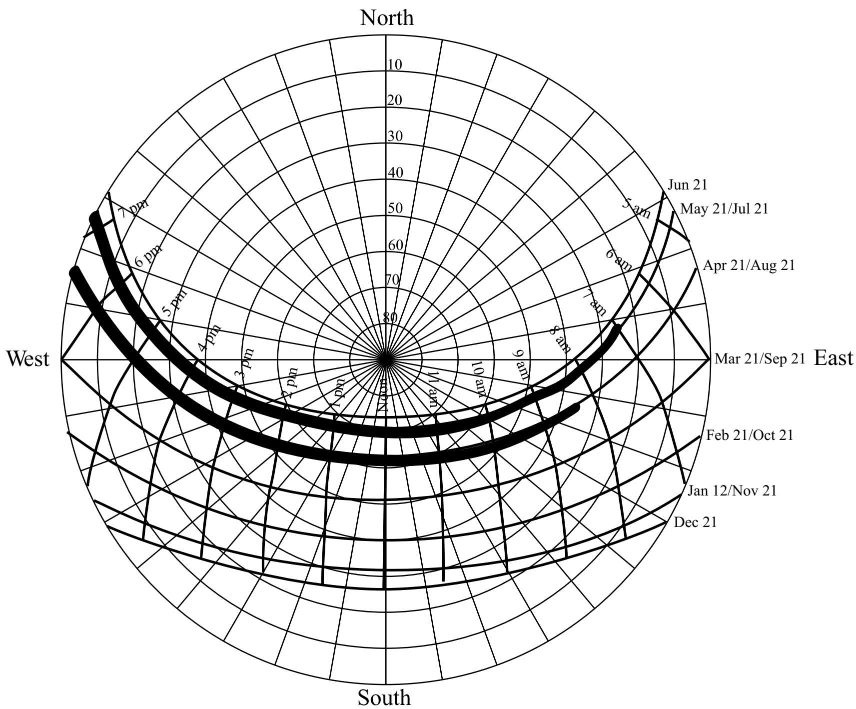

FIGURE 13.14 The overheated period can be transferred from the bioclimatic chart to the sun chart.

The peak temperature of the day happens in the early afternoon, which means that the upper half of the plot lines representing each month in Figure 13.13 represent the daytime part of the plot. On the bioclimatic plot for Baltimore, Maryland, July is completely above the comfort zone during the day. August is also above the comfort zone from midmorning on. September is in the comfort zone during the day. Using this information from the climate plotted on the bio-climatic chart, the overheated period for Baltimore, Maryland, can be plotted onto the sun chart (Figure 13.14). The overheated period on the sun chart can then be used to create a specification for an appropriate shading configuration.

To construct the shading device specification (Figure 13.15), first draw the arrow line in the direction the window faces and the wall line perpendicular to the arrow line. Then draw a curve from one end of the wall line that just skims the bottom of the overheated period to the other end of the wall line. This curve sets the horizontal overhang cutoff angle. Then draw a curve toward the west that starts at the intersection of the arrow line and the horizon and meets the wall line where it just covers up the overheated period. Draw a similar line toward the east. These two lines will provide a specification of how far the horizontal overhang should continue past the end of the window (Figure 13.16; see also Figure 13.17).

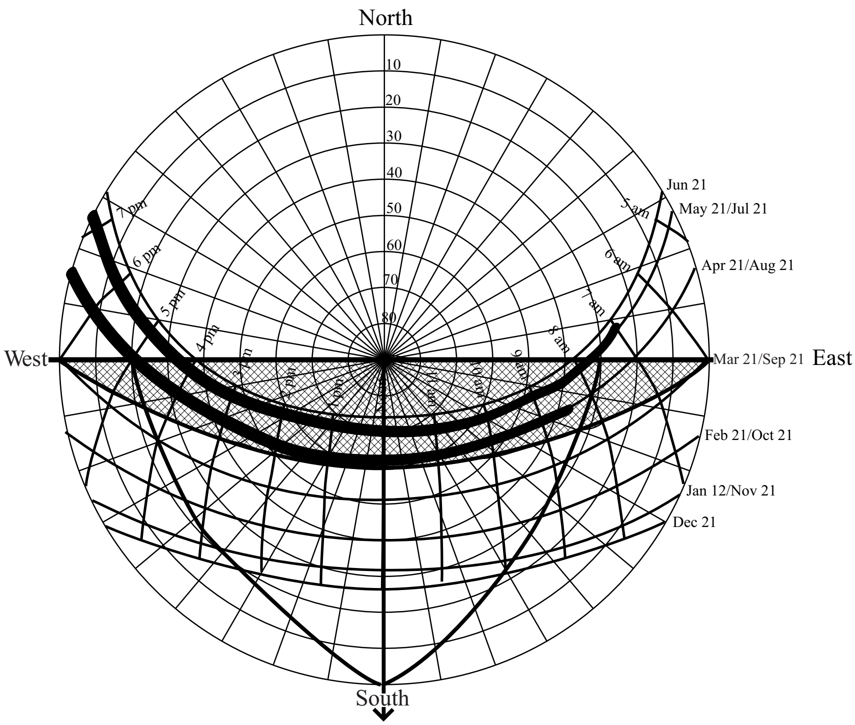

FIGURE 13.15 A shading mask can be constructed that will cover the overheated period in order to define the cutoff angles of the required horizontal overhang.

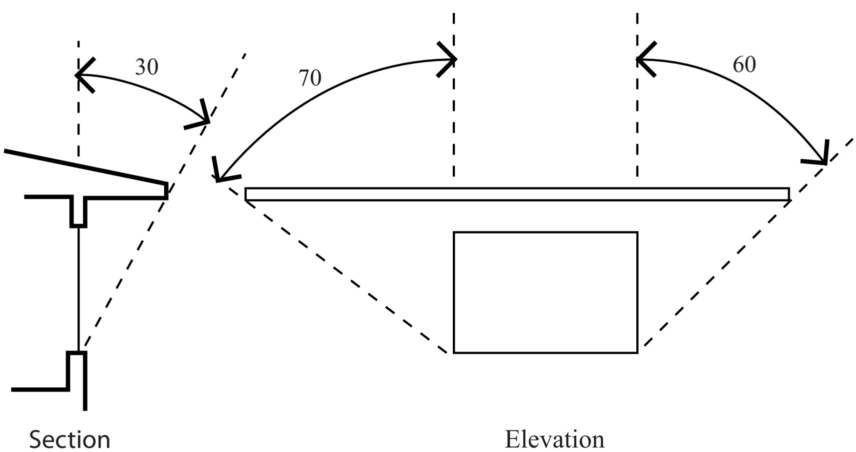

FIGURE 13.16 The horizontal overhang in section and elevation that was determined by the shading mask constructed in Figure 13.15.

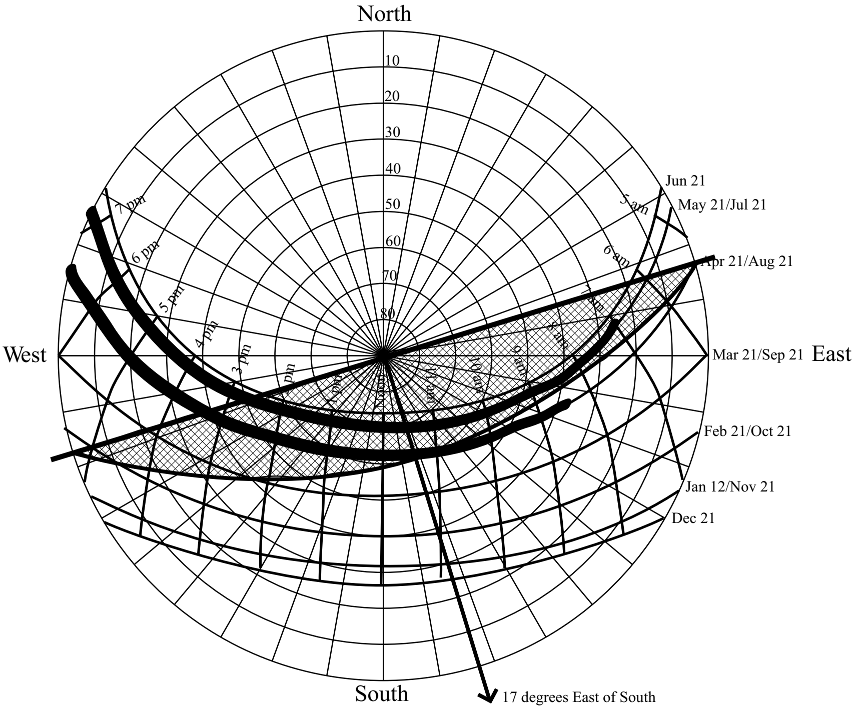

FIGURE 13.17 If the building is rotated 17 degrees east of south it receives a little boost of morning sun and avoids afternoon sun.

The reality is that the horizontal overhang is likely to run all the way along the southern elevation of the house. The overhang will not continue past the end of the house. The simple way to make the overhang effective all the way along the southern elevation is to plant a tree at the south-east end of the house and another tree at the south-west end of the house. The trees then act as fins at the end of the horizontal overhang completing the horizontal overhang to infinity (Figure 13.18). In addition the trees shade the roof from solar gain especially in the afternoon when the air temperature is highest.

A little trigonometry can help determine the optimum horizontal overhang. Look at the sun chart with the overheated period and the horizontal overhang specification. The chart calls for blocking the sun anytime that the altitude angle is greater than 60 degrees. In January at noon the altitude of the sun is 30 degrees. One would like the window to be wide open to solar penetration in January. A section diagram of a window with a horizontal overhang can be used to set up the trigonometry to determine the location and extent of an optimum overhang that blocks out the summer sun and lets in the winter sun (Figures 13.19 and 13.20).

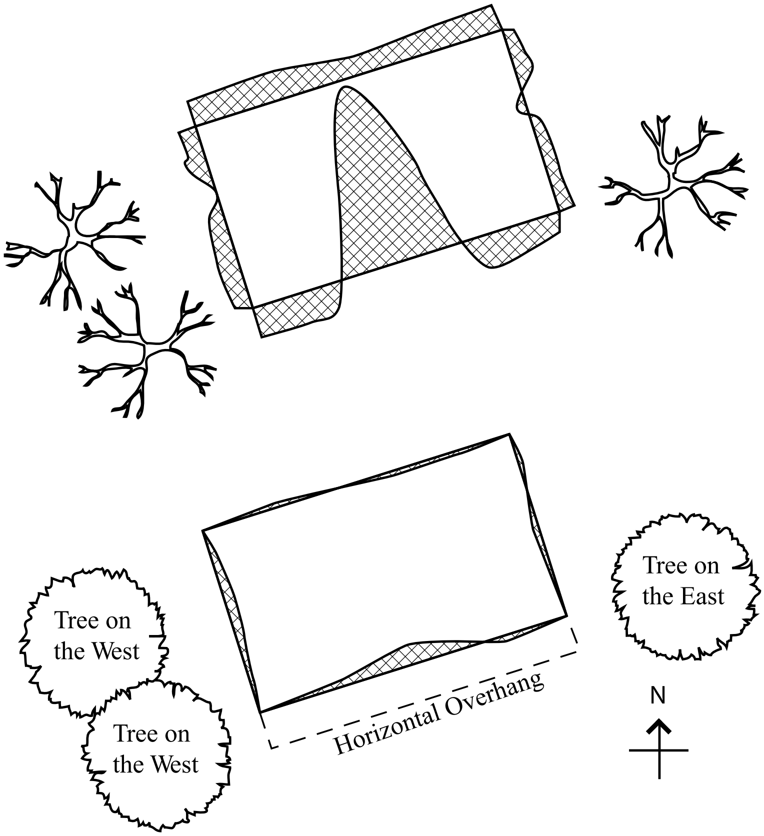

FIGURE 13.18 Trees planted to the west and east of a house act as large fins making the horizontal overhang more effective.

Source: Olgyay, Victor. *Design With Climate*. Copyright 1963: Princeton University Press. 1991 renewed PUP. Reprinted by permission of Princeton University Press.

$$\text{Tan } 30 = OH/H \qquad (\text{Tan } 30 = 0.577)$$

$$0.577 = OH/H$$

$$H(0.577) = OH \tag{13.1}$$

$$\text{Tan } 60 = OH/(H - WH) \qquad (\text{Tan } 60 = 1.732)$$

Setting WH to 4.5 feet,

$$1.732 = OH/(H - 4.5)$$

$$H(1.732) - 4.5(1.732) = OH$$

$$H(1.732) = OH + 7.794 \tag{13.2}$$

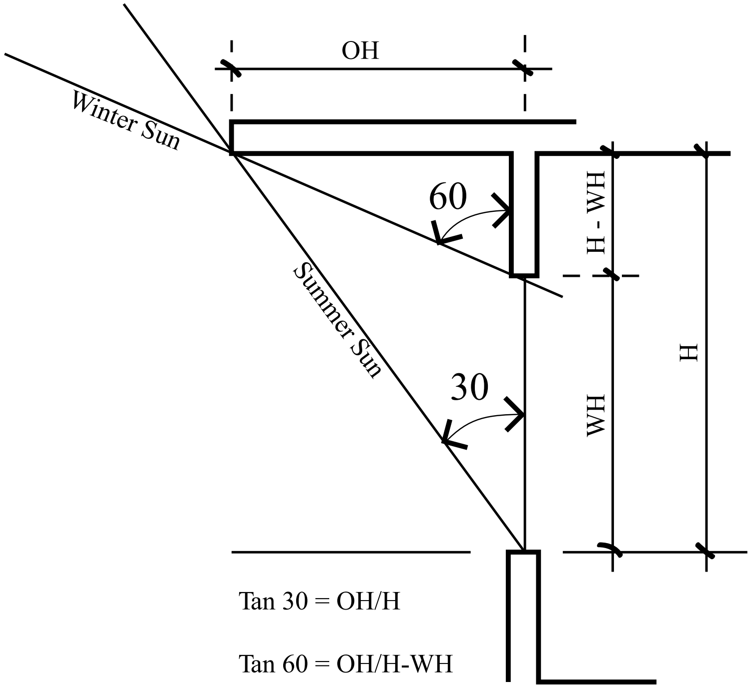

FIGURE 13.19 An optimum overhang lets the winter sun in and blocks the summer sun. Trigonometric equations can be used to solve for the optimum overhang dimension in relation to window height.

Substituting Equation (13.1) (H(0.577) = OH) into Equation (13.2) yields:

$$H(1.732) = H(0.577) + 7.794$$

$$H(1.155) = 7.794$$

$$H = 6.742 \text{ feet or } 6 \text{ feet } 9 \text{ inches}$$

Substituting the H back into Equation 13.1, gives the overhang dimension

$$H(0.577) = OH$$

$$(6.742)(0.577) = OH$$

$$OH = 3.89 \text{ feet or } 3 \text{ feet } 10\tfrac{1}{2} \text{ inches}$$

The bottom edge of the overhang is equal to the window height (H) plus the window sill height (2.5 feet) which gives the ceiling height:

$$6.743 \text{ feet} + 2.5 \text{ feet} = 9.243 \text{ feet or } 9 \text{ feet } 3 \text{ inches}$$

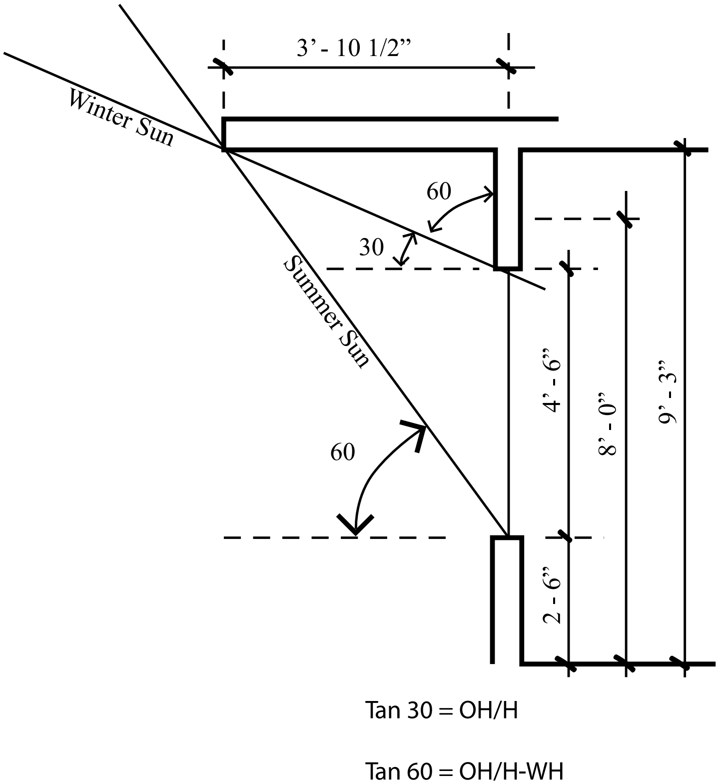

FIGURE 13.20 The solution to the optimum overhang problem creates an interior ceiling height higher than 8 feet.

However, the realities of residential construction will usually constrain the overhang to be an extension of the customary eight foot ceiling height. Thus a compromise of optimum horizontal overhang is necessary.

With a two and a half foot window sill height and a window height of 4.5 feet, which allows for the header framing above the window, the relationship between the height from the window sill to the ceiling and the extent of the overhang is two to one (Figure 13.21). The two to one ratio is a compromise but provides an easy to remember design heuristic.

The same ratio also works well as one looks at warmer locations further south than the 40 degree north latitude of Baltimore, Maryland. The reason the same ratio works is that as the overheated period expands to include another month, the sun paths through the sky move to be more overhead. The ratio also works as one looks at colder climates further north. The overhang will block out less of the summer sun as the sun paths move lower in the sky but the summer is shorter as one goes north. Of course the best procedure is to plot the weather on the bioclimatic chart followed by a plot of the overheated period on the sun chart. The resulting shading design will then be tuned to the local circumstances.

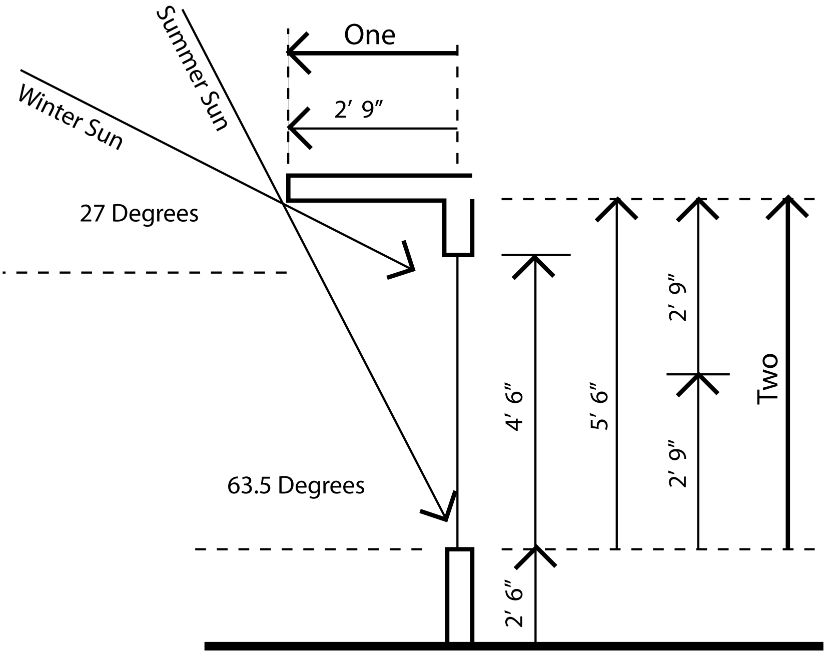

FIGURE 13.21 A compromise solution to the optimum overhang problem with realistic window size and ceiling height creates a two to one relationship between window height and overhang depth.

14

PASSIVE SOLAR HEATING

Passive solar heating is the simple concept of allowing solar gain into a building when heat is needed in the winter. The solar gain during the day is partially stored in thermal mass for later use during the night. The thermal mass (concrete, brick, adobe) will heat up during the day and then deliver heat to the space it is located in through two processes. Convection air currents across the thermal mass will heat the air in the room, and radiation from the warm thermal mass will increase the mean radiant temperature of the room. The increase in the mean radiant temperature of a room allows the thermostat controlling room air temperature to be set lower while still providing thermal comfort.

For passive solar to work it is necessary to maximize solar gain in the winter and minimize solar gain in the summer. South facing glass provides this balance (Figure 14.1). East and west facing glass has about three times more solar gain in summer than in winter. Horizontal glass has almost three and a half times more solar gain in summer than in winter. South facing glass has the opposite characteristic of having close to three times more solar gain in winter than in summer.

Before passive solar techniques are used to size south facing windows and the necessary thermal mass, it is important to design the envelope of the building to minimize heat loss and heat gain. On the heat loss side this involves insulating the walls, roof, and floors. Walls should be at least R-19, roofs should be at least R-30, and exposed floors should be at least R-11. It also involves minimizing infiltration of cold outside air and the accompanying exfiltration of warmed interior air. This is achieved by sealing up all the construction cracks around windows, doors, the top and bottom plates of stud walls, and openings through the ceiling into the attic. On the cooling side solar gain needs to be minimized through window orientation and appropriate shading devices.

Passive solar heating and cooling techniques apply best to buildings of modest size where the heating and cooling requirements are determined primarily by heat

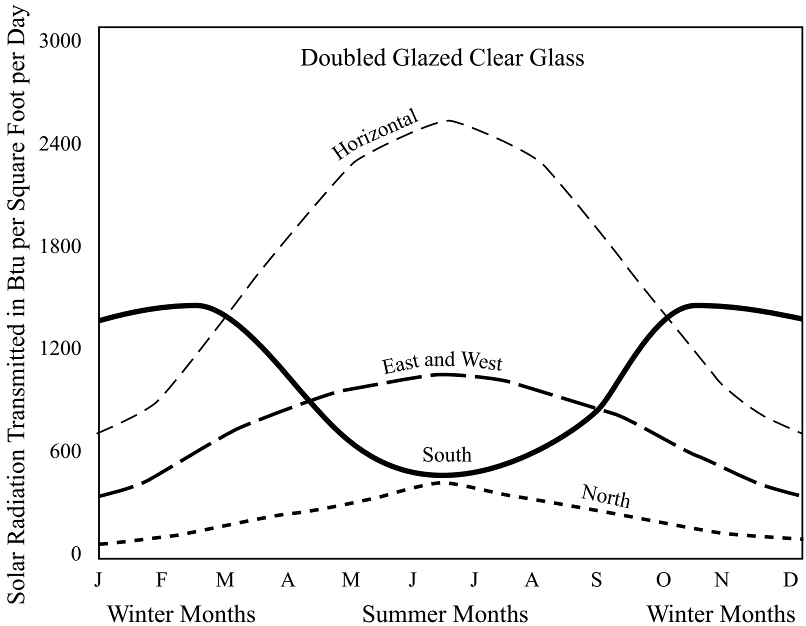

FIGURE 14.1 Solar radiation by wall orientation and season.

Source: Moore 1993.

flows out of and into the building through the envelope of the building. Single family houses are the best example of this type of building, but other types like multifamily housing and small commercial buildings will approach an envelope dominated thermal flow building type.

Since passive solar buildings will need to respond to their local macro and micro climates, it is not likely that what is good design in one location will be good design in another. The result is that energy efficient passive solar buildings can provide national, regional, and local diversity of form and design.

Direct gain is the simplest passive solar strategy (Figure 14.2). The building is oriented to the south. Remember that bioclimatic design suggests an orientation slightly east of south. The window area necessary is approximately 10 to 30 percent of the served floor area. The served floor area is the room that the solar gain is going into. Solar heat will not magically travel across a hall and into a room on the north side of a house. There needs to be an accompanying amount of thermal mass to soak up the solar gain or the room will overheat during the day and be cold at night. The appropriate amount of thermal mass is four to five times the window area, four inches thick. Four inches is the thickness of concrete that heat will flow into and out of in a 24 hour cycle of charging and discharging.

A computer energy simulation can be used to study how much thermal mass is necessary in a direct gain solar heating design (Figure 14.3). An Energy-10 simulation of a passive solar design for Sterling, Virginia, included an infinite

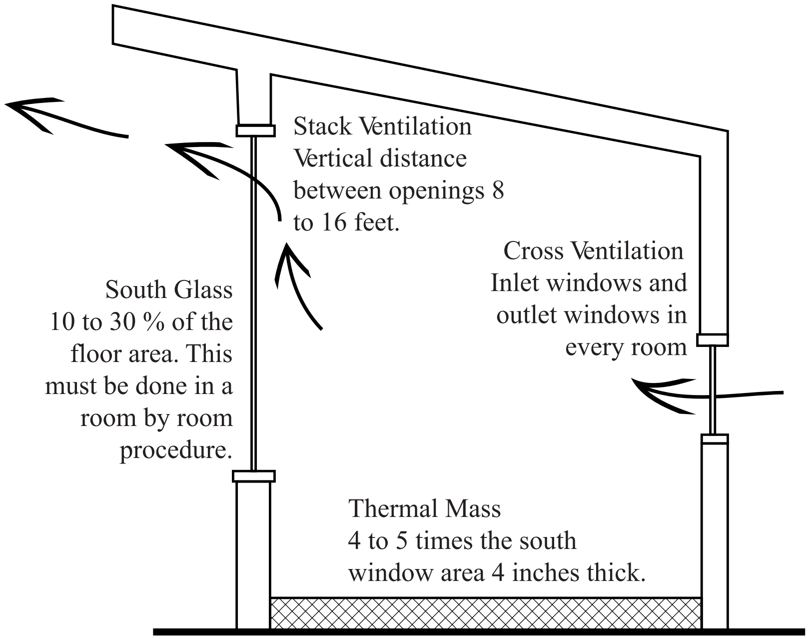

FIGURE 14.2 Passive solar direct gain distributed mass.

insulation layer below the thermal mass concrete floor slab. For both the heating only and the heating and cooling simulations the energy benefit of thermal mass is not improved much beyond four inches thick. The optimum south glass area can also be explored with multiple computer simulation runs. For heating only the optimum window area is indicated by the flat bottom of the curve, which extends from about 16 to 24 percent of the floor area. For heating and cooling the optimum south glass area is in the range of 10 to 15 percent of the floor area (Figure 14.4).

The *Passive Solar Energy Book* (Mazria, 1979) provides the following window area ratios. For winters with average temperatures of 20 to 30 degrees Fahrenheit, set the south window area to 19 to 38 percent of the floor area. And for winters with average temperatures of 39 to 45 degrees Fahrenheit, set the south glass area to 11 to 25 percent of the floor area (Mazria 1979, 119).

The Solar Savings Fraction method suggests 17 to 35 percent south glass for Chicago, with 5,753 heating degree days and a heating design temperature of 3.1 degrees Fahrenheit. It suggests 12 to 23 percent south glass for Washington, DC, with 4,047 heating degree days and a heating design temperature of 20.2 degrees Fahrenheit. And finally, for the milder climate of San Francisco, it suggests 6 to 13 percent south glass with 3,016 heating degree days and a heating design temperature of 40 degrees Fahrenheit (Grondzik et al. 2010, 1646–1649).

The *California Energy Commission Passive Solar Handbook,* based on multiple Calpas computer simulations, suggests a range of 0 to 33 percent of the floor area in south

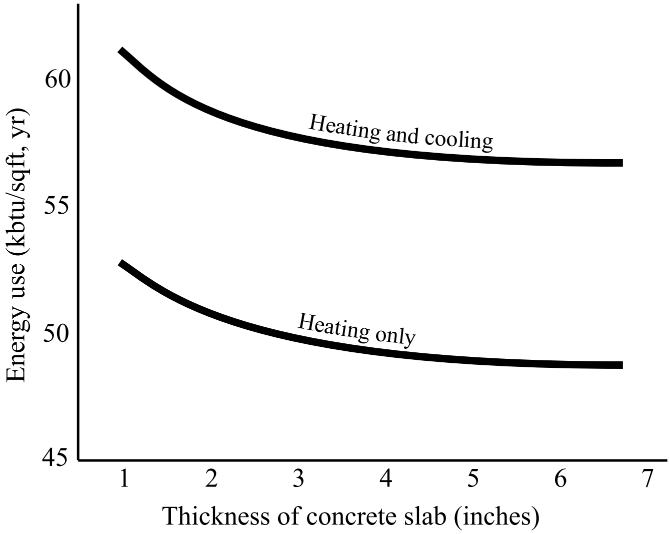

FIGURE 14.3 Energy-10 simulations to determine the optimum concrete floor thickness when used as thermal mass. An R-1000 insulation layer was placed under the concrete floor, which was increased in thickness in inch increments.

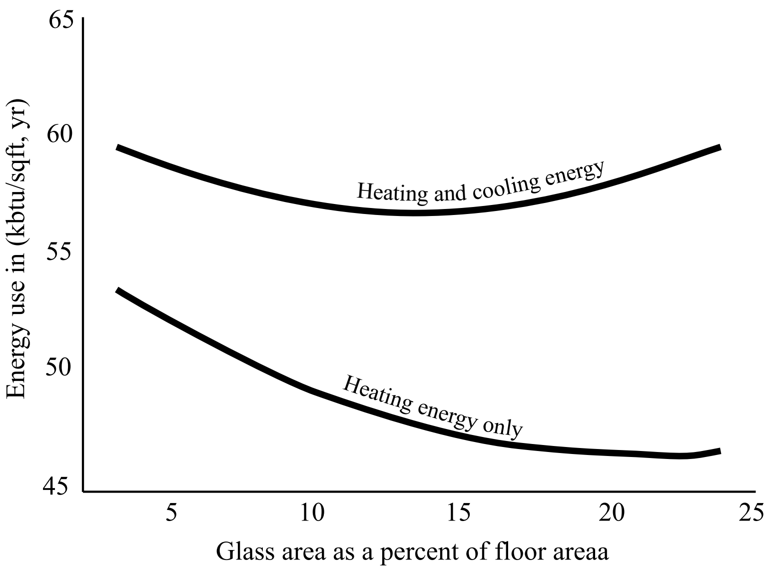

FIGURE 14.4 Energy-10 simulations to determine optimum south window area for Sterling, Virginia. The floor area of the house was 2,000 square feet with 2,000 square feet of 4 inch thick concrete floor as thermal mass.

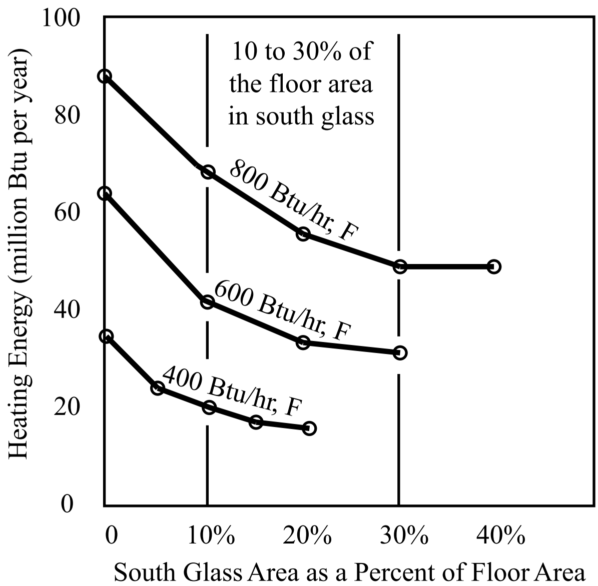

FIGURE 14.5 Computer simulations of passive solar glass area for Alturas, California, with 6,553 heating degree days for three different house insulation levels. The floor area of the house was 2,000 square feet with 2,000 square feet of 4 inch thick concrete floor as thermal mass.

Source: Data from Niles and Haggard 1980.

glass (Niles and Haggard 1980, 90). The insulation level of a house has a large effect on heating energy use and on the amount of south glass area required for passive solar heating. Data from the *California Energy Commission Passive Solar Handbook* for Alturas, a cold climate, and for San Rafael, a mild climate, illustrates the importance of insulating a house very well before applying passive solar design methods (Figures 14.5 and 14.6).

Thermal mass can be divided into two categories. Thermal mass that is directly warmed by the sun is radiation coupled. Thermal mass that is not directly warmed by radiation from the sun can be warmed by the air in the room. This is called convection coupled thermal mass. Radiation coupled thermal mass is preferred since it will charge the thermal mass quicker and deeper. The thermal mass, usually the floor, is spread out, so it is desirable to spread out the solar gain by bouncing it off light colored surfaces, or blinds. Diffusing glass would be excellent but then the owners of the house could not see out. In all direct gain passive solar configurations, the owners of the building will be living in the collector. Sunlight glaring across the room will probably not be acceptable from a thermal and visual comfort standpoint. In addition sunlight blasting onto furniture and carpets day after day will fade and eventually destroy fabrics. Diffusing the solar gain helps charge the thermal mass more effectively and helps make the passive solar heated room more livable.

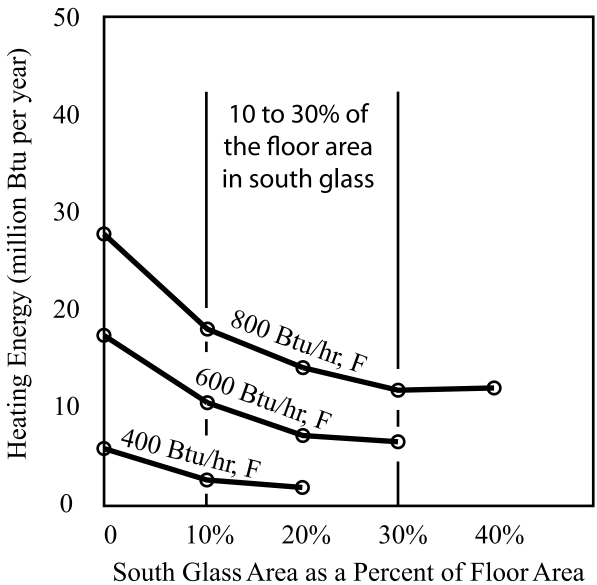

FIGURE 14.6 Computer simulations of passive solar glass area for San Rafael, California, with 2,773 heating degree days for three different house insulation levels. The floor area of the house was 2,000 square feet with 2,000 square feet of 4 inch thick concrete floor as thermal mass.

Source: Data from Niles and Haggard 1980.

If light comes predominantly from one direction, it can cause visual difficulties seeing detail when one is looking in the direction the light is coming from. There are methods to improve this situation. The first is to have light colored interior surfaces. The floors could be a little darker. Light colored floors will bounce light all over the room. Remember radiation coupling. The second method is to splay the window openings. This creates a gradient of brightness from the window, to the splayed window surround, and finally to the light colored interior wall surface. The third is to have windows in other walls. The light coming in through windows in other walls illuminates the wall that the major windows are in decreasing glare in the room. In addition light coming from multiple directions provides a more pleasing visual environment.

It is important to remember that direct gain passive solar window areas and the accompanying thermal mass need to be applied to each room individually. Thus in the usual two room deep house, the southern rooms can have south window areas and thermal mass floors or walls. North facing rooms can either not have passive solar heating, or solar gain can be introduced through clerestory windows. Solar gain through clerestory windows is best bounced off a light colored wall to be distributed evenly over the whole room and the thermal mass in the room.

Finally, the south glass needs to have a horizontal overhang designed to allow the winter sun in and keep out the summer sun (Figure 14.7). The ratio between

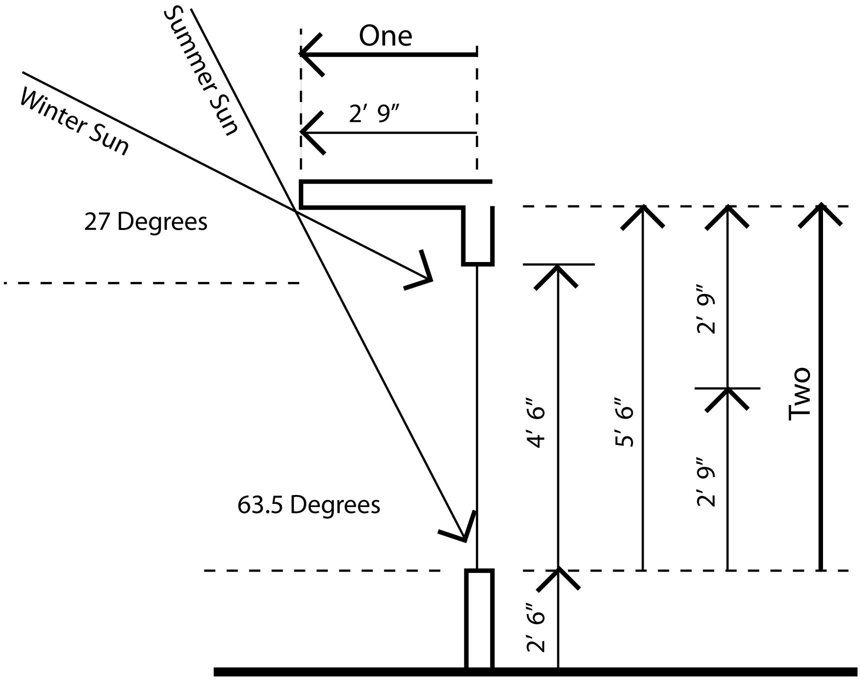

FIGURE 14.7 An optimum overhang blocks out the summer sun and allows the winter sun in.

the extent of the horizontal overhang and the height from the window sill to the bottom of the overhang is 1 : 2. See Chapter 13 on solar shading for a more complete discussion of shading.

Eutectic salts can be designed to melt, go from a solid to a liquid, at a defined temperature when they are heated by the sun. Then during the night the eutectic salts will slowly turn back to a solid as they give off heat into the space again at the defined temperature. In an MIT demonstration building the eutectic salts were incorporated into ceiling panels. Blinds just inside the window were mounted with the curved side up. The blinds could then be adjusted to bounce the sunlight coming in through the south windows onto the ceiling. The resulting heating of the eutectic salt ceiling panels caused them to change phase at their defined temperature thus storing thermal energy. The advantage of phase change thermal storage materials is that a much lower volume of material is necessary because of the large amount of heat required to change the state of a material from solid to liquid. The disadvantage of phase change materials is that they turn from a solid to a liquid after being heated. A liquid can leak out of its containment. This creates a potential liability problem for the designer that concrete or brick thermal mass does not have.

In concentrated thermal mass direct gain systems, water tubes are placed just inside the south facing glass (Figure 14.8). The south glass area is the same as direct gain systems with distributed mass. The solar gain heats the water in the tubes.

Water is a great thermal mass material. Its volumetric heat capacity is very high and convective currents in the water distribute the heat gained on one side of the tube evenly over the whole volume of water. Heat is transferred to the room in two ways. Room air will be warmed by the tubes and convective air currents will distribute the air to the room. A slow moving ceiling fan can help move heat down to where people are. The water tubes will be warmer than the air in the room at night. The warm surfaces will increase the mean radiant temperature of the room. A room with an elevated mean radiant temperature can provide thermal comfort with a lower air temperature. The water tubes should be painted black or a very dark color on the side facing the window where sunlight hits the tubes. This will maximize the solar gain into the tubes. The side facing the room can be a light color. The modest temperatures being radiated into the room will not be affected much by the color on the room side as long as it is not a metallic surface (Niles and Haggard 1980, 158).

There are two main disadvantages of water tubes as solar storage. The first is that there is a large amount of water in the tubes that can leak out if not maintained over time. The second is that the water tubes need to be placed between the south glass and the room. This blocks the view out the window. The blocked view has one benefit. The sunlight does not blast over the entire room. It is filtered around and sometimes through the water tubes. Good designs take advantage of this filtering of the light.

Thermal storage walls provide an indirect path to heating the space behind them (Figure 14.9). A wall of concrete or other thermal mass material is constructed on the south side of the room to be heated. For a house the wall is approximately 12 inches thick. The outside face of the wall is painted black to absorb the maximum amount of sun. Leaving an air space of four to six inches, a glass wall is placed outside the concrete wall. Solar radiation penetrates the glass and heats up the outside face of the concrete wall. The black outside face of the concrete wall reaches its peak temperature slightly after noon solar time. Solar noon is when the sun is half way across the sky. With a 12 inch thick concrete wall, the heat wave pushed into the wall from the outside takes approximately 8 hours to reach the inside. Thus the peak of the heat wave reaches the inside of the wall at about 8 pm. An 8 inch thick wall will have a time lag of six hours, and a 4 inch thick wall will have a time lag of four hours (Moore 1993, 126). A thermal storage wall should be 20 to 60 percent of the floor area it heats.

The *Passive Solar Energy Book* suggests 43 to 100 percent of the floor area in thermal wall area for cold climates, and 22 to 60 percent of the floor area in temperate climates (Mazria 1979, 153).

The *California Energy Commission Passive Solar Handbook* suggests a range of 35 to 75 percent of the floor area in thermal storage wall (Niles and Haggard 1980, 195).

Thermal storage walls are sized for the room the wall is facing into not for the whole house floor area. The temperature swing on the inside face of a 12 inch thick thermal storage wall will be about 25 degrees Fahrenheit, from 65 to 90 degrees

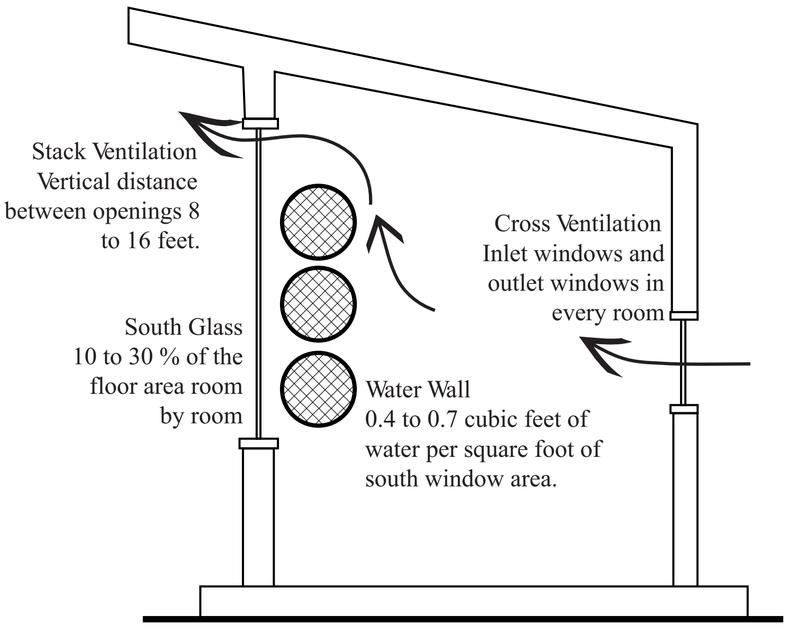

FIGURE 14.8 Passive solar concentrated mass.

Fahrenheit. The outside face of the wall will swing from 55 to 155 degrees Fahrenheit. In a house that is occupied day and night a 12 inch thick concrete thermal storage wall moves heat into the mid-evening hours. A commercial venue that closes at 6 pm or a camp meeting house that closes at 9 pm would call for thinner thermal storage walls with shorter time lags (Niles and Haggard 1980, 195).

Vents can be located at the top and bottom of the wall into the airspace between the wall and the glass. The vents allow some of the warm air trapped between the outside face of the wall and the glass to rise and come into the room through the openings in the top of the wall. This process draws room air into the bottom vents, which is then heated completing the cycle. The area of the vents should be approximately 1 square foot of vent per 100 square feet of wall. However, there is a problem with using vents. At night the outside air space between the wall and the glass will be colder than the inside air. If left uncovered, warm room air will enter the upper vents; the air will be cooled and fall down the outside air space between the wall and the glass and come back into the room through the lower vents as a cold draft along the floor. The simple solution is to put light weight flaps of some kind over the upper vents so that air can come in but when air wants to go out the flaps close. Another solution is to avoid the vents in the wall and add some direct gain windows for early in the day solar gain, with the thermal storage wall providing heating for the evening (Moore 1993, 126–127). A Los Alamos study comparing thermal storage walls with and without thermo circulation

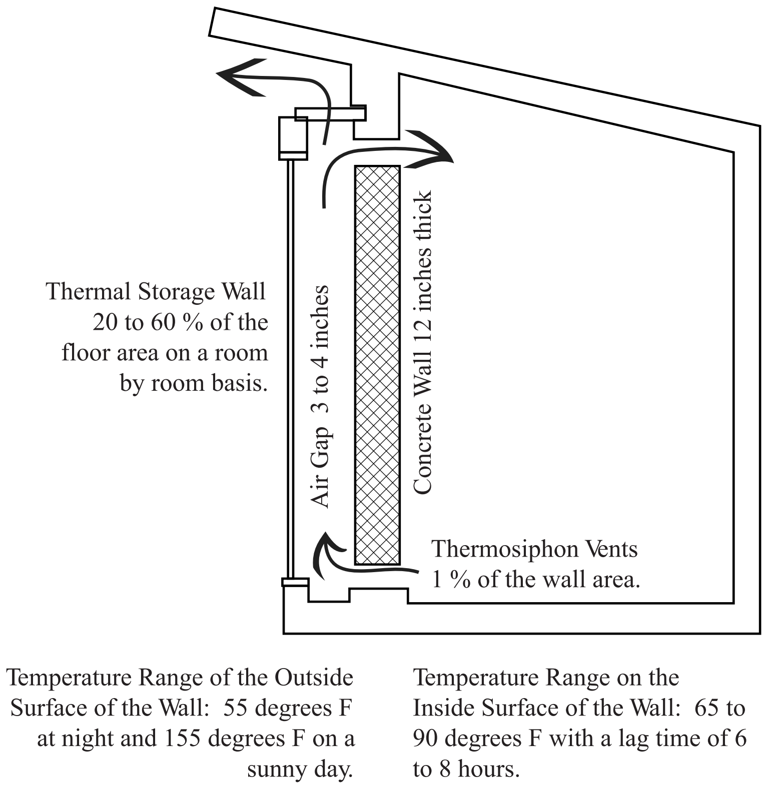

FIGURE 14.9 Passive solar thermal storage wall.

vents showed that there was very little difference in the solar heat produced (Mazria 1979, 167).

The thermal storage wall needs to be shaded from summer sun and exposed to winter sun, thus an overhang similar in proportions to the overhang protecting a south window needs to protect a thermal storage wall (Figure 14.7). In addition, there needs to be a method of venting the air gap between the wall and the glass to the outside to further minimize heat buildup in the wall during the summer months.

Building a thermal storage wall on the south side of a room cuts off view in that direction from the room. This is a problem that can be partially solved by incorporating windows in the wall. There should be a reveal around the window to minimize glare, and there needs to be glass in the window to maintain the separation of the heated air space along the outside face of the wall.

As in the concentrated mass water tubes of direct gain systems, the inside wall temperatures are only modestly above the room air temperature; thus the color of the inside of the thermal storage wall is not important to radiant thermal transfer. The wall could be a very light color concrete or be painted a light color. Light colors also bounce interior light around creating a more comfortable visual environment.

The exterior south elevation of a building with a thermal storage wall creates a design challenge. The outside face of the concrete wall is painted black and is covered with a glass curtain wall. The result is a large semi-reflective black surface area with little or no human scale elements. The large shiny black surface area can dominate all other features of the design.

Solar greenhouses come in two basic variations. One has a concrete thermal storage wall that separates the greenhouse from the house (Figure 14.10). The greenhouse heats up during the day, the thermal storage wall heats up and passes the heat with a time delay to the interior of the house. The other version has a lightweight insulated wall between the greenhouse and the interior of the house. The heat from the greenhouse is transferred to the house through natural or forced convection. The thermal mass to stabilize temperatures from day to night is located in the house, usually the floor. The glass area of the greenhouse should be approximately 30 to 60 percent of the floor area of the rooms in the house adjacent to the greenhouse.

The *Passive Solar Energy Book* suggests 65 to 150 percent of the floor area of the house in greenhouse glass area for cold climates, and 35 to 90 percent of the floor area of the house in greenhouse glass area for temperate climates (Mazria 1979, 173).

The *California Energy Commission Passive Solar Handbook* suggests 10 to 50 percent of the area of the house in greenhouse glass area, and it suggests 60 to 160 percent of the floor area of the greenhouse in greenhouse glass (Niles and Haggard 1980, 284).

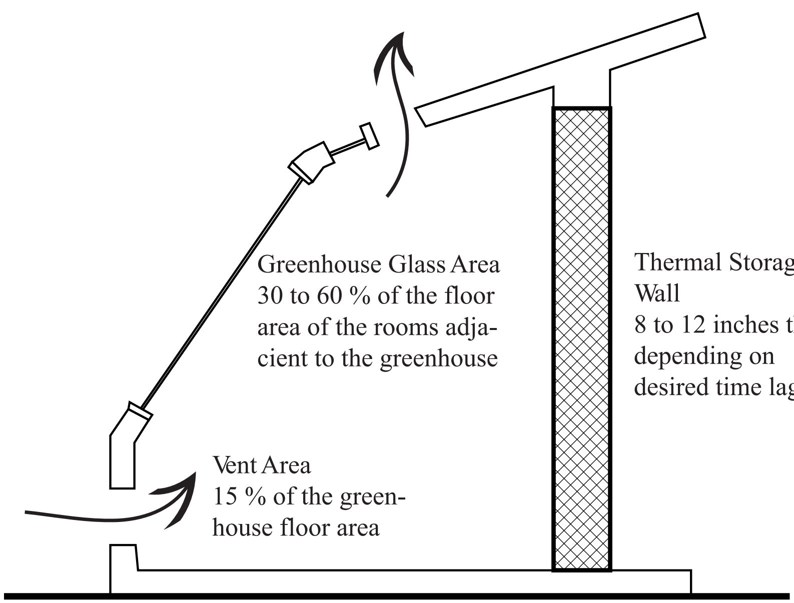

FIGURE 14.10 Passive solar attached greenhouse.

The greenhouse can be used as a sunroom and as a place to grow plants, while it is also providing useful heat for the house. If growing plants is a primary concern, the north wall of the greenhouse needs to be a light color to reflect light back toward the plants. This causes problems with the thermal storage wall version but not with the insulated frame wall version.

A variation on the basic attached greenhouse design discussed above is to use a fan and some ducting to draw warm air off the top of the greenhouse and blow it through a rock bed storage system under the floor of the house. The rock bed will then either radiantly heat the floor above the rock beds, and/or a fan can draw room air across the rock bed to heat the interior air (Moore 1993, 138–139).

Another variation on the attached greenhouse is to create a two story greenhouse on the south side of a house and then design a double roof and double north wall and a plenum under the house to create what is called a double envelope house. In a double envelope house during the day, air is warmed in the southern greenhouse. It rises up through the plenum across the roof. It starts to cool. As the air reaches the back wall, it cools and drops down the back wall and returns to the greenhouse through the plenum under the house. This slowly heats the ground under the house. At night, the flow reverses. The greenhouse will be colder than the plenum on the north side of the house because the greenhouse is mostly glass and the north plenum is a double insulated wall with a few windows. Thus, air will drop on the greenhouse side and be warmed by the soil under the house and then rise up the north plenum returning to the greenhouse through the plenum over the roof. The daytime and nighttime flows of air create a milder temperature surrounding the house than the outside air temperature.

Another form of passive solar system is to set up a collector that warms air and is located below the level of the house. A rock bed is used to store heat for use during the night and through cloudy periods. Locating the air collector below the rock bed and the rock bed below the house allows natural convection to move the warm air around. Air warmed in the collector will rise up into the top of the rock bed and then fall through the rock bed warming the rocks before returning to the bottom of the air collector. Air can also be delivered directly to the house from the collector if needed during the day. During the night, air will rise through the warmed rocks and flow into the house and the colder return air will drop back to the bottom of the rock bed (Moore 1993, 147–150).

There is potential for the air collector to reverse flow at night and cool down the rock bed. This can be avoided by designing the exterior glazing on the air collector so that the upper edge of the exterior glazing is lower than the inlet and outlet location at the top of the collector (Niles and Haggard 1980, 263).

The addition of a fan to push the air around provides freedom to locate the air collector and the rock bed anywhere. One example of this freedom is to create a glass plenum on the south elevation. Place blinds in the plenum and a rock bed below the floor. A fan can then draw warm air created when the sun hits the blinds through the rock bed under the house and then back to the house where the air can then reenter the glass plenum. Heat can be transferred to the house by radiation through the floor and or by a fan. A fan driven system also has the option of drawing cooling air at night through the rock bed thus providing cooling during summer days.

The vast majority of passive solar buildings are direct gain systems because they are simpler and more straightforward. Thermal mass located as the floor is less expensive than thermal mass in a wall, which requires more structural reinforcement.

15

PASSIVE COOLING

Passive cooling is more difficult than passive heating. It is easier to insulate a house to hold on to internal heat when it is cold outside and then let in a controlled amount of solar gain to be stored in thermal mass. Passive cooling requires a method to take heat out of a house when it is warmer outside than it is inside.

Passive cooling opportunities can be explored through the use of the bioclimatic chart (Figure 15.1). An overlapping array of cooling methods is plotted out above the comfort zone. The area of the chart that is above the comfort zone labeled natural ventilation provides the easiest and most straightforward method of cooling when the air temperature is above the comfort range. Air motion across a person's skin speeds evaporation from the surface of the skin. The evaporation draws energy off the skin causing a cooling sensation. Air motion can be natural from breezes coming in through open windows or artificial from ceiling fans.

The area of the chart labeled high thermal mass overlaps part of the natural ventilation area and also extends above the natural ventilation area. The area where the high thermal mass overlaps the natural ventilation area calls for ventilating a house at night to cool off the thermal mass of the house and keeping the house open to natural ventilation during the day. The cooled down thermal mass will draw heat by radiation away from occupants, while the air motion cools them by speeding the evaporation of sweat.

As a climate gets very hot and dry the temperature swing between day and night becomes large. This large diurnal temperature swing can be used to cool thermal mass off during the night. During the day the outside temperature is too hot for air motion cooling to be effective, so the house is closed up during the day. The cool thermal mass cools people by radiation exchange and cools the inside air by convection.

Also overlaid on top of high thermal mass and natural ventilation is an area labeled evaporative cooling. When the air is hot and dry, moisture can be added to the air, which causes the air temperature to drop at the expense of raising the

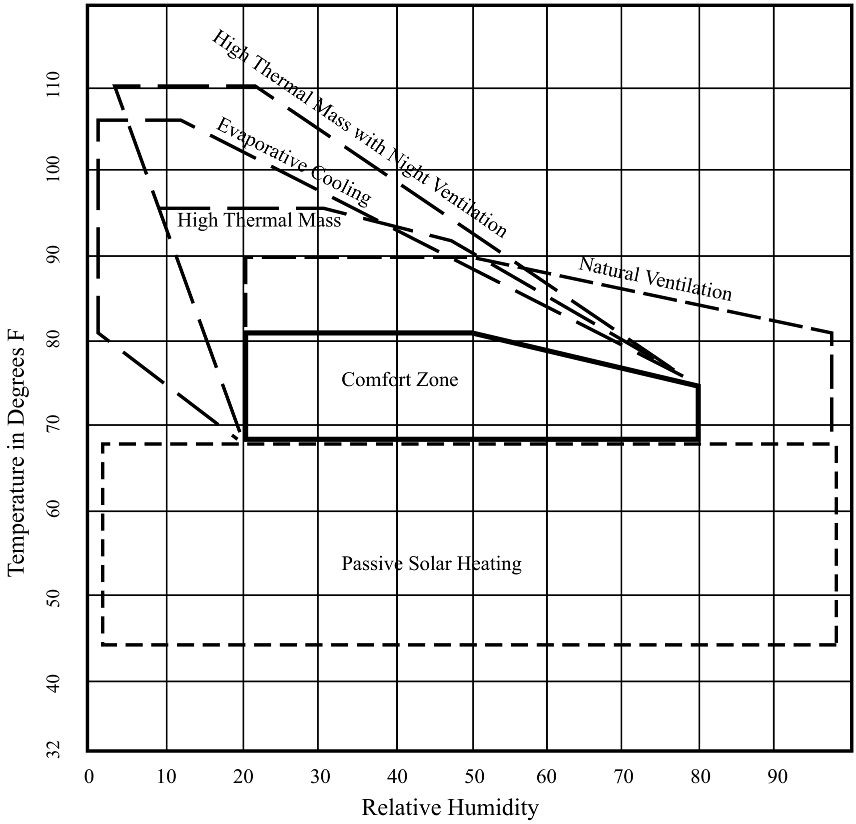

FIGURE 15.1 Cooling strategies are mapped out in the area above the comfort zone on the bioclimatic chart.

Source: Brown and DeKay 2001.

relative humidity. The water vapor evaporating in the air takes energy out of the air molecules causing a decrease in molecular velocity and thus a decrease in air temperature. Evaporative cooling requires air flow through a building. Air flowing in receives the evaporative cooling. Air has to flow out somewhere else for the process to work.

Air flows from high pressure to low pressure and in a relatively open environment, minor obstructions will not substantially alter the general direction of the air flow. However, where there is an urban area with houses and trees close together, or a forested area, the wind speed at the ground will be significantly lower than the reported air speed. Air speed for climate data is usually measured in an open area on a high pole. The air speed near the ground in a built up area will be at best one-third of the reported air speed (Olgyay 1963, 39).

When air flows around an object like a building, it creates a high pressure zone on the upstream side of the building and low pressure zones along the sides, over the top, and especially on the downwind side of the building (Moore 1993, 180).

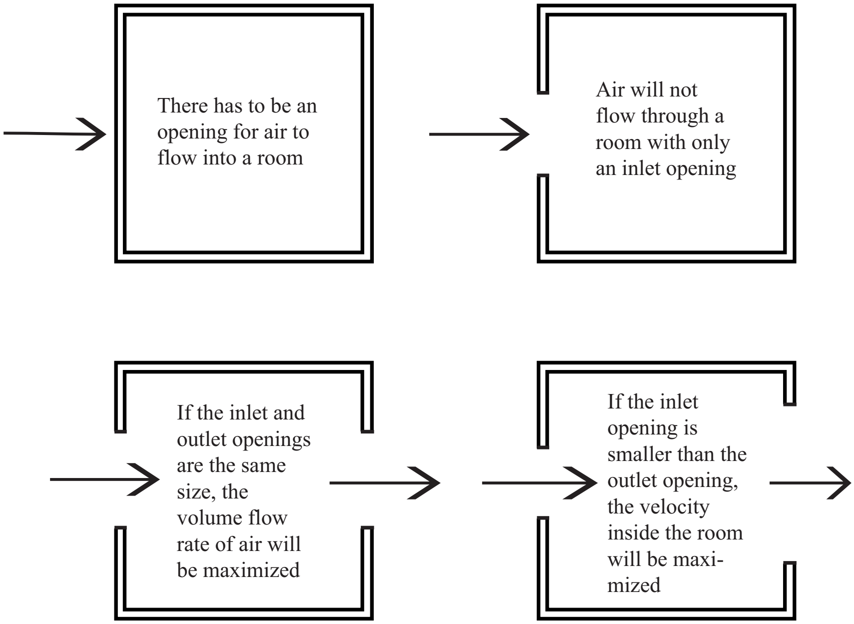

FIGURE 15.2 Ventilation cooling requires inlets and outlets for air to flow.

Air flows through a space from the high pressure side toward the low pressure side as long as there are openings to let the air in on the high pressure side and let it out on the low pressure side (Figure 15.2). Maximum air flow volume happens when the inlets and outlets are of equal size. Maximum air speed inside the space happens when the inlets are smaller than the outlets (Olgyay 1963, 104–105). The faster the air speed across a person's skin, the larger the evaporation of sweat, and thus the larger the cooling sensation. Since ventilation cooling functions by increasing evaporation off skin surfaces, as the humidity gets high, ventilation cooling becomes less effective.

Inlets and outlets that are on adjacent walls should be spread as far apart as possible to create air flow throughout the entire space. Inlet and outlet windows located close to one corner of a room will localize the ventilation effects near that corner, thus not providing air motion cooling relief in the rest of the room.

Air motion provides its cooling effect by evaporating sweat off of skin surfaces. Thus the air flow must be at occupant level in a room (Figure 15.3). The location of the inlets determines how the air motion travels through a room. Low inlets will cause air to flow across people in the room. High air inlets will cause the air to flow over the heads of the people in the room resulting in a much reduced cooling sensation. The location of the outlet has almost no effect on the air flow path through the room (Olgyay 1963, 108–109).

In an ideal situation the wind comes from a consistent direction during the warm months when ventilation is desirable. In real situations the wind direction is not

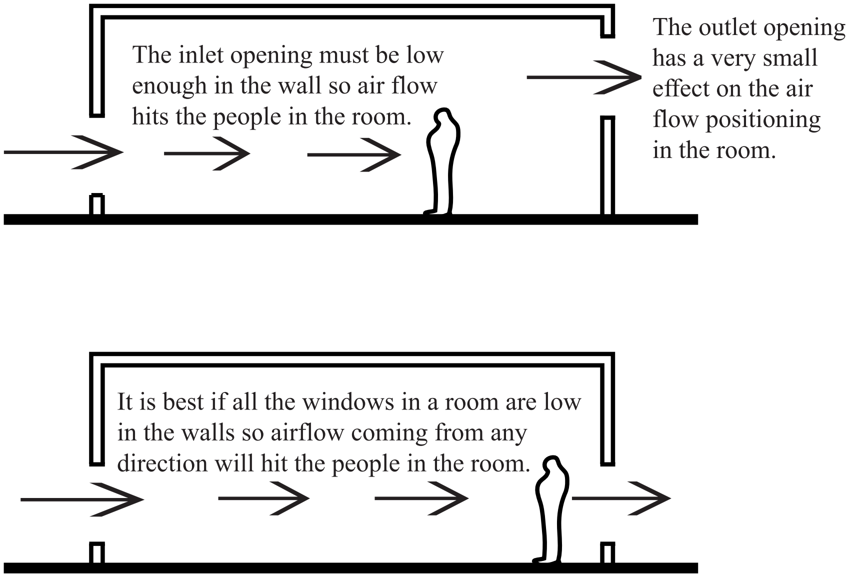

FIGURE 15.3 Window openings need to be low enough so the air flow is at the people level. Air flow evaporates moisture off of skin surfaces creating a cooling sensation.

predictable. The design solution is to have operable windows on multiple sides of every space so the occupants can open inlet and outlet windows as necessary. Double hung and sliding windows can only approach 50 percent open. Awning windows can approach 75 percent open. Casement windows can approach 90 percent open.

Sometimes it is not possible to have inlets and outlets on different walls. In the case where there is only one wall exposed to air motion, casement windows swung in opposite directions from the inside jambs of two windows spaced as widely apart as possible will cause air to circulate through the space (Figure 15.4).

Warm air expands and is thus lighter than colder air, so it rises. Stack ventilation uses this to move air out of a building (Figure 15.5). As long as there is a height difference between the lower and upper openings and the average temperature of the air in the building is warmer than the air outside the building, air will move up and out the upper openings. This can provide ventilation when there is no wind speed. It is important to remember that for the stack to work the average inside temperature has to be warmer than the outside temperature. A 3 degree Fahrenheit difference will cause flow. Thus stack ventilation will never make the air in the house cooler than the outside air. This is also true of wind driven cross ventilation. The best either cross or stack ventilation can do is approach the outside temperature inside the building. The average temperature inside the building stack can be boosted by solar heating part of the stack. This will create air in the stack that is significantly higher than the outside air, which will increase the air flow out the stack.

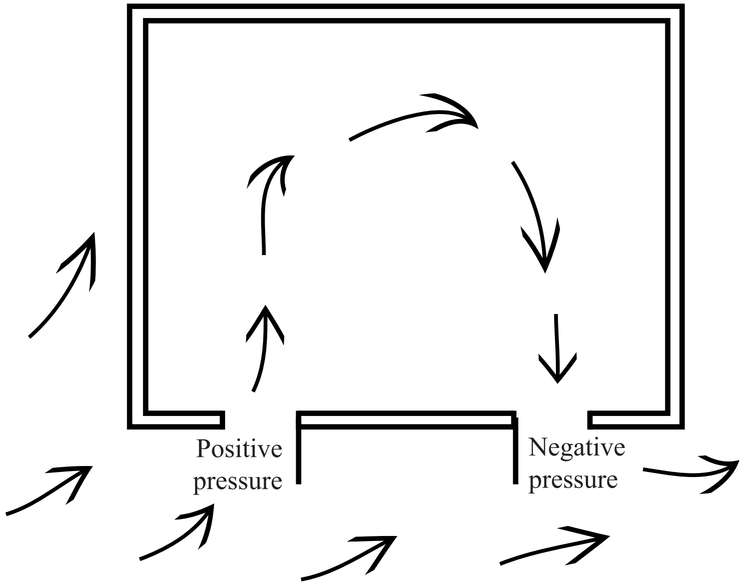

FIGURE 15.4 Casement windows can create air flow into and through a room with openings on only one side.

Source: Moore 1993.

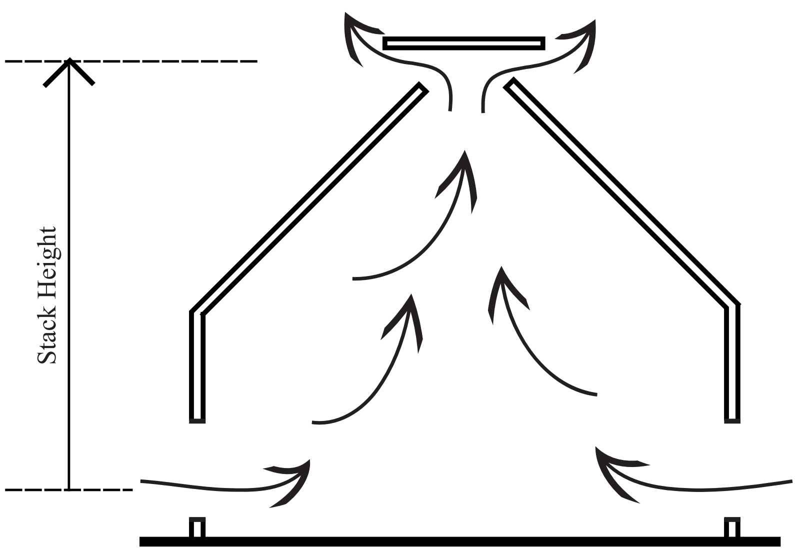

FIGURE 15.5 Stack ventilation requires high and low openings and is driven by the air inside being warmer than the air outside.

In dry inland climates there is a large temperature change from day to night. In these environments the cool night air can be brought through a building with internal thermal mass. The thermal mass will be cooled down to approach the minimum night time temperature. Then during the day the cool thermal mass will provide cooling by radiation exchange with the people in the space and by convectively cooling the air in the space (Figure 15.6).

The air flow can be driven by cross ventilation, stack ventilation, or fan powered ventilation. A higher thermal mass building needs less diurnal temperature swing between night and day. However, a higher diurnal temperature swing provides faster night cooling, which translates into a smaller air flow rate to do the job. An average mass building has an exposed thermal mass floor or the equivalent thermal mass in walls. A high mass building has twice the amount of thermal mass.

In very hot climates, night ventilation is used to cool down the interior thermal mass, and then during the day windows are kept closed to hold on to the cool stored in the walls (Figure 15.6). In the evening the interior space will be warmer than the cooling off outside air (Figure 15.7). The traditional response to this

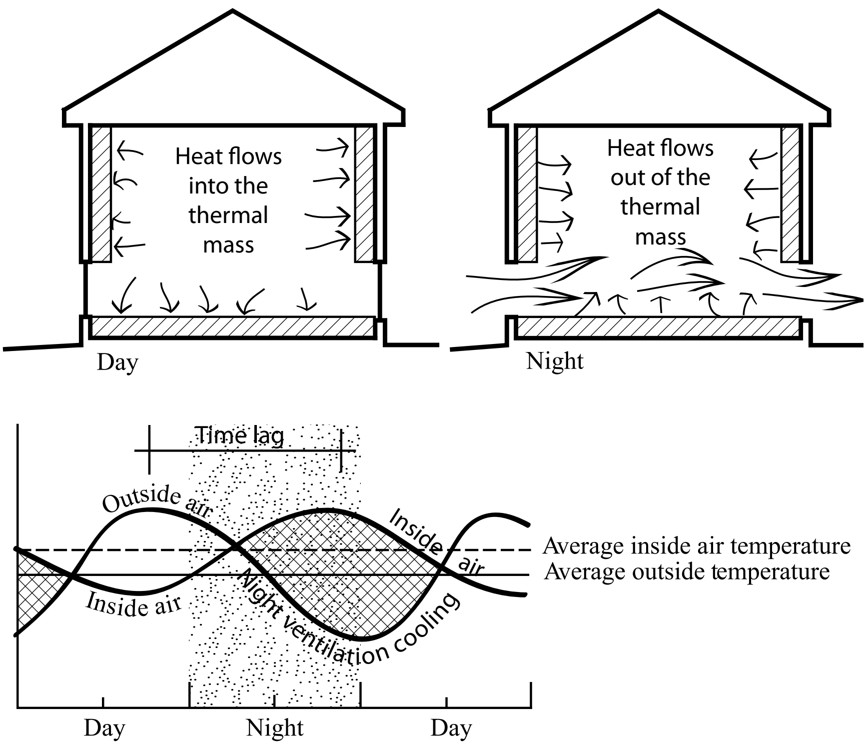

FIGURE 15.6 Night ventilation cooling brings in cool night air to cool interior thermal mass, which then cools the interior during the day.

Source: Moore 1993.

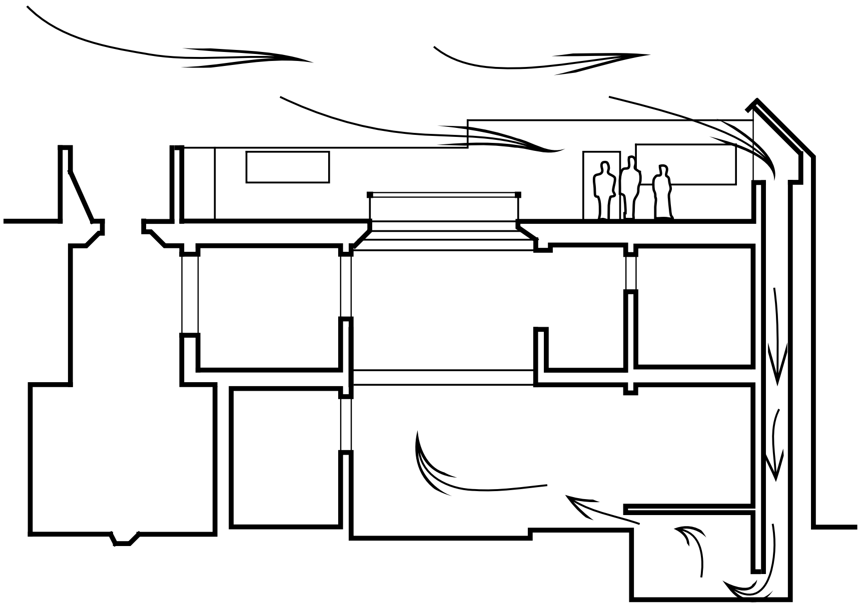

FIGURE 15.7 During the evening and through part of the night the interior of a night ventilated house will be warmer than the air outside. The traditional solution is to go outside on the roof.

Source: Brown and DeKay 2001.

situation is to have a light weight upper floor open to the night breezes to use in the evening and at night (Figure 15.7).

In milder climates, after the interior thermal mass has been cooled down, the windows are left open during the day to take advantage of the cooling effect of air motion as well as the cooling effect of the radiant exchange with the cool thermal mass. The radiant exchange will be higher if the thermal mass is on walls as well as floors. This climate situation is located on the bioclimatic chart where high thermal mass overlaps natural ventilation.

Ground source cooling is a form of high thermal mass cooling. As one goes deeper into the ground the ground temperature approaches the annual average air temperature. Thus, an earth-sheltered building is exposed to milder conditions than a building completely above the ground. Three feet into the ground, the ground temperature is 5 degrees Fahrenheit below the air temperature, and one month out of phase with the air temperature. Six feet into the ground, the ground temperature is 12 degrees Fahrenheit below the air temperature and two months out of phase. The ground temperature trails the air temperature. In winter, the ground temperature will be above the air temperature and also out of phase with the air temperature (Moore 1993, 211–213).

In underground construction it is important to add insulation to the underground walls either inside or outside. The insulation raises the wall surface temperature above the dew point so moisture will not form on the surface. Insulation on the outside of the concrete wall needs to be closed cell insulation board so moisture will not compromise it. Insulation on the inside of the concrete wall needs a vapor barrier on the inside of the wallboard that covers the insulation. This keeps interior moisture out of the insulation (Moore 1993, 214).

In climates with low humidity, heat can be rejected by radiant exchange with the night sky. The low humidity is important because humidity and clouds block infrared radiant exchange with the sky. One mode of capturing this radiant exchange is to run water over a metal roof exposed to the sky and then use the cooled water to cool interior thermal mass, or store the cool water to use during the day in a fan coil unit to cool interior air (Moore 1993, 195).

Another method developed by Harold Hay, in Atascadero, California, is to place water beds above a corrugated steel ceiling. Then provide movable insulation above the water beds. In the cooling season the water beds are exposed to the night air and sky, which cools the water. During the day the insulation covers the water beds, which provide a cool ceiling that cools people inside by radiant exchange and by cooling the air by convection. In the heating season the operation is reversed, heating the water beds during the day and covering them during the night. The water beds need to cover the entire ceiling (Moore 1993, 197–198).

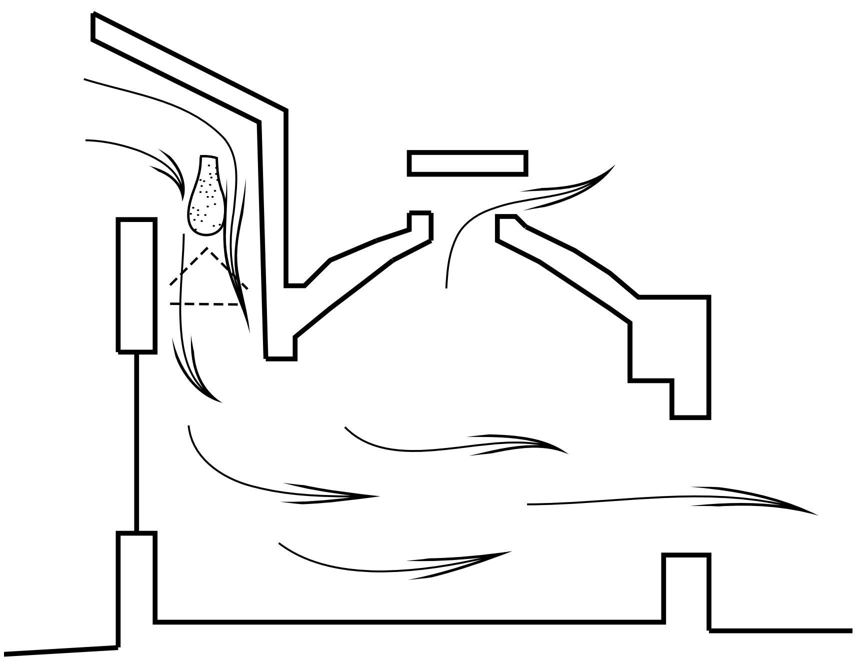

FIGURE 15.8 A cool tower in a Hassen Fathy designed school. A cool tower introduces water at the top of a tower, which cools the air with evaporation; then the air drops down the tower to cool the spaces below.

Source: Moore 1993.

Evaporative cooling is effective where the air temperature is hot and the humidity is low. Evaporative cooling adds water, usually in small droplets, to an air stream entering a space. The water droplets evaporate, which takes sensible heat out of the air lowering the air temperature and increasing the relative humidity. This is a good trade off in a hot dry climate. The air has to flow through the house. As much air is exhausted from the house as is drawn in and cooled by evaporation. This is traditionally done with a large fan.

Another form of evaporative cooling that does not need a fan is a cool tower (Figure 15.8). A cool tower is a hollow tower open at the top. Water, again in the form of small droplets, is sprayed in near the top of the tower. The water evaporates cooling the air, which is now heavier than the surrounding air, and thus drops down the tower creating a flow of cooled air to the space below. Of course there need to be openings from the space being cooled for the air to exhaust to the outside (Brown and Dekay 2001, 194–195).

In conclusion, the most commonly used passive cooling method is air flow driven by wind in cross ventilation, by temperature difference in stack ventilation, and by electricity in ceiling fans and whole house fans. This can be aided by evaporative cooling and thermal mass cooled by night ventilation.

16

EMBODIED ENERGY AND THERMAL MASS

Sustainability is the careful use of resources to accomplish the fulfilment of current needs so that there will be resources remaining to accomplish the fulfilment of future needs. Easter Island is one of the most remote places on earth. It is 1,400 miles from the main part of Polynesia to the west and 2,300 miles from Chile to the east. Polynesians settled the island around 400 AD. The 64 square mile island was covered with a forest of palm trees. The population of the island grew, and the culture prospered. The Easter Islanders produced spectacular statues as part of their religious observances that they sculpted from volcanic stone and then transported the statues to sites near the water by rolling them on tree trunks. Along with other uses of the palm trees on the island, this practice eventually used up all the trees on the island. As the population exceeded resources and there were no trees to create boats and rafts to move on to other islands, a population crash reduced the once thriving culture to a primitive few survivors (Van Tilburg 1994, 50–53). One wonders, when the islanders cut down the last few trees, what were they thinking? Would we do such a thing?

This is a cautionary tale. The Easter Islanders did not use their resources in a sustainable manner. The combination of deforestation and isolation trapped them on their small island. With no escape and resources used up, the society and the population crashed into a primitive state. The Earth is our island. There is no effective escape to another Earth.

The decisions we make about construction are not unrelated to slowly cutting down all the trees on Easter Island. A simple choice between wood panel interior doors versus flush interior doors is a choice between 800,000 Btu/panel door versus 400,000 Btu/flush door in embodied energy. Which do you choose? Another example is tempered glass versus regular annealed glass. Tempered glass is stronger against breakage, and when it does break it falls apart into many glass granules. Annealed glass is not as strong and it breaks into shards of various sizes that can cut people badly. The building codes require tempered glass in doors and in windows that have sills below 18 inches from the floor. These requirements are to protect people from danger. Regular one-eighth inch annealed glass has an embodied energy of 35,000 Btu/square foot. Tempered glass is made from annealed glass by reheating annealed glass that has been cut to the appropriate size and then quick cooling it. The result is a glass with tension stresses on the surfaces of the glass, which gives tempered glass its strength and granular breaking characteristics. Tempered glass has about double the embodied energy of regular annealed glass, 70,000 Btu/square foot. An architectural choice to extend windows sills below 18 inches is comparable to the Easter Islanders' cutting down the palm trees for the important job of rolling religious statues down from the quarry to sites near the water.

In thermodynamic calculations a control volume is mentally constructed around the process that is being studied. Then energy and mass flows entering and leaving the process can be accounted for using the first and second laws of thermodynamics. This is a useful procedure to apply to a passive solar design in order to include embodied energy along with annual energy use in design decisions. Decisions about the embodied energy of material choices like doors and glass can be made in a fairly straightforward way as long as the embodied energy information is known. However, a decision about how much thermal mass to use in a passive solar design involves both embodied energy and annual energy use. Likewise the balance between insulation levels and passive solar involves embodied energy and annual energy use.

The *Passive Solar Handbook* published by the California Energy Commission documents Calpas computer energy simulations for a 2,000 square foot house in various climate locations around California. Heating energy use variations caused by area of south glass and surface area of thermal mass for two levels of insulation for the house are presented in the handbook (Niles and Haggard 1980, 18–38).

The embodied energy of 1,000 square feet of four inch concrete with a quarry tile surface is 83 million Btus. The embodied energy of 1,000 square feet of wood frame floor with a hard wood surface is 18 million Btus. The difference is 65 million Btus. The 65 million Btu number is the additional embodied energy of 1,000 square feet of thermal mass floor over the choice of a wood frame floor.

Data from two locations was used to compare yearly heating energy savings from passive solar with the embodied energy in the concrete thermal mass necessary to achieve the savings (Table 16.1). Santa Maria, in the central coast of California, has a very mild climate (Niles and Haggard 1989, 120–121). Alturas, California, in a northern mountain location, has a much colder climate (Niles and Haggard 1980, 94–95). Dividing the annual passive solar heating energy savings into the embodied energy of the concrete thermal mass provides the years of annual energy savings needed to payback the embodied energy in the thermal mass.

The years to energy payback are all reasonable numbers until a closer look shows that the first 1000 square feet of thermal mass saves 21 million Btus per year, but the addition of another 1,000 square feet of thermal mass only adds a few more Btus of savings. It would be more accurate to compare the marginal energy saving benefit of adding additional thermal mass (Table 16.2).

TABLE 16.1 Simple energy payback of the embodied energy in concrete thermal mass, with the yearly energy savings from a direct gain passive solar heating system

Thermal mass area (sq ft)	*Embodied energy (MBtu)*	*Yearly energy savings (MBtu)*	*Years to energy payback*
Santa Maria, California, 300 sq ft of south glass			
1,000	65	21	3.1
2,000	130	23	5.7
4,000	260	25	10.7
Alturas, California, 300 sq ft of south glass			
1,000	65	21	3.1
2,000	130	25	5.2
4,000	260	28	9.3

Source: Niles, Philip, and Kenneth Haggard. 1980. *The California Energy Commission Passive Solar Handbook*. Sacramento, CA: The State of California Energy Resources Conservation and Development Commission. Pages 95 and 122.

TABLE 16.2 Marginal energy payback of the embodied energy in concrete thermal mass, with the yearly energy savings from a direct gain passive solar heating system

Thermal mass area (sq ft)	*Embodied energy (MBtu)*	*Yearly energy savings (MBtu)*	*Years to energy payback*
Santa Maria, California, 300 sq ft of south glass			
1,000	65	21	3
2,000	130	2	33
4,000	260	2	65
Alturas, California, 300 sq ft of south glass			
1,000	65	21	3
2,000	130	4	16
4,000	260	3	43

Source: Niles, Philip, and Kenneth Haggard. 1980. *The California Energy Commission Passive Solar Handbook*. Sacramento, CA: The State of California Energy Resources Conservation and Development Commission. Pages 95 and 122.

The payback on the embodied energy in the concrete and quarry tile floor beyond the first 1,000 square feet jumps up dramatically. It jumps up faster in the Santa Maria case because there is less heating energy to save in this mild climate.

A graph of the marginal annual heating energy use versus the years to payback the embodied energy in the concrete thermal mass necessary to create the savings presents the data more clearly (Figure 16.1). Note the diminishing return of adding

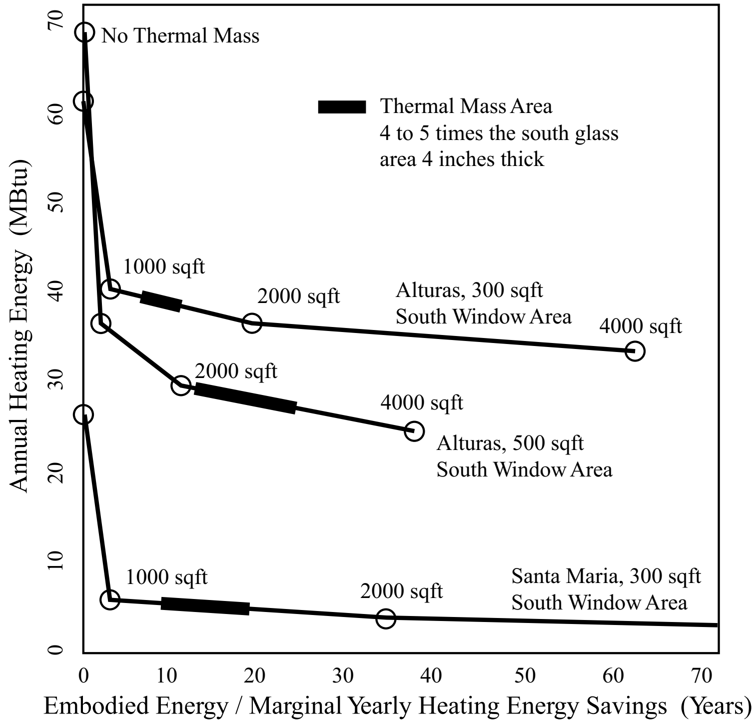

FIGURE 16.1 Marginal embodied energy payback times in years for concrete thermal mass used in a direct gain passive solar heated house in Alturas, California, heating degree days 6,553, and in Santa Maria, California, heating degree days 2,773.

excess thermal mass. The rule of thumb to provide four to five times the window area in thermal mass four inches thick is reinforced by this analysis. Four to five times 300 square feet of glass is 1,200 to 1,500 square feet of thermal mass area. This suggested thermal mass area is located on the curves at the beginning of the point of diminishing returns. Installing more thermal mass than this is a waste of the embodied energy involved.

The insulation level on the Alturas house can be increased reducing the heat loss rate from 600 Btu/Hr-F to 400 Btu/hr-F. The additional insulation has an embodied energy of 40 million Btus. The curve of marginal heating energy use versus embodied energy payback for the better insulated house starts out lower and slightly to the right because the insulation saves energy but does cost some embodied energy. It is clear in this comparison that insulation pays back its embodied energy much faster than passive solar pays back embodied energy (Figure 16.2). A sustainable society needs to pay attention to efficiently using its resources, in this case the embodied energy in thermal mass.

In their book *Five Degrees of Conservation*, Lance LaVine, Mary Fagerson, and Sharon Roe compare the cost benefit of five different houses in Minnesota. They studied a moderately insulated house, a super insulated house, a partially

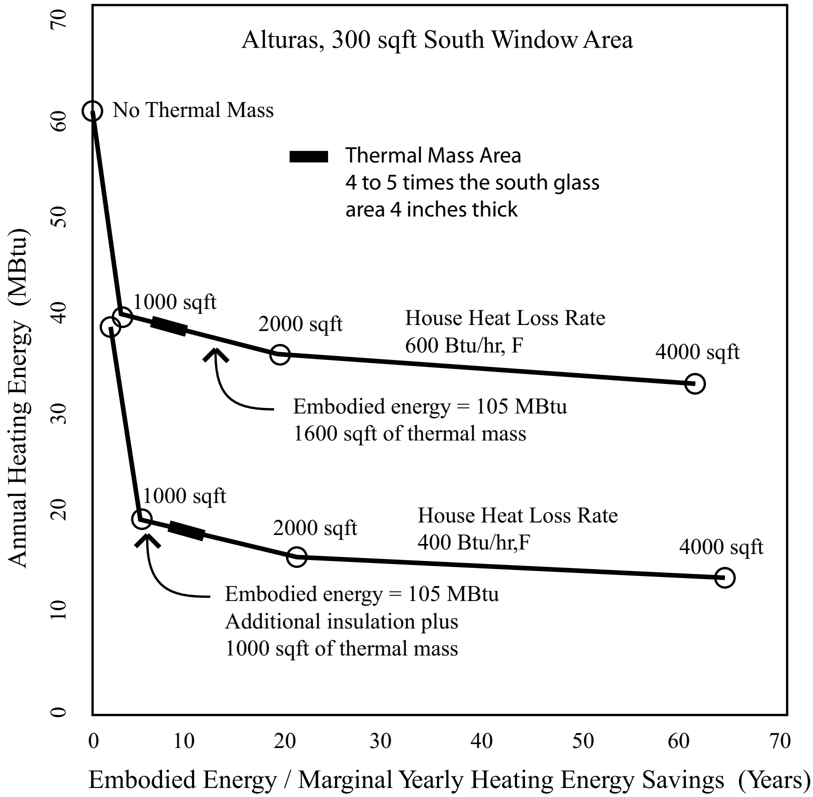

FIGURE 16.2 Marginal embodied energy payback times in years comparing using more concrete thermal mass, with using higher levels of insulation for a solar heated house in Alturas, California, heating degree days 6,553.

underground passive solar house, a double envelope house, and a house with both active and passive solar. Their results in order of cost effectiveness were as follows. The super insulated house cost \$23 per 10 million Btus saved. The moderately insulated house cost \$42 per 10 million Btus saved. The double envelope house cost \$76 per 10 million Btus saved. The partially underground passive solar house cost \$391 per 10 million Btus saved. The house with both active and passive solar cost \$398 per 10 million Btus saved (LaVine et al. 1982, 60).

These results clearly indicate that the most cost effective way to reduce energy use in houses is to insulate them very well. Adding complicated passive and active solar features decreases the cost effectiveness of the houses.

The embodied energy and cost effective analysis presented above indicate that high gain (large glass area and lots of thermal mass) passive solar doesn't make sense. The fact that insulation is considerably more efficient at saving energy than high gain passive solar is an opportunity to apply more sophisticated low gain passive solar. Make sure the sun comes into the kitchen and breakfast area in the morning.

Also provide morning sun in the master bedroom to provide a gentler wake up than an alarm clock. In addition an eastern location for the master bedroom provides a cooler environment for sleep at night. The living room and or the family room are mid-day uses and thus should have mid-day sun. The dining room, an evening use, can benefit from western light. All of these low gain passive solar features can be handled with a modest glass area and a modest amount of thermal mass since the thermal insulation is doing most of the work.

17

HIGH INSULATION LEVELS

Conventional platform framing with insulation bats filling the open spaces between the 2 × 4 stud framing leaves multiple thermal bridges through the wood framing to the outside (Figure 17.1). Each stud reaches all the way through the wall. The framing around windows and doors reaches all the way through the wall. The sill plates reach all the way through the walls and often insulation is not placed against the band joists. Ceilings are usually insulated at a higher level than floors and walls. The heat losses from a typical house are as follows: infiltration, 26 percent, floors, 28 percent, windows, 20 percent, walls, 14 percent, roof, 11 percent, and doors, 1 percent (Nisson and Gautam 1985, 38).

The framing around doors and windows provide air gaps between the inside of the house and the outside. These gaps, especially the gaps between the rough framing and window and door frames, need to be filled with sealant to minimize air leakage. It is also important to put a bead of sealant on sill plates to limit air leakage. The most overlooked air leakage problems are openings through the ceiling into the attic. Recessed light fixtures, attic access hatches, pluming pipe and HVAC vents need to be sealed. The ceiling surface should be extended from plate to plate with any dropped soffits added later to avoid a large heat loss path to the attic.

Air infiltration heat loss in a well-insulated and sealed house causes about one quarter of the heating needs. Infiltration heat losses come from the following places (Figure 17.2): sills at the ceiling and floor, 31 percent, HVAC, 15 percent, fireplace, 14 percent, pipes, 13 percent, doors, 11 percent, windows, 10 percent, vents, 4 percent, and electrical outlets, 2 percent (Nisson and Gautam 1985, 42). Note how much air infiltration happens at the sill plates where the wall meets the floor and the ceiling. Also note how much air leakage happens through a fireplace even with the flue closed. If one leaves the flue open the air leakage will increase. The air leakage through a fireplace dramatically increases when there is a fire in an open fireplace. The fire creates a thermal draft drawing heating system warmed

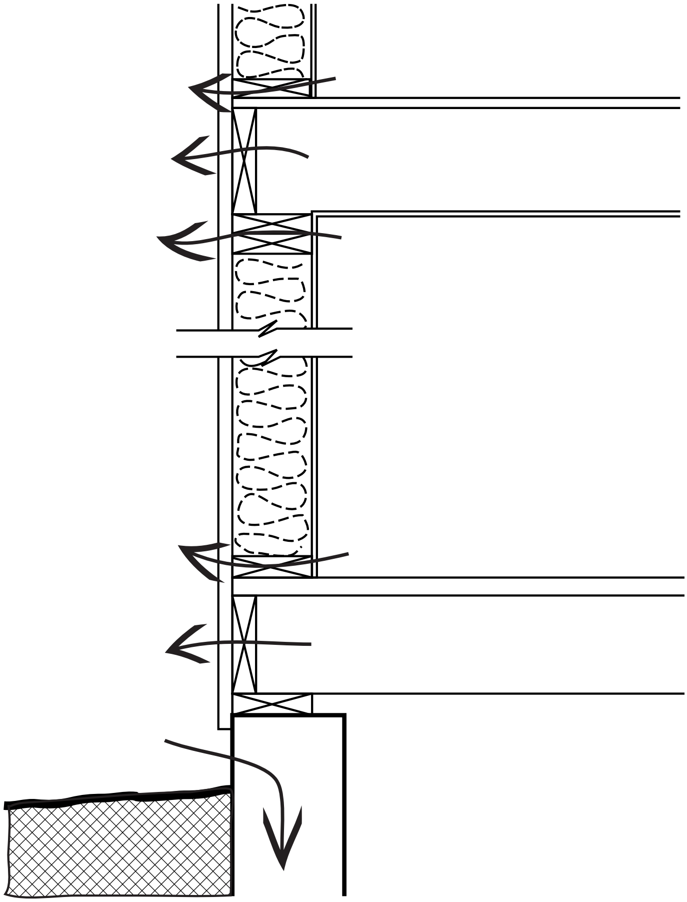

FIGURE 17.1 Thermal bridging in traditional platform framing.

air out of the house which will suck outside cold air in through cracks around windows, doors and through sill plates. A fireplace with glass doors, access to outside combustion air, and a path for room air to circulate behind the steel fire box and back into the room will add heat to the room.

Sealing up all the cracks around windows, doors, sill plates, and openings through the ceiling caused by light fixtures, pipes, dropped soffits, and access hatches can cause a house to be sealed too tightly. The answer is to install an air-to-air heat exchanger to bring in outside air. The most effective heat exchangers are counter flow, where the outside air is flowing in the opposite direction to the inside air. This creates a constant temperature difference between the two air flows, which maximizes the heat transfer.

High levels of insulation are easier to achieve with simple shapes. Corners are harder to insulate than straight walls. Flat ceilings with a vented attic above are easier to insulate to a high level than cathedral ceilings. Cathedral ceilings with

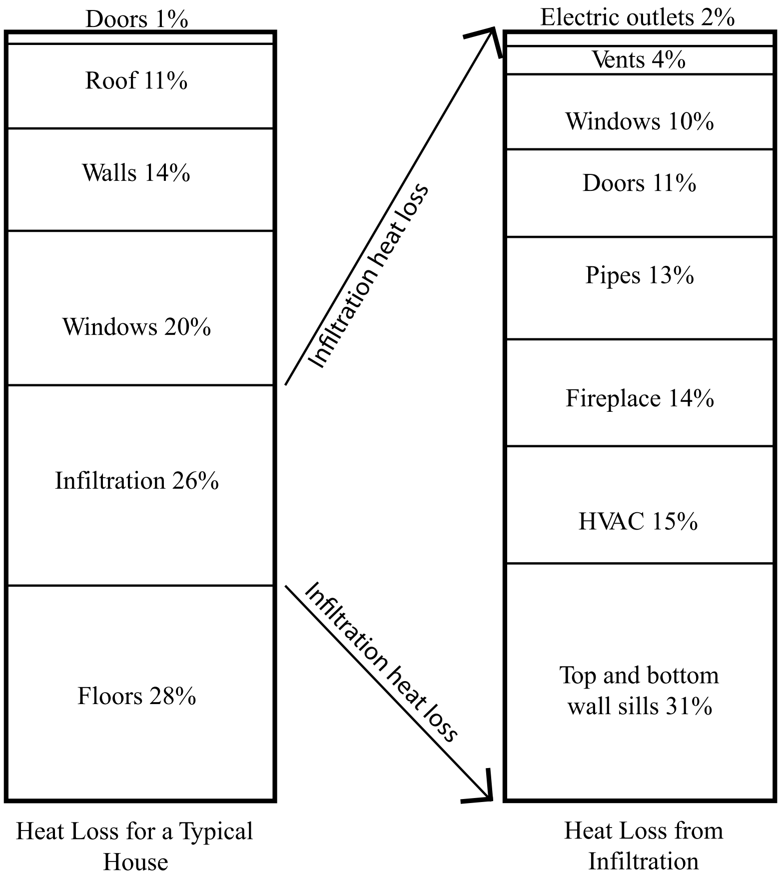

FIGURE 17.2 Heat loss paths for a typical American house.

simple gable shapes are easier to insulate than cathedral ceilings with complex dormer windows added on. (See Figure 17.3 and Table 17.1 for insulation levels by climate zone in the US.)

A two story house with the same floor area as a single story house will have less exposed exterior surface area. However, the single story house is easier to insulate to a high level because it is easier to insulate a ceiling to very high levels than a wall. Single story houses have a higher ceiling to wall ratio (Nisson and Gautam 1985, 69).

Ceilings with vented attic space above are fairly easy to insulate to very high levels. When using batt insulation, use two layers with the top layer placed perpendicular to the batts that are placed between the ceiling rafters. This reduces thermal bridging through the ceiling rafters. R levels (resistance to heat flow) of 50 to 60 (hr, sqft, F/Btu) are relatively easy to achieve. Plastic inserts are often necessary to ensure that air can circulate from the eaves past the insulation into the vented attic above. Cathedral ceilings are best done with trusses. Trusses provide more depth than traditional rafters. The extra depth can contain more insulation while still providing for ventilation above the insulation from the eaves to the ridge (Nisson and Gautam 1985, 142–147).

A typical 2 × 4 stud wall is framed at 16 inches on center with the spaces between the studs filled with fiberglass batt insulation. The resulting insulation level is R-11 to R-15 depending on the batt used. The most straightforward way to increase the insulation levels is to go to 2 × 6 framing which can be insulated to R-19. If 2 inches of rigid insulation is added on the outside of the wall the insulation level becomes R-29, and the thermal bridging of the wood studs is interrupted by the continuous rigid insulation. Using 2 × 8 framing with the cavities filled with batt insulation also produces an R-29 insulated wall. Another way to achieve high insulation levels is to frame a double wall with 2 × 4 studs with a 3.5 inch space between the two stud walls. All three of these spaces are filled with fiberglass batt insulation, resulting in an R-33 wall (Nisson and Gautam 1985, 85). Plywood is necessary to span between the double walls to close off openings for doors and windows and to connect sills and plates. Rough openings need to be sized ½ inch larger than called for to accommodate the ½ inch plywood (Nisson and Gautam 1985, 101).

Basements lose heat primarily through the foundation wall. The basement floor may be cool because the ground underneath is cool but the primary heat loss is through the walls, especially the part of the walls near the surface of the ground. Concrete is a much better conductor of heat than earth, so concrete basement walls should be insulated on the outside of the wall. If the insulation is placed on the inside of the concrete basement wall, winter cold will be conducted down the

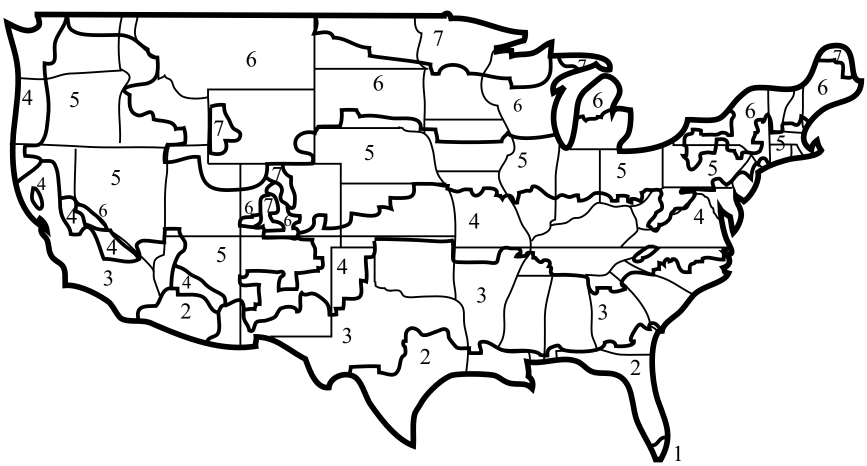

FIGURE 17.3 Map of the United States with weather zones. Thermal insulation levels for these zones are listed in Table 17.1.

Source: U.S. Department of Energy, Tips, Insulation. http://www.energy.gov/energysaver/articles/tips-insulation.

TABLE 17.1 Insulation levels for attics, cathedral ceilings, cavity walls, sheathing, and floors by weather zone

Zone	*Attic*	*Cathedral ceilings*	*Wall cavities*	*Sheathing boards*	*Floor*
1	R30 to 49	R22 to 38	R13 to 15	None	R13
2	R30 to 60	R22 to 38	R13 to 15	None	R19
3	R30 to 60	R22 to 38	R13 to 15	None	R25
4	R38 to 60	R30 to 38	R13 to 15	R2.5 to 6	R25 to 30
5	R38 to60	R30 to 38	R13 to 15	R2.5 to 6	R25 to 30
6	R49 to 60	R30 to 60	R13 to 21	R5 to 6	R25 to 30
7	R49 to 60	R30 to 60	R13 to 21	R5 to 6	R25 to 30
8	R49 to 69	R30 to 60	R13 to 21	R5 to 6	R25 to 30

Source: U.S. Department of Energy, Tips, Insulation. http://www.energy.gov/energysaver/articles/tips-insulation.

concrete wall causing the ground near the wall to be colder than if the insulation were on the outside of the wall. Concrete block basement walls need to be completely filled with grout or concrete. If the hollow spaces of the concrete blocks are left open, convection currents will pump cold air down from where the wall is exposed to the lower parts of the wall, causing excessive heat loss (Nisson and Gautam 1985, 120–123).

18

GREEN MATERIALS

To truly consider the use of green materials it is necessary to think about where materials come from, how they are used, and where they go when their useful life is over. Materials come from the earth or the biosphere. They need to be mined or harvested, transported to a manufacturing location where they are produced, and then transported to a distribution point before being transported to the point of use. All of these processes require energy use and have a waste stream associated with them. At the point of use, the product needs to be installed, which also requires energy and produces a waste stream. During use the product will need maintenance to extend its life, and at the end of its useable life span the product will become part of the waste stream unless it is recyclable (Freed 2008, 76–80). It would be ideal if perfect information about product lifecycle was available for all products. This is generally not the case but the situation is improving.

One way to approach the material choice situation is to consider the following concerns. Can a reclaimed material be used? An example would be flooring materials reclaimed from another building. Is there recycled content in the material? An example would be tiles made with recycled glass. Recycled content can come from the waste stream of a manufacturing process or from recycled consumer products. Is the material sustainably harvested? The best example of this is wood from forests taken in a manner that maintains the forest for future production. Is the material rapidly renewable? A good example of this is bamboo, which is a rapidly growing grass. Is the material durable? A longer usable life reduces the waste stream. Is the material recyclable? Materials are easier to recycle if they are one material not a composite of multiple materials. It is also better if the material can be recycled as the same material. As an example, steel can be recycled as steel. Is the material biodegradable? Most materials made from ecosystem entities, wood, paper, bamboo, will biodegrade if they end up in the waste stream in a landfill (Freed 2008, 84–86). Another consideration is low outgasing of volatile organic compounds (VOCs).

New car smell or new carpet smell is an example of VOCs coming off the new material. Many products can now be purchased with very low VOC outgasing. Finally there is the concept that smaller is better. Living in an appropriately sized house for one's needs saves materials and energy (Bradley 2010, 10–14).

Houses in the U.S. are mostly constructed with a wood frame. The wood should be specified as certified by the Forest Stewardship Council (FSC), which ensures that it was produced in an ecofriendly way. It is important to seal all the openings left between the rough frame openings and the finished doors and windows. It is also important to seal the top and bottom plates. Insulation can be placed between the vertical wall studs, and an insulation board sheathing can be applied to the outside underneath the exterior finish material to minimize thermal bridging through the wood framing. Light gauge steel can be used to frame a house. The construction process is very similar to wood framing with sheet metal screws replacing nails. Steel doesn't require cutting down trees and it is recyclable as steel. Steel's main drawback is that it conducts heat very well, so it is very important to sheath the building with insulation boards to reduce thermal bridging.

Exterior siding can range from wood horizontal or vertical boards, wood shingles, and fiber cement boards, to stucco. Wood siding is a renewable product and, finished properly, will have a long life. Fiber cement boards come in many textures, take paint well, and are very durable. Stucco is a dry concrete mix that is sprayed onto a paper backed wire mesh. Color can be incorporated into the stucco reducing the need for paint (Bradley 2010, 153).

Alternative methods of residential building would include rammed earth, which is earth mixed with some cement that is pressed into wooden forms to make a solid wall. The walls are about a foot thick, which provides thermal mass but not much insulation. Insulation can be added to the exterior and then covered with stucco. A similar thickness wall can be made with adobe bricks. A wall that has similar thickness and a high insulation value can be constructed with straw bales. Straw bale houses are usually framed with timbers using the straw bales as infill. The outside is covered with stucco and the inside with plaster (Bradley 2010, 150–152).

Roofing should be relatively light in color to help keep the house cool in summer. Asphalt shingles are a common choice because of the price, durability, and fire resistance. Wood shingles also provide durability but are not fire resistant. Metal roofing has great durability and can aid in water collection. Tile roofs also have great durability but have high embodied energy because the tile needs to be fired (Bradley 2010, 155).

Floors can be covered in many materials. Wood is durable, and when it comes with a Forest Stewardship Council label (FSC) it is a sustainable choice. Solid unfinished wood floors will need to be sanded and finished. Engineered wood flooring comes prefinished so there will be no outgasing from the stains and sealers necessary for an unfinished floor. Look for adhesives without formaldehyde. Bamboo is a grass that grows to usable size in about 5 years. However, bamboo primarily comes from Asia so there is a transportation cost. Bamboo can be solid, a solid surface engineered on a backing board, or shredded and glued together on a backing board. The solid bamboo products are more durable. Cork comes from the cork oak tree which grows in Mediterranean regions. Cork is the bark of the tree and is harvested on a 9-year cycle without hurting the tree. Modern cork flooring comes prefinished and often is an engineered product with a backing board. Engineered floor products should use formaldehyde free glues. Laminate flooring is high density particle board with a thin layer of wood veneer or other material with the image of wood on it. Laminate flooring cannot be refinished, and there are issues with the use of formaldehyde glues in the particle board. Linoleum is made from linseed oil, cork dust, tree resins, and limestone, with natural pigments. It comes in tiles and sheets and can be glued down or floated. Unlike vinyl, which is made from poly vinyl chloride, linoleum when it becomes part of the waste stream will decompose and will not add toxins to the environment. Rubber tiles come in many colors, are excellent in wet areas like laundry rooms, and are often made from recycled tires. Tile floors provide an almost unlimited choice of color and design. Ceramic tiles require firing which uses energy. Concrete tiles use less energy to produce. Tiles are also available that incorporate recycled material: the most common are tiles that incorporate recycled glass. The grout between the tiles should be sealed. Two floor options that apply to new slab on grade construction are terrazzo and stained concrete. Terrazzo is concrete with small pieces of colored stone incorporated in the concrete. After setting, the terrazzo floor is polished to a smooth surface. A concrete floor can be stained to a desired color and then waxed. Carpet is the most popular floor covering. Most carpet is made from synthetic materials such as nylon or polyester. New carpet smell is the outgasing of VOCs from the carpet and underlayment. Wool carpeting is a more ecofriendly choice. Carpet of any kind is harder to keep clean than solid flooring like wood or linoleum (Bradley 2010, 30–45).

Most interior walls and ceilings in residential construction are sheathed with gypsum board. Gypsum board has a core of gypsum plaster surfaced with paper on both sides. A fair amount of gypsum board ends up in the waste stream during construction, but there are no toxic components involved, and if separated at the job site it can be recycled into new gypsum board. Often the paper containing the gypsum core is a recycled product (Freed 2008, 91).

Interior walls can be finished with paint, wallpaper, wood paneling, and or tiles. Paint is the most common wall finish. Water based, latex paint has a much lower VOC rating than oil based paints and cleanup is possible with soap and water. In addition, most paint manufacturers now offer low and no VOC paint. Wallpaper is another way to finish an interior wall. Unfortunately most commonly used wallpaper is paper backed vinyl. Vinyl is not ecofriendly and moisture may get trapped behind the wallpaper causing mold growth. There are vinyl free wallpaper choices available. Also, choose low VOC adhesives. Wainscot and paneling is often wood, which should be FSC certificated and finished with low VOC stains and sealants. Tiles can also be applied to walls. The same eco concerns expressed for floor tiles apply to tiles on a wall (Bradley 2010, 48–57).

Cabinets should last a long time. Particleboard and medium density fiberboard (MDF) are not very durable and do not stand up to moisture well. Plywood is a more durable choice and can be specified without formaldehyde glues. Cabinet doors can be made of solid wood or plywood and can be finished with low or no VOC paint, stain, and sealant. A natural oil finish can also be used. The oil protects the wood against moisture, and damaged spots can be retouched fairly easily (Bradley 2010, 74–78).

Countertops need to be strong and handsome. Granite is a popular countertop material. However, most stone sold in the United States comes from overseas and thus has a large transportation footprint. Composite counter tops are made from recycled glass, porcelain, or stone in a concrete binder. When ground up quartz or glass are set in a polymer the result is a durable low porosity surface. Some of these composite counter tops can rival granite in appearance. Wood can make a good looking counter top. The wood needs to be sealed and can be resurfaced. Stainless steel produces a surface that is easy to clean and very durable. Stainless steel is also recyclable as stainless steel, so it is ecofriendly. Ceramic tiles make a durable surface, but the grout between the tiles can be a problem (Bradley 2010, 80–91).

In conclusion, the consumer should ask, *Is the material reclaimed, recycled, sustainably harvested, rapidly renewable, and does it have low VOCs?* There is a growing list of certification programs that can help in making green choices. The Carpet and Rug Industry has a Green Label Plus. The Forest Stewardship Council certifies that wood was sustainably harvested. Greenguard provides standards for low VOC materials. Green Seal tests paints, household cleaners, and window products for environmental quality.

PART IV

The Commercial Scale

At the commercial scale, buildings are larger and their energy use is less dependent on the exterior environment. The United States Green Building Council's LEED rating system for new commercial buildings provides a good overview of the important features to consider, from site selection, through water conservation, to energy usage, materials, and indoor air quality. The energy efficient design of a commercial building requires multiple focused computer runs to point the design in the right direction and find optimum solutions to specific design issues. In most of the United States, heating and lighting are the major energy users that can be dramatically reduced. Heating energy is reduced by insulation and high quality windows. Lighting energy is reduced by daylighting and careful artificial lighting design. The heating and cooling system needs to efficiently condition a building's many thermal zones while delivering good indoor air quality. As in residential design, material choices for the construction, finishing, and furnishing of the building are important for the long term sustainability of the project. The Chesapeake Bay Foundation building provides a good example of energy efficient green construction at the commercial scale. It is a LEED Platinum building.

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19

BUILDING EXAMPLE

The Chesapeake Bay Foundation Building

The Chesapeake Bay Foundation is committed to protecting and restoring the health of the Chesapeake Bay. It does this through monitoring, research, community outreach, and publications. The foundation was scattered around Annapolis, Maryland, in various offices when the opportunity to build a new headquarters building on bay frontage property in Bayside, Maryland, a little south of Annapolis presented itself. The foundation decided that they should build a building that was as green as possible. They hired the Smith Group with the brief to create a building to sit lightly in nature. The list of desired climate responsive features included daylighting, passive solar heating, natural ventilation cooling, rainwater collection, composting toilets, local and minimally processed materials, low maintenance and indigenous landscaping, photovoltaics, solar hot water heating, high efficiency lighting, efficient HVAC equipment, and recycled building materials (Figure 19.1). The LEED rating system was just beginning. The owners and design team set out to achieve a LEED Platinum rating.

The site in Bayside was large. There had been a beach club on the site. The decision was made to locate the new building over the footprint of the preexisting building, which left most of the site to be conserved as woodlands and wetlands.

The building is oriented 17 degrees east of south so that the southern exposure is aimed slightly into the morning sun, when the air temperatures are usually lower, and away from the western evening sun, when the air temperatures are higher (Figure 19.2). Tom Eichbalm, the principal in charge of the design, chose this orientation because he remembered the lessons from *Design with Climate* by Victor Olgyay.

Parking for employees is located under the building on a concrete slab. Parking for visitors is located in front of the building and has a gravel surface. The guiding concept was to minimize rain water runoff. The slab under the building does not

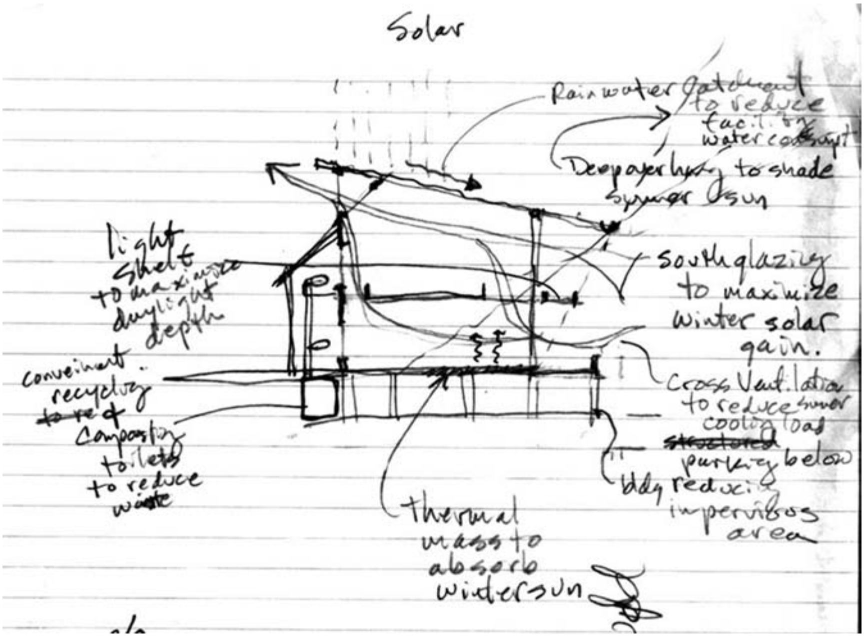

FIGURE 19.1 The architect's design concept sketch of the Chesapeake Bay Foundation's Merrill Building.

Source: Reproduced with permission of The Smith Group JJR.

receive any rain. The gravel surface is porous to water penetration. The water that does run off the gravel parking lot is collected in a planted swale that collects the water and channels it through a filtration system before discharging it to the Bay.

Rainwater is collected from the roof surfaces and stored in cisterns. The collected rainwater is used for hand washing, laundry, mop sinks, irrigation and in the fire suppression system. The collected water goes through a particulate filter, a chlorine injection, a static mixer, and a charcoal filter before being used in the building. The cisterns are a prominent feature on the north elevation of the building, which is the entry point into the building.

The primary window area is on the elevation oriented 17 degrees east of south, with minimal window area on the west, north, and east elevations (Figures 19.3 and 19.4). The east of south window area provides solar heating in winter and daylighting throughout the year. These east of south windows are protected from summer sun penetration with exterior horizontal shading made from pickle barrel staves. The building is sheathed with structural insulated panels (SIPs). The SIPs contribute to lateral bracing and provide a high R-value exterior wall. Lighting and heating are the easiest energy use categories that can be reduced through design features.

The proximity to the Bay provides an opportunity to use ventilation cooling in spring and fall when the winds coming off the Bay can provide cooling. The

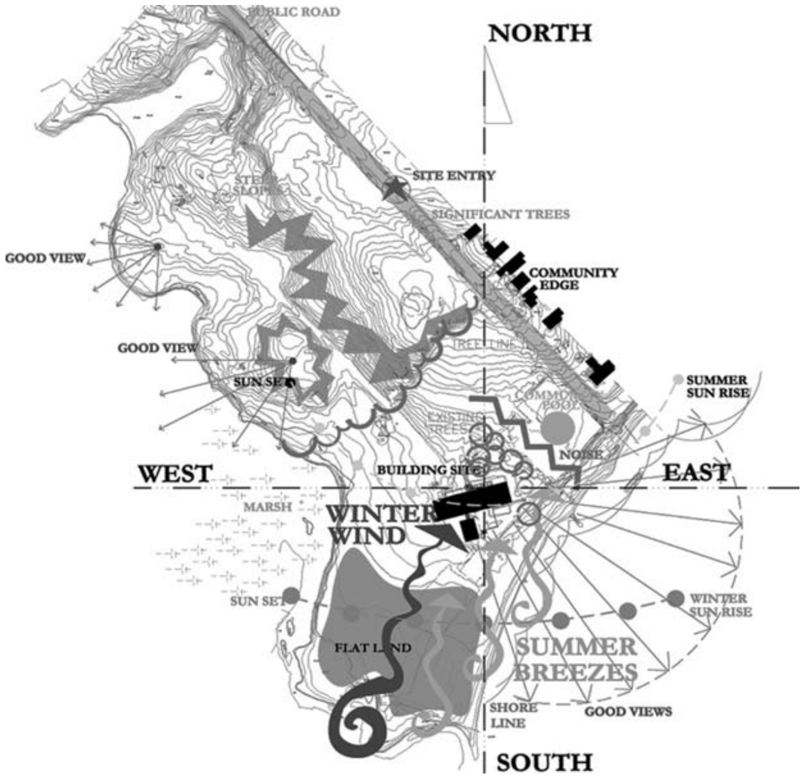

FIGURE 19.2 The site plan for the Chesapeake Bay Foundation's Merrill Building showing its orientation 17 degrees east of south and showing that most of the site is left in its natural state.

Source: Reproduced by permission of The Smith Group JJR.

building has an energy monitoring system that can determine when the outside air is cool enough for ventilation to be effective. The system turns on a light, indicating that windows should be opened, and turns off the mechanical cooling. The building occupants then open the windows on the south and north to allow cross ventilation. The open plan interior organization provides a clear path across the building.

The artificial lighting system is designed to interact with daylighting. Daylight comes in through the large expanse of south windows. Daylight also comes in through the smaller north windows, which are coordinated with the furniture layout (Figure 19.6). The artificial lighting is controlled in rows parallel to the south windows so that fixtures close to the windows can be dimmed when daylight is available. On the lower level the lighting is indirect, being bounced off the ceiling (Figure 19.5). On the upper level the lighting is direct indirect. The general illumination level is 30 foot-candles.

FIGURE 19.3 The south elevation of the Chesapeake Bay Foundation's Merrill Building. Photo by Carl Bovill.

FIGURE 19.4 The north elevation of the Chesapeake Bay Foundation's Merrill Building. Photo by Carl Bovill.

FIGURE 19.5 Indirect lighting provides high quality diffuse illumination in the Chesapeake Bay Foundation's Merrill Building. Photo by Carl Bovill.

FIGURE 19.6 North windows are modest in size but positioned to provide significant illumination to work spaces on the north side of the Chesapeake Bay Foundation's Merrill Building. Photo by Carl Bovill.

The building's HVAC system is based on ground source heat pumps. There are 17 heat pump thermal zones, mostly organized as north, center, and south zones on the two floors with additional zones for the entry lobby and the conference center wing of the building. The duct work delivering the tempered air runs parallel to the south elevation of the building. The ground source heat pumps are aided by a dehumidification system, which is driven by natural gas. The building uses 25 percent less energy than an energy code compliant building of the same size and location (Griffith et al. 2005, 56).

The material choices were driven by the following guidelines; recycled, rapidly renewable, salvaged, locally manufactured, locally harvested, recyclable, minimally processed, low embodied energy, and non-toxic. The building is framed with parallel strand lumber, which is made by gluing small strands of lumber together parallel to the long dimension of the framing member under high pressure. The result is timber sized framing members made from smaller trees. The building is sheathed with structural insulated panels, which provide high insulation value and contribute to lateral bracing. The north, east, and west facades with their modest punched window openings are finished with galvalume siding. Galvalume is an Al–Zn coated sheet steel product used for roofing and siding. Interior floors use bamboo in the formal areas, cork in the office areas, and linoleum in the break room kitchen. The interior walls are unfinished oriented strand board trimmed with medium density fiberboard. The ceilings on the lower floor are white acoustical panels used to reflect indirect artificial lighting to create even shadow-less lighting. The ceiling on the upper floor is exposed oriented strand board. The shading protecting the south glass is made from unused pickle barrel staves.

The building minimizes water use in two ways. First, the toilets are all composting toilets that do not use any water. Second, water for hand washing and laundry needs comes from the rainwater collected off the roof.

The indoor environmental quality is driven by the openness of the building interior and its orientation to large shaded south glass looking out over the Chesapeake Bay. Everyone in the building has a view to the outside. Daylight streams through the building. The circulation along the south glass minimizes sunlight glare on workstations. High indoor air quality is ensured by interior finishes with minimal VOC outgasing combined with good mechanical ventilation. Excellent natural cross ventilation also contributes to indoor air quality when conditions allow.

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OVERVIEW OF THE LEED FOR COMMERCIAL BUILDINGS RATING SYSTEM

LEED is a rating system developed by the United States Green Building Council. The rating system outlines important sustainable design features that commercial buildings should incorporate, and provides a scoring system to rank success. The rating system is available on the USGBC website: www.usgbc.org/Leed/Rating-systems. LEED does a good job of outlining the important aspects of green design applied to commercial buildings. Where a building is located is an important consideration. How a building uses water and how much water it uses will become more important as population increases. Minimizing energy use is obviously a primary concern. Material choices must balance embodied energy, recycle content, and durability. And finally, indoor environmental quality is very important to the people who occupy a building. LEED creates a list of features under the headings mentioned above. Each of the items in the list has points related to it. The total points earned by a design grades the design as certified, silver, gold, or platinum. This grading system is not perfect but it does create a clear definition of green. The discussion below is based on the LEED 2009 rating system. The LEED green rating system is adjusted every few years but the basic structure stays stable.

The site selection category aims site selection away from sensitive locations like wetlands, undeveloped land, farmland, and critical habitat areas. Maximizing open space on the site is given importance. There is also credit given to locating the building on a brownfield site. All of these considerations restate the old adage to site a building on the worst piece of land in order to improve the environment of the site. The next group of criteria relate to where the building is located in an urban setting. A building that is located close to services like banks, cleaners, libraries, theaters, supermarkets, and so on, and also reasonably close to housing opportunities will create more walking and less driving. A building's location can also reduce driving by creating opportunities to use public transportation, and can design features to promote bicycle use, carpooling, and the use of low emitting vehicles.

Storm water design features are encouraged that reduce the amount of runoff by minimizing impervious ground cover (paved areas), and by filtering the runoff that does occur through constructed wetlands. Urban areas are warmer than unbuilt areas because of massive areas of paving and dark roofs. Replacing paving with green areas and shade trees and replacing dark traditional roof coverings with white surfaces and green roofs can mitigate the heat island effect. The final site feature addressed is light pollution caused by street and building lighting. The stars are barely visible in the night sky over a city when compared to the night sky in open, undeveloped country.

Water is used in buildings for drinking, washing, and waste removal. The washing and waste removal streams can be minimized with low flow fixtures. The waste removal stream could use non-potable water sources like rain water. The waste stream could be eliminated with composting toilets or by treating waste water on site and then reusing it to operate the waste stream. Building sites can be designed to minimize or eliminate the need to irrigate planting by using local plantings that can survive on the local rainfall and or collecting rain water to use for irrigation.

The primary focus of the energy and atmosphere category of the code is minimizing the energy use of the building. The base line is 10 percent better than ASHRAE 90.1–2007. Most of the available points are for reducing energy use below the baseline. There are requirements for building commissioning to confirm that the mechanical and electrical equipment is installed correctly and that the owner has documented knowledge of how to operate the equipment. Consideration is also directed to on site renewable energy generation as well as purchasing green energy through the utility company. Finally there are points for a measurement and verification system to confirm that the energy use predictions from the design are achieved in the actual building.

The materials category is set up to reward material reuse and recycling. At the building level, the structure of the walls, floors, and roof can be saved, and in addition nonstructural interior construction elements can be saved. At the materials level credit is given for reusing materials, for materials with recycled content, for regional materials, for rapidly renewable materials, and for the use of certified wood.

Indoor environmental quality covers air quality, lighting and daylighting, and thermal comfort. Air quality is addressed on two fronts. Increased ventilation will dilute any volatile organic components in the air, and low emitting materials for adhesives, sealants, coatings, paints, flooring, and composite wood products reduce the amount of volatile organic components in the air. Lighting is required to be controllable, and daylighting and views to the exterior are encouraged. Thermal comfort also needs to be controllable and verifiable.

Using design features that are innovative and not considered by the point structure of the LEED system is viable and can earn credits. In addition, one credit is given for using a LEED accredited professional to guide the process.

Regional LEED organizations can define some of the LEED criteria as very important in the local environment. Bonus points are then given for the implementation of those criteria.

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DAYLIGHTING

Daylighting design starts with an understanding of the sky. An overcast sky has a luminance that is 3 times brighter at the zenith than at the horizon (Figure 21.1). An overcast sky is also equally bright in all directions. This equal brightness feature is the result of water vapor scattering all wavelengths of light all over the sky. Because all wavelengths are scattered the sky appears white. A clear sky is 10 times brighter in the area around the Sun than it is in an area of the sky that is opposite the sun in the sky (Figure 21.2). The clear sky is blue because the nitrogen, oxygen, and carbon dioxide molecules that make up our atmosphere scatter the higher energy blue wavelengths leaving the rest of the spectrum to penetrate through without any scattering (Moore 1985, 30–32).

Our eyes evolved under daylight, so it is not a surprise that daylight provides high efficacies. The efficacy of the Sun and sky is 100–150 lumens/watt. Incandescent light is 20–40 lumens/watt. Fluorescent light is 50–80 lumens/watt (Moore 1985, 30). Daylight has a high amount of visible light in relation to the total amount of thermal heat involved.

The solar spectrum starting from the high energy side has an ultraviolet part, a visible part, and an infrared part (Figure 21.3). Our eyes are designed to see the visible part from blue through green, yellow, and red. When all of these wavelengths are combined together as they are in daylight our eyes perceive this as white light. The ultraviolet part of the spectrum has high energy and causes materials to fade. The infrared part of the spectrum is felt as thermal heat.

Clear glass allows the entire solar spectrum through the glass. This energy hits interior surfaces and furniture, heating them up. These interior surfaces then reradiate infrared energy at a much lower energy level than the solar spectrum. Regular clear glass is opaque to this room infrared radiation. The result is that the room infrared is absorbed by the glass as if the glass were a black wall. Some of the energy returns to the room, and some of the energy goes back outside. Double glazing reduces this heat loss to the outside (Figure 21.4).

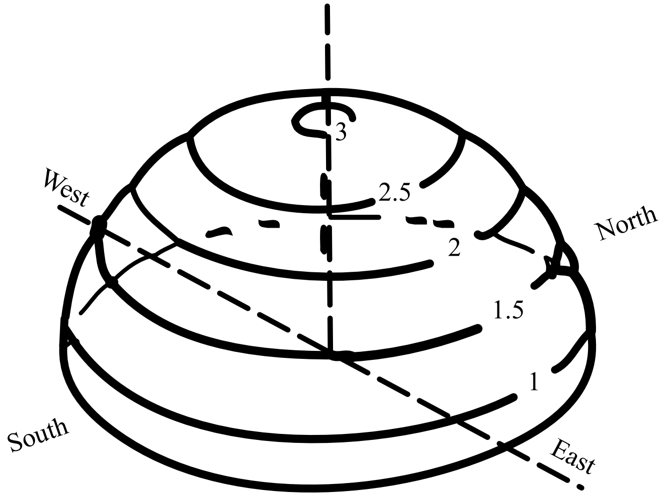

FIGURE 21.1 An overcast sky is three times as bright overhead compared to the horizon and is equally bright in all directions because clouds scatter all the frequencies of light around the sky.

Source: Moore 1985.

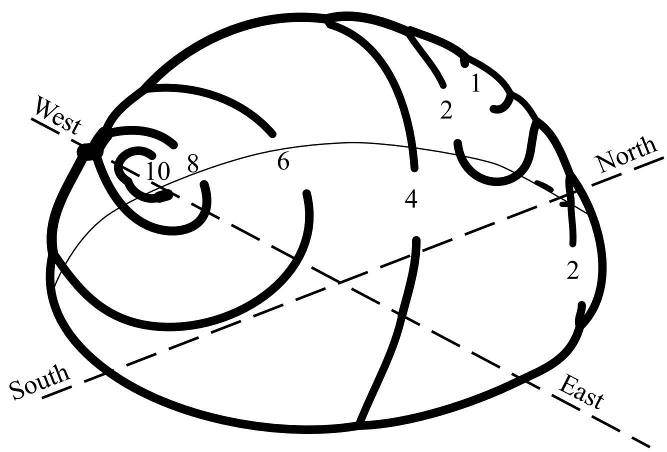

FIGURE 21.2 A clear sky is ten times as bright near the Sun compared to locations on the other side of the sky from the Sun. The sky is blue because air molecules scatter only the blue light.

Source: Moore 1985.

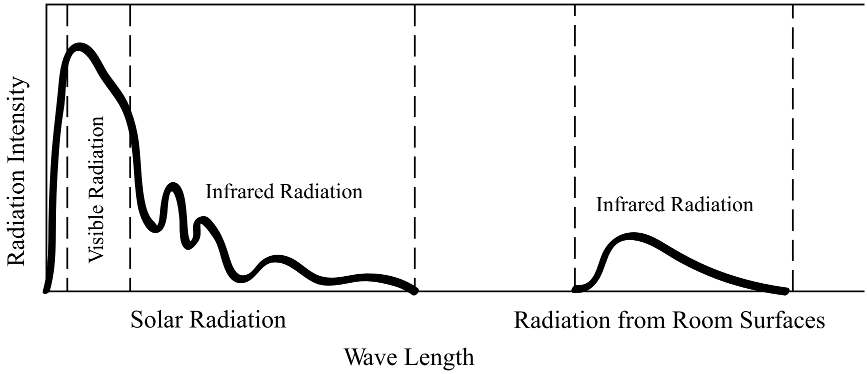

FIGURE 21.3 The solar energy spectrum compared to the infrared radiation emitted from warm room surfaces.

Source: Moore 1985.

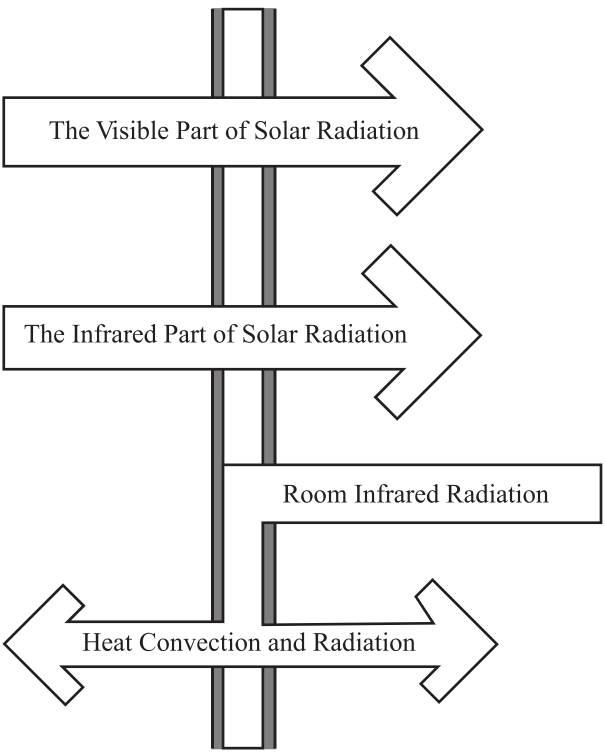

FIGURE 21.4 Radiation transfer through clear double glass.

Source: Moore 1985.

Modern glazing can have a selective reflecting coating applied to its surface. A selective surface makes the glass appear like a mirror to thermal radiation. So when the thermal radiation approaches the glass it is reflected back into the room and/or back outdoors, depending on the nature and location of the selective surface. The selective surface can be set so that it reflects the infrared part of the solar spectrum and the infrared radiation coming off interior surfaces. Alternatively, the selective surface can be set so that it allows the entire solar spectrum through the glass but is reflective to the infrared radiation coming off interior materials.

For passive solar heating in residential buildings, the selective coating that lets in the entire solar spectrum and then is reflective to the room infrared is ideal because a maximum amount of solar gain is admitted while minimizing heat loss through the window from the interior (Figure 21.5). For daylighting in commercial buildings, heating is less of an issue. The primary concern is providing lighting. The selective surface that reflects both the infrared part of the solar spectrum and the infrared room radiation allows the visible part of the solar spectrum to penetrate

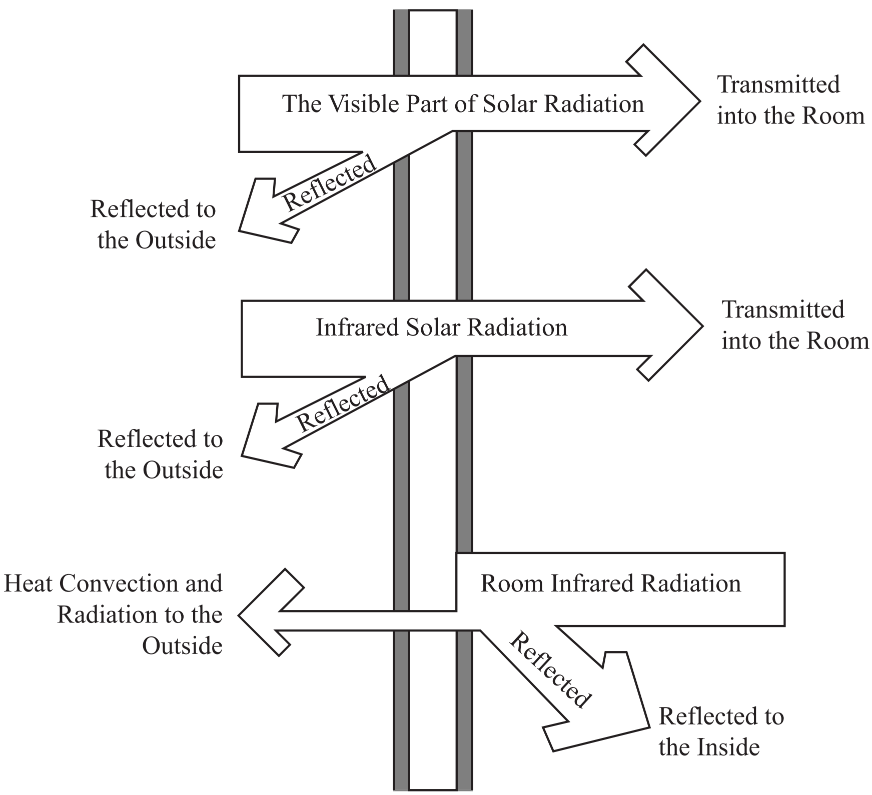

FIGURE 21.5 Radiation transfer through low-e double glass designed to maximize solar heat gain through the glass and minimize heat loss back out the glass.

Source: Moore 1985.

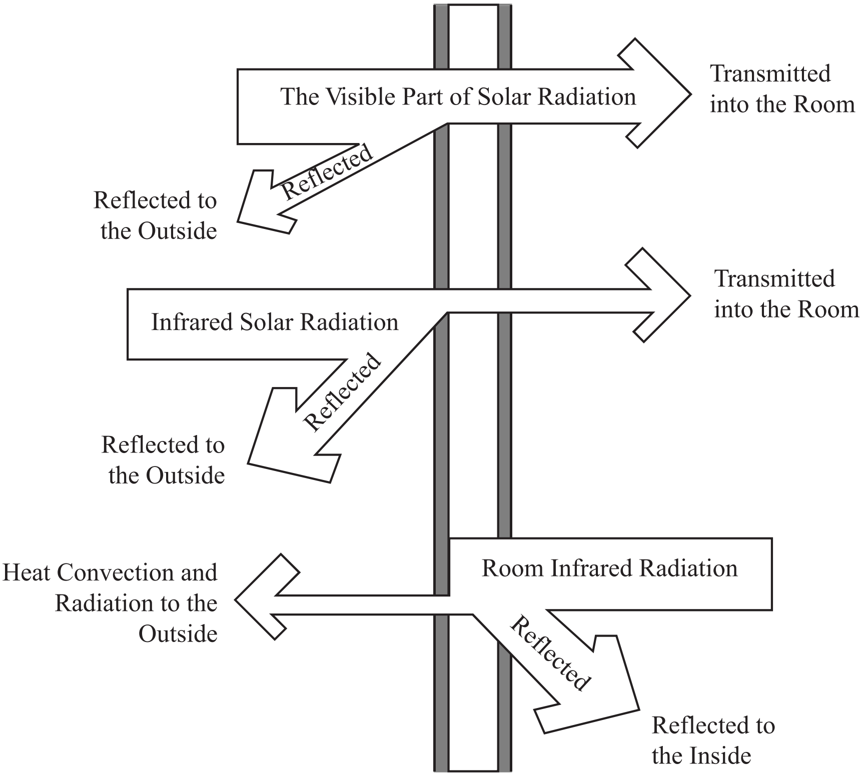

FIGURE 21.6 Radiation transfer through low-e double glass designed to maximize daylight penetration and limit solar thermal radiation transfer.

Source: Moore 1985.

through the glass while reflecting the infrared part of the solar spectrum away from the building (Figure 21.6). It also reflects room infrared back into the room, which reduces the heat loss through the glass.

Most modern glazing is doubled glazed. The double glazing adds an air space between the two panes of glass which reduces heat loss. The selective coatings are normally applied to one of the inside faces of the double glazing. In the passive solar heating case, the selective coating is best placed on the inside face of the inside glass pane where it can best reflect the room infrared back into the room. When daylighting dominates, the selective coating is best placed on the inside face of the exterior pane of glass where it can best reflect the infrared part of the solar spectrum away from the building.

Properly designed and oriented windows will allow daylighting to penetrate into a building without too much direct sun penetration. However, to save electric lighting energy, there needs to be an automatic dimming system. As the daylight is available to illuminate the areas near the windows the electric lights need to be dimmed. People do not get up from work to dim the lights.

Daylight when introduced in a controlled manner can replace artificial lighting. As the window area increases more daylight is allowed into the room. However, in addition, as the window area increases the heat loss in winter increases and the heat gain in summer increases. Combining these three energy flows produces an optimum window area. The procedure to determine the optimum window area requires multiple computer simulation runs. The window area is slowly increased. At each window area two computer runs are needed. One simulation is run with all the lights left on all the time, thus not using the admitted daylight. The second run simulates the continuous dimming of the artificial lights so that the daylight can be used to save energy.

If the design uses regular clear double glazing, there is an energy savings associated with daylighting, but the heat loss in winter and the heat gain in summer limit the amount of savings. The optimum glass area for daylighting is only 10 percent of the wall area.

The heat loss and heat gain that increase as the window area increases can be reduced by using low-e selective coatings on the glass, by shading the glass from excess summer solar penetration, and by avoiding east and west glass. The largest drop in overall energy use from daylighting comes from the introduction of double glass with a low-e selective coating. This is because heat loss through the increasing window area increases faster than heat gain. However heat gain is harder to control than heat loss. The addition of horizontal shading is the primary means of reducing heat gain. It is easier to control direct solar gain if all the glass is on the north and south elevations. The north windows receive only diffuse skylight and the south

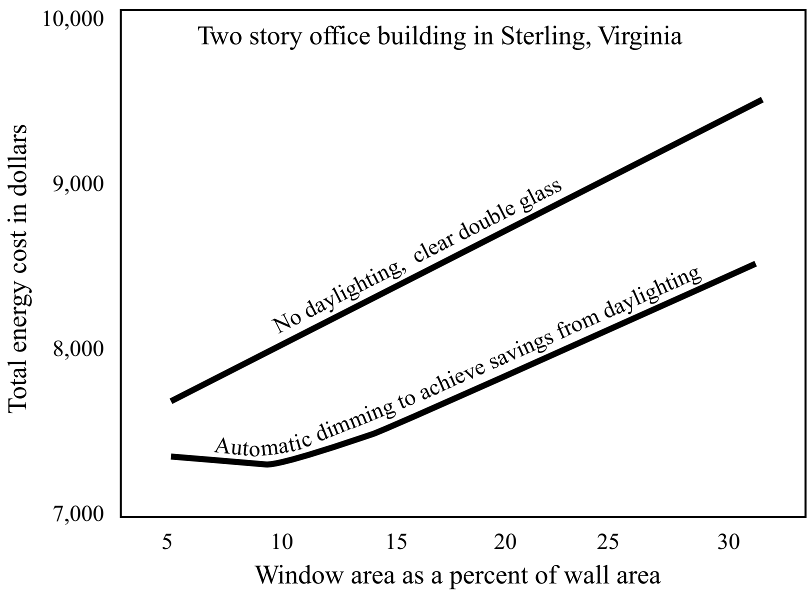

FIGURE 21.7 Energy savings from daylighting with regular double glass.

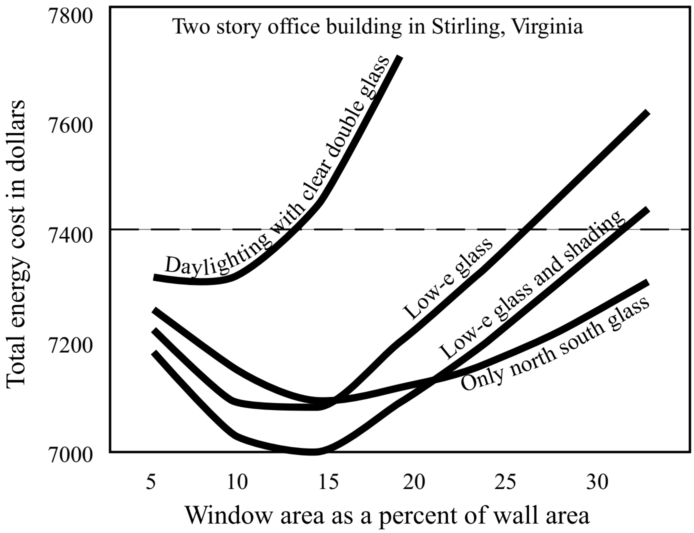

FIGURE 21.8 Energy savings from daylighting using double low-e glass, double low-e glass and horizontal overhangs for shading, and double low-e glass with shading and only north and south glass. The dashed line across the plot represents the energy use of an insulated wall with no windows in it.

windows can be easily protected from direct solar penetration with horizontal overhangs and interior blinds. This change flattens the optimum curve (Figure 21.8). Note that the optimum glass area for daylighting is 15 percent of the wall area.

The dashed line that runs across the graph of the daylight simulations represents the energy cost of an insulated wall with no windows in it. Where the optimum daylighting curves cross this line represents the window area that can be in an insulated wall that has the same energy cost as the insulated wall without any windows. Windows provide benefits other than daylighting, including views out, which provide a restful distant view and a connection to changing outside weather conditions. Operable windows can also provide natural ventilation. Thus window areas of from 15 percent to 35–40 percent of the wall area provide good energy performance.

Another way to look at the issue of how much glass area is appropriate for daylighting is to look at the growth of energy cost savings as the ratio of window area to wall area increases. As the window area approaches 35 to 40 percent of the wall area, the energy cost savings from daylighting reach a diminishing return (Figure 21.9). Window areas beyond this range will not improve the energy performance of the building. The energy codes like ASHRAE 90.1 list appropriate window area as a range from 20 to 40 percent of the gross wall area.

In the daylight literature, a quantity referred to as the daylight factor is used to indicate interior daylight levels. The daylight factor is the ratio of interior illumination divided by the exterior illumination. For example, if an interior

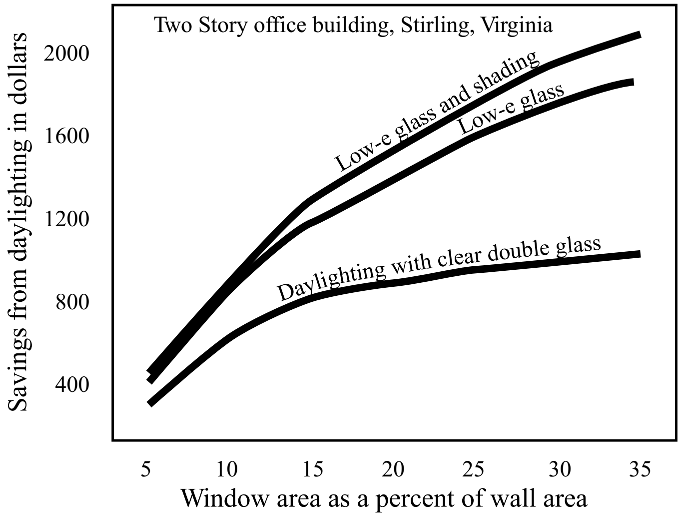

FIGURE 21.9 The increase in energy savings from daylighting as the window area is increased from 5 to 35 percent of the wall area.

illumination is measured as 50 foot-candles and the illumination outside is measured as 1000 foot-candles (50/1000) will produce the decimal fraction 0.05. The daylight factor is usually listed as a percentage, so 0.05 would be listed as 5 percent. The interior illumination is 5 percent of the exterior illumination. The advantage of this method is that, once the measurement is made, illumination levels can be extrapolated to brighter and darker skies by multiplying the daylight factor times the outside illumination level (Hopkinson et al. 1966, 17).

An overcast sky is white and equally luminous in all directions. It is three times brighter at the zenith than at the horizon. In an overcast sky there is no worry of direct sunlight penetrating into the work space. However, the area right next to the window will be much brighter than areas deeper into the room. This can create a glare problem near the window. The solution is to provide a light shelf to lower the illumination near the window and slightly increase the illumination deeper in the room. A clear sky is 10 times as bright in the area around the Sun compared to the brightness of the sky opposite the position of the Sun. As the day progresses, the brightest part of the sky moves from the east through the south to the west. The direct sunlight is even brighter. Direct sun needs to be blocked and or bounced into the room. A partly cloudy sky needs to be considered a clear sky for design purposes because direct sun will pop into play periodically. In all cases light shelves improve the situation (Figure 21.10).

Light shelves should be one-third outside the window and two-thirds inside the window on a south exposure. The outside portion should create a 25 degree cutoff angle from high summer sun. North exposures only need the interior part of the light shelf, which will reduce excess brightness near the window. East and west exposures should be avoided but if necessary can be similar to the south exposure.

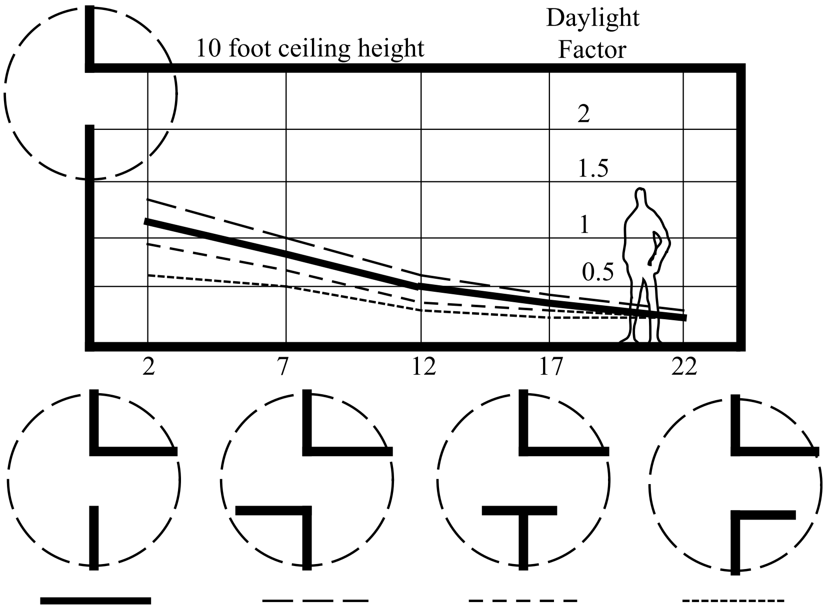

FIGURE 21.10 The effect on interior light levels of interior and exterior light shelves.

Source: Moore 1985.

The level of the light shelves can and should be coordinated with the level of direct indirect light fixtures.

Daylight can penetrate into an office area about two times the window height. The height is measured from the working plane, which is the desk height above the floor, usually 30 inches. Daylighting is about illuminating the working surfaces not the floor. There need to be layered controls to control Sun penetration and overly bright skylight near the window. These controls are often a light shelf to reduce the amount of daylight near the window and bounce some light deeper into the space, and blinds inside the window to provide personal control of the amount of light admitted. The walls and ceiling need to be white or a very light color so that light easily reflects around the room. The electric lighting needs to be wired together in parallel bands so that the lights near the window can be dimmed more than the lights further away from the window. The dimming needs to be automatic and continuous, driven by photocells that measure the illumination on the desk surfaces. The photocells reduce the amount of electric light when daylight is capable of providing illumination.

Useful daylight will penetrate into a room to a depth of approximately two times the window height (see Figure 21.11). This calculation should be made from the working plane, desk height, 2.5 feet above the floor.

Light from above frees up the orientation of the building, and can bring daylight deep into the interior of single height spaces. Skylights can be translucent or use baffles to control direct sun penetration, unless they slope far enough to the

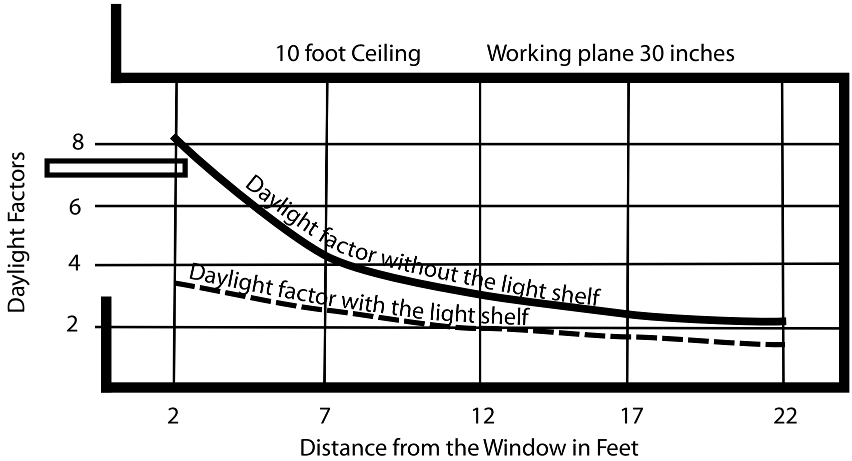

FIGURE 21.11 Daylight factor illumination levels for a 22 foot deep room with 10 foot ceilings with and without a light shelf.

Source: Moore 1985.

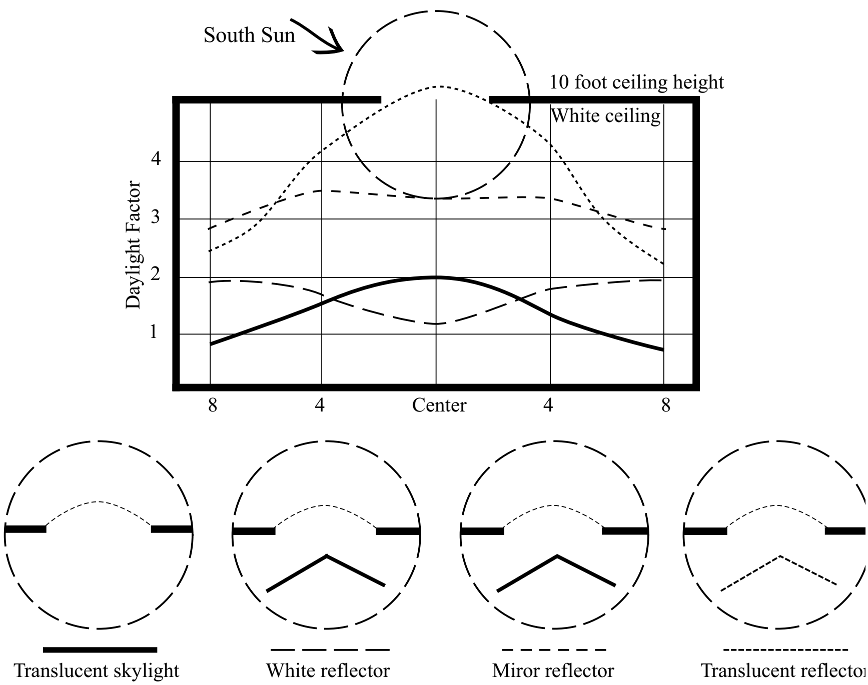

FIGURE 21.12 Reflectors can be used under skylights to distribute daylight around the room.

Source: Moore 1985.

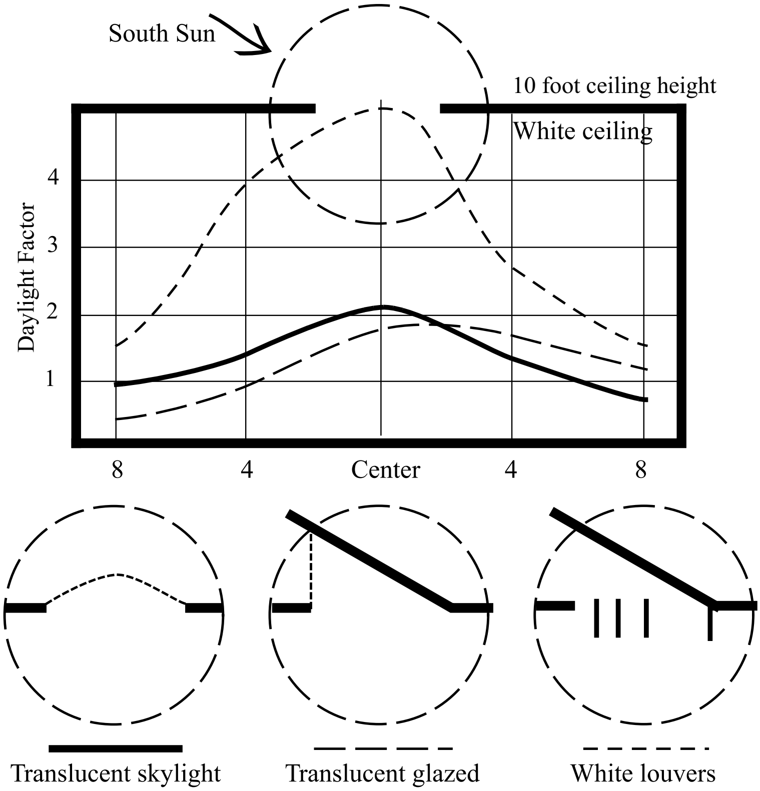

FIGURE 21.13 White baffles can be used to block direct sun penetrating from south facing monitors and distribute light in the interior.

Source: Moore 1985.

north so that direct sun never strikes the skylight. A south orientation produces a warm and variable light while a north orientation produces a blue more stable light. The light coming in through a skylight can be spread around the room with reflectors placed under the skylight (Figure 21.12). The Kimbell Art Museum in Fort Worth Texas uses this principal to illuminate the underside of concrete vaults from a strip skylight along the peak of the vault. Another method of controlling the light coming in through top lighting is to design baffles that intercept the direct sun coming in. The baffles should be white to redistribute diffuse light into the room.

In his book *Concepts and Practice of Architectural Daylighting* (1985), Fuller Moore illustrates multiple ways to construct baffles on varying skylight types (Figures 21.13 to 21.16).

The Menil Collection Art Gallery uses baffles below a skylight roof to provide an even, diffuse illumination. The heating and cooling comes out of the floor, so no ducts need to be at the ceiling level, which would interfere with the diffuse lighting.

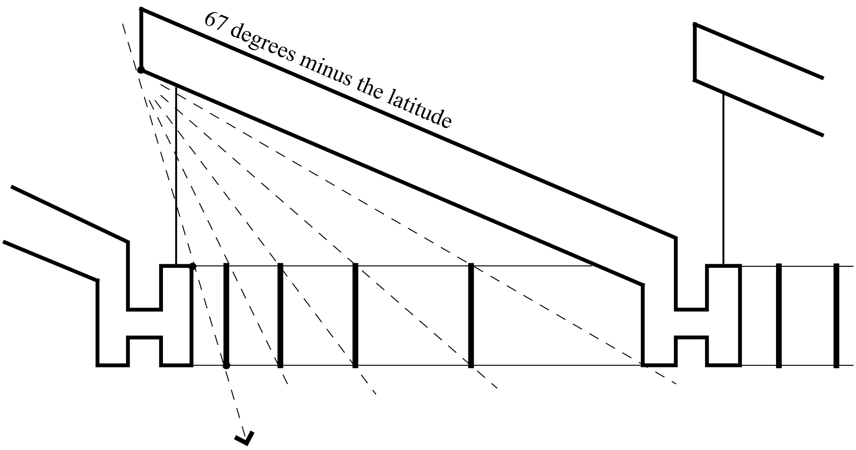

FIGURE 21.14 The construction of baffles to block direct sun penetration through a vertical south facing monitor.

Source: Moore 1985.

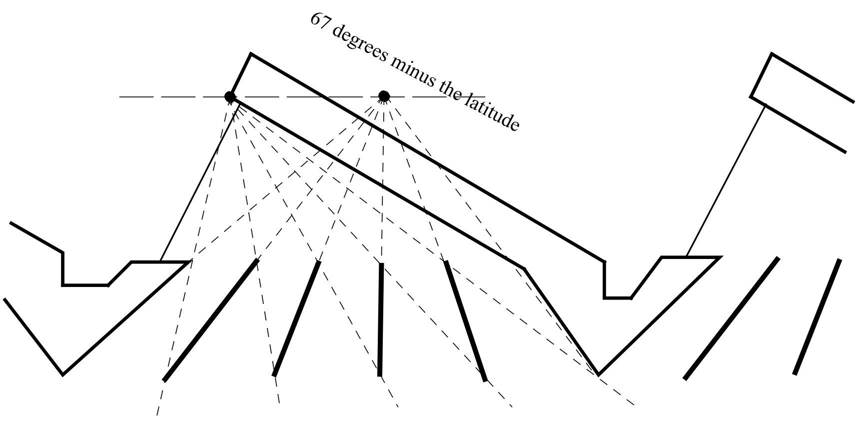

FIGURE 21.15 The construction of baffles to block direct sun penetration through a sloping south facing monitor.

Source: Moore 1985.

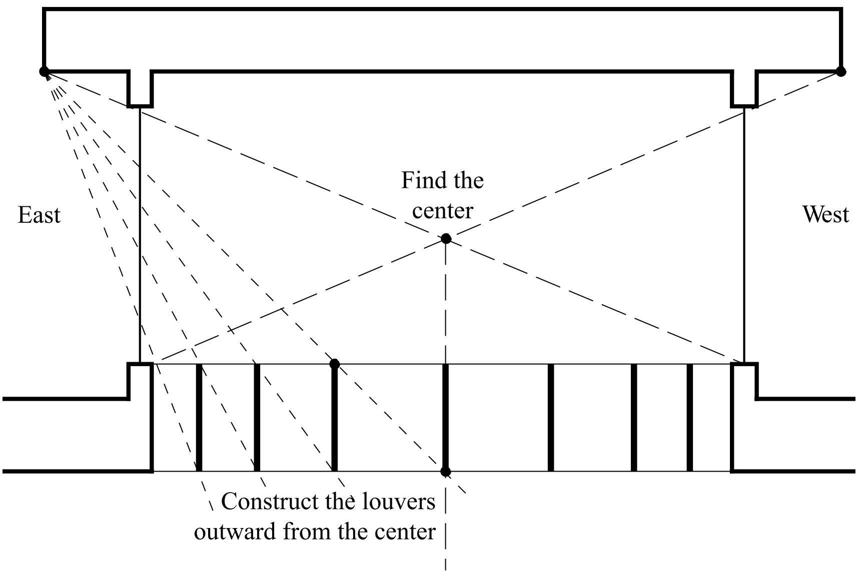

FIGURE 21.16 The construction of baffles to block direct sun penetration through a vertical east west facing monitor.

Source: Moore 1985.

22

ELECTRIC LIGHTING

Most of the energy use of commercial buildings in the United States is electricity and natural gas. Electricity accounts for 56 percent of the energy use, and natural gas accounts for 32 percent (Figure 22.1). The natural gas is primarily used for heating, which suggests that increasing the thermal resistance of the building envelope can save significant energy. The electricity use in commercial buildings is 38 percent lighting, 14 percent cooling, and 12 percent ventilation (Figure 22.2). Lighting, being the largest usage of electricity in commercial buildings deserves considerable attention in any energy saving schemes.

There are multiple dimensions involved in good energy efficient lighting. The efficacy of the light source is important. Efficacy is the lumens of light produced per watt of input energy (see Table 22.1). The quantity of light distributed onto working surfaces needs to be enough for the work that needs to be performed, but this quantity should be concentrated if possible only on the work area. The amount of light needed to walk around in lobbies and circulation spaces is lower than needed on work surfaces. When daylight is available to illuminate spaces, the electric lighting needs to be dimmed to save energy. When rooms, such as conference rooms, are not always occupied, there should be occupancy sensors to automatically turn off the lights.

Commercial buildings are primarily illuminated with linear fluorescent lamps. Newer fluorescent lamps are thinner, five eighths of an inch in diameter, than the traditional inch and a half diameter fluorescent lamps. Fluorescent lamps produce light by running an electrical current through a gas with mercury vapor in it. When electrons hit the mercury atoms the outer valence electrons of the mercury atoms are pushed to a higher level. When they fall back to their standard level they give off a limited multiline spectrum of light. This light is barely visible. The mercury spectrum is transformed to a useful spectrum of visible light with phosphors on the inside surface of the fluorescent lamp. Current phosphors provide a spectral

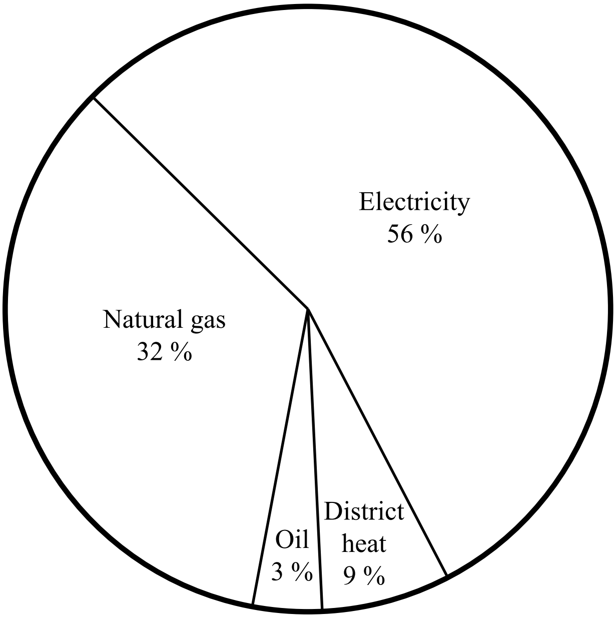

FIGURE 22.1 Commercial building energy use by source for the United States.

Source: United States Energy Administration, Annual Energy Review 2011. www.eia.gov/are.

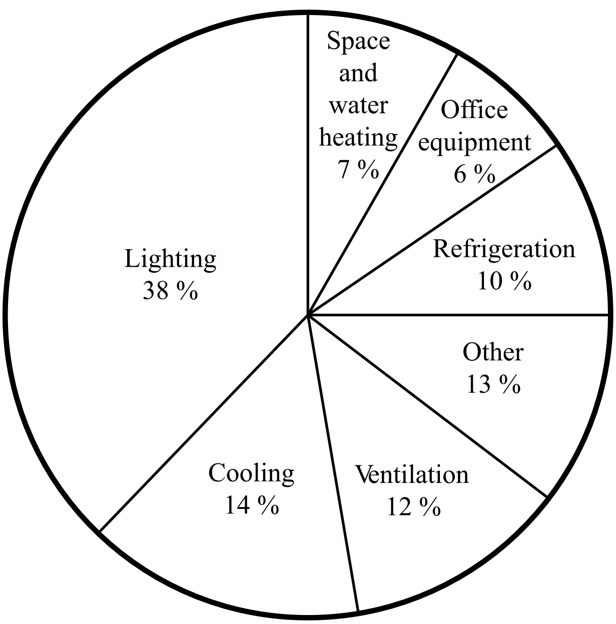

FIGURE 22.2 Commercial building electricity use by function in the United States.

Source: United States Energy Administration, Annual Energy Review 2011. www.eia.gov/are.

TABLE 22.1 Lamp wattage, efficacy, life, and color rendering index (CRI).

Lamp type	*Watts*	*Efficacy (lm/W)*	*Lamp life (hours)*	*CRI*
Incandescent	60	11	1,000	100
Incandescent	150	15	1,000	100
Halogen	75	24	2,000	100
Light emitting diode	13	61	40,000	80
Light emitting diode	35	71	50,000	80
Compact fluorescent	15	65	10,000	80
Induction lamp	23	48	10,000	82
Induction lamp	85	70	60,000	82
Fluorescent T8	32	87	20,000	85
Fluorescent T5	28	93	20,000	85
Metal halide	175	73	38,000	85
Metal halide	250	80	20,000	85
Metal halide	400	95	12,800	85
High pressure sodium	150	72	10,000	60
Sulfur lamps	1,320	100	60,000	79
Low pressure sodium	35	128	18,000	0
Direct sun	100	100		
Sky light	153	100		

Source: United States Department of Energy, U.S. Lighting Market Characterization, Volume II: Energy Efficient Lighting Technology Options.

mix of red, green, and blue light, which mixes together to produce white light with good color rendering, and high efficacy.

The quality of the light distribution from light fixtures is a very important feature of energy efficient lighting and indoor environmental quality. Overhead lighting can create two types of glare, which can reduce the effectiveness of the light. Direct glare comes from bright lamps in one's field of view. This is fairly easy to control with lenses or baffles that block the direct view of the bright lamp within the light fixture. Reflected glare is more difficult to control. Reflected glare manifests itself as a reflection of the bright lamp on top of the work product that a person is trying to see. One solution to this problem is to have light come from a large diffuse source, but this can be energy inefficient. A compromise solution seen often in energy efficient office lighting is direct indirect light fixtures hung on pendants 8 to 12 inches below a white ceiling. Half the light reflects off the ceiling and half the light is directed down. This produces a good mix of direct and diffuse light. The quantity of light is generally set at 30 foot-candles, which is enough light to read a book and plenty of light to move around in an office. Where more illumination may be needed, task lighting can be built into the furniture system. Ideally the task lighting has the same color temperature and efficacy as the general illumination.

Lobbies and circulation spaces often have down lights recessed into the ceiling. The amount of illumination needed to navigate circulation spaces can be as low as 10 to 20 foot-candles. These down lights are primarily compact fluorescents which have significantly higher efficacies than the incandescent lamps that they replaced. A 15 watt compact fluorescent lamp can replace a 60 watt incandescent lamp, and a 25 watt compact fluorescent lamp can replace a 100 watt incandescent lamp. Light emitting diodes (LEDs) have slightly better efficacies than compact fluorescent lamps but are more expensive.

In retail stores the lighting is a mix of fluorescent and metal halide. Metal halide lamps are a high pressure gas with a mix of metals in the gas including mercury that, when an electric current is sent through the gas, give off a wide and diverse spectrum of light. Metal halide lamps provide similar, and at high voltages higher efficacies than fluorescent light. The multiline wide spectrum of metal halide lamps produces a kind of sparkle along with good color rendering. Metal halide, along with mercury and sodium lamps, are collectively called high intensity discharge (HID) lamps because of the high pressure of the gas in the lamp. Fluorescent lamps have very low gas pressure.

All gas discharge lamps require a ballast to provide a surge of current to start the lamp and then to control the current flow through the lamp during use. Electronic ballasts consume ten to twenty percent of the electricity sent to the lamp. After a power failure, high intensity discharge lamps require from 3 to 20 minutes to restart. Fluorescent lamps restart right away (Hong, Conroy and Scholand 2005, 45–60). Retail stores also use spotlights to illuminate merchandise in order to draw our attention to what they want us to buy. These spotlights are often incandescent lamps because incandescent lamps produce light from a relatively small glowing

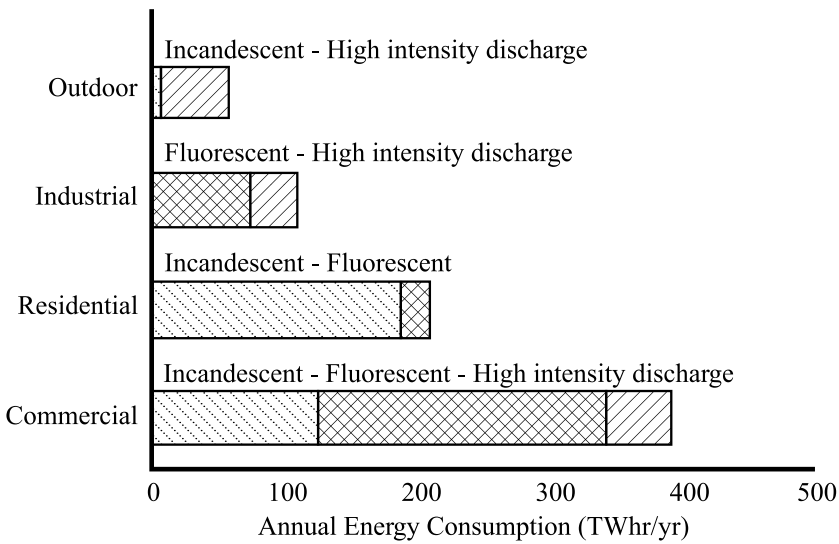

FIGURE 22.3 Lamp types used and annual energy consumption in outdoor, industrial, residential, and commercial buildings.

Source: United States Department of Energy, U.S. Lighting Market Characterization, Volume II: Energy Efficient Lighting Technology Options.

filament, which can be focused into a beam of light. Gas discharge lamps do not focus well.

There are rooms that are not always occupied, such as conference rooms, break rooms, and bathrooms. These spaces should have motion or infrared detectors that automatically turn off the light in the room when there is no one using the room. Buildings do not need light; people need light.

LEDs are becoming more efficient and are penetrating many lighting markets. Initially, LED lamps were comparable in efficacy to incandescent halogen lamps. Currently, LED lamps are comparable to compact fluorescent lamps. As efficacy increases, LED lamps can provide a major reduction in lighting energy use. There is also the added benefit that LED lamps have no current surge as they start, and have no delayed restrike time after a power interruption. Gas discharge lamps, fluorescent and high intensity discharge lamps like metal halides, need a current surge to strike the electric arc through the gas in the lamp. LED lamps dim much easier than gas discharge lamps, and the long lifetime of LED lamps can reduce the waste stream. Another advantage is the ability to produce LED lamps free of ultra violet (UV) and infrared (IR) energy. LED lamps will most likely replace incandescent lamps before making inroads into the fluorescent and high intensity discharge markets.

In 2001 lighting in the United States used 8.3 quads of electrical energy. Of this, 3.5 quads were incandescent lamps, 3.4 quads were fluorescent, and 1.4 quads were high intensity discharge. If white LED lamps can approach 160 lumens per

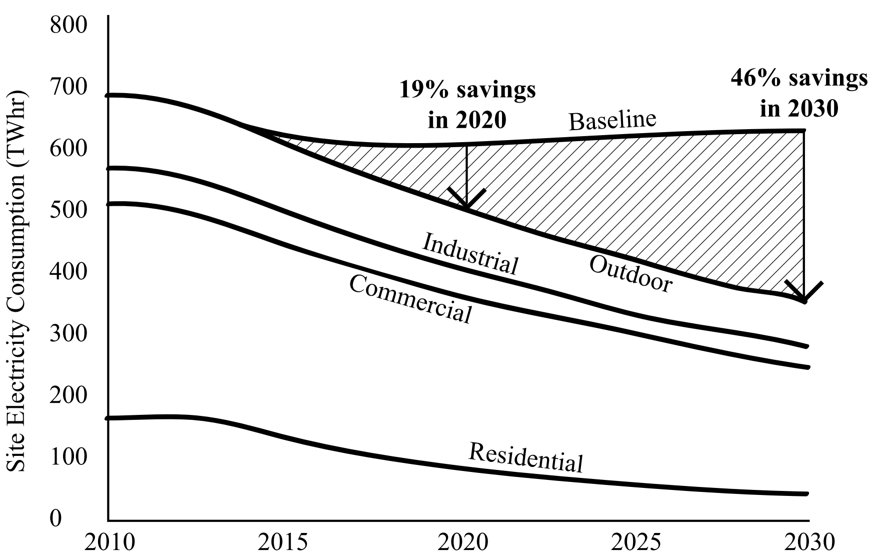

FIGURE 22.4 Potential electricity savings from the further development and use of light emitting diodes.

Source: United States Department of Energy, Solid State Lighting Program.

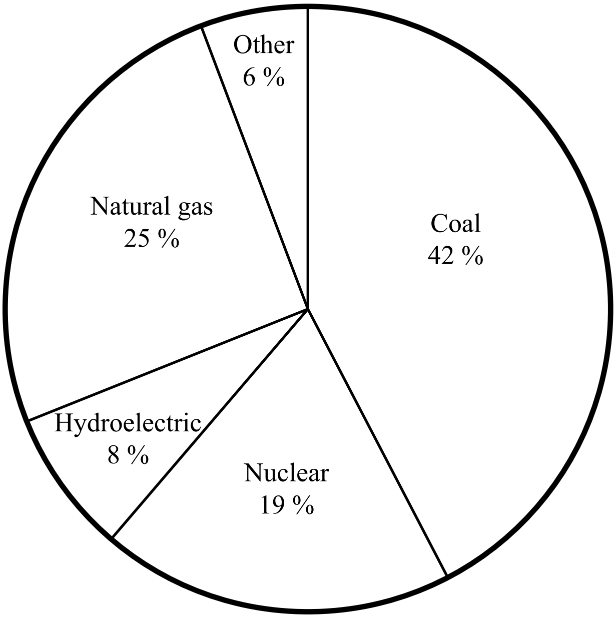

FIGURE 22.5 Electricity generation by fuel type in the United States.

Source: United States Energy Administration, Annual Energy Review 2011. www.eia.gov/are.

watt and can penetrate 20 percent of the market, there is a potential savings of 1.1 quads. That would be a 13 percent reduction in electricity use for lighting (Hong et al. 2005, 92–98). The U.S. Department of Energy Solid State Lighting Program reports that by 2010 LEDs will be able to reduce lighting electrical needs by 19 percent, and by 2030 the reduction will be 46 percent.

Since coal, the energy source that creates the most carbon dioxide per quantity of energy, produces 42 percent of electrical energy in the United States (Figure 22.5), any reduction in lighting energy use has a magnified effect on decreasing global warming.

23

HEATING AND COOLING

Heating and cooling in commercial buildings involves multiple zones with differing characteristics. Zones can have different schedules, temperature set points, air quality needs, internal heat, and need for heating, cooling, and/or ventilation. In addition there are interior and exterior zones. For example, outside air requirements are higher in an auditorium than in an office area. To minimize energy use these two uses should have separate air handlers. The following list of questions used as a series of filters can aid the partition of a building's uses into similar thermal zones.

- Do areas have similar schedules of use?
- Do areas have similar temperature set points?
- Do areas have similar ventilation and air quality?
- Do areas have similar internal heat generation?
- Do areas have similar needs for heating, cooling, and ventilation?

As an example consider a modest art gallery building with art galleries, art storage, exhibit preparation, administrative offices, and circulation. Similar schedules divide the uses into two groups. Group one, the galleries, art storage, and exhibit preparation, needs 24 hour thermal control because of the art. Group two, the administrative offices and the circulation, only needs about 10 hours of HVAC operation while people are in the building. Similar temperature set points do not change the groupings because they all will have similar set points. Similar ventilation and air quality creates some new groupings. The galleries, administrative offices, and circulation need ventilation amounts for people. The art storage area does not need as much outside air ventilation because there are very few people involved. The exhibit preparation will require high ventilation rates and separate exhaust so that dust and fumes are not spread around the rest of the building. Similar internal heat, and similar need for heating, cooling, and ventilation, do not create any new groupings. The final partition of the building into zones with similar HVAC needs is as follows. The galleries need 24 hour HVAC with possible humidity as well as temperature control. The art storage also needs 24 hour HVAC but as a storage space considerably less outside air ventilation will be required. The exhibit preparation requires high ventilation rates and separate exhaust and, when delicate art is in the space, 24 hour operation. The administrative offices and the general circulation only need to operate about 10 hours per day when people are present in the building. The result is that the building should have a minimum of four air handlers, one for each distinct thermal zone. Matching air handlers to thermal needs allows the building to be tuned for minimum energy use.

Commercial buildings also have exterior and interior zones (Figure 23.1). The exterior zones are the exterior offices, or the 15 to 20 feet of an open plan building closest to the exterior windows. These exterior zones face different directions. In a cardinal oriented building the exterior zones face north, south, east, and west. These zones will have different thermal needs at different times of day and in different seasons of the year. In summer high cooling needs will move around the exterior zones, starting with the east followed by the south and then the west. In winter the need is mostly heating but on a clear sunny day the south zone may need cooling. The energy use of exterior zones is driven by exterior climate conditions and thus insulated walls and high quality glass are important. The interior zones of a building need cooling all year long. Consider the thermal situation of an interior zone on a middle floor of a building. It is surrounded by conditioned space above and below by other floors and all around by the exterior zones. There is no path for heat loss to the exterior no matter how cold it is outside. However, there are plenty of heat gains from people, lights, computers, printers, and copy machines. This internal heat needs to be conditioned away with the introduction of cool air to these internal spaces all year long. Because of the different loads on exterior zones and interior zones, it is essential that exterior and interior zones be treated as separate thermal zones with separate air handlers.

Air handlers condition the air delivered to a space through the use of heating and cooling coils (Figure 23.2). The hot water for the heating coils comes from a boiler that will require a flue to vent exhaust gases to the outside. Chilled water comes from a chiller that requires a cooling tower located outside the building to reject the heat, taken out of the chilled water, to the outside air. There is usually one mechanical room location for the boiler and chiller and their accompanying pumps. As buildings get larger, there is usually more than one boiler and chiller for two reasons. The first reason is to avoid interruption of service when a boiler or chiller needs maintenance. The second reason is energy efficiency. Most of the year buildings operate at considerably less than their peak heating and cooling needs. Boilers and chillers run more efficiently at full output so having a sequence of boilers and chillers to turn on as the load increases is more efficient than having one large boiler and/or chiller running at part load.

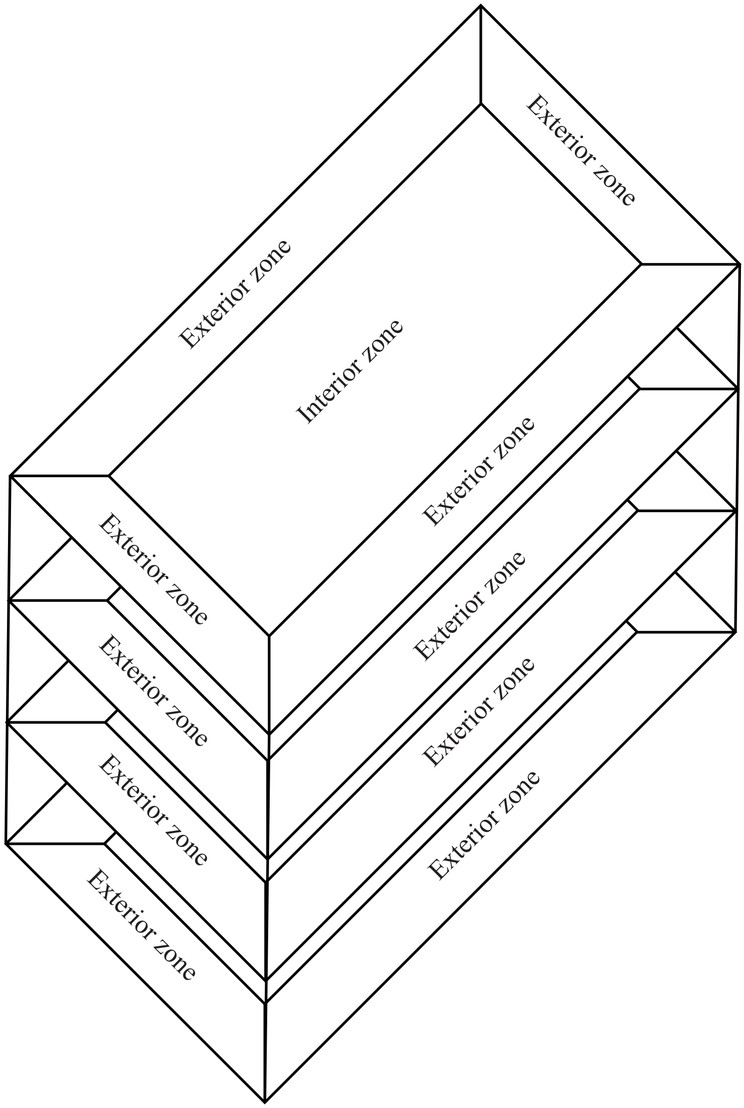

FIGURE 23.1 Interior and exterior zones.

Air handlers can be located around the building to minimize the length of duct runs. In multistory office buildings they are located either on every floor serving that floor or on about every 16 floors serving 8 floors up and 8 floors down.

The functioning of an air handler needs to include return air drawn back by the return fan, a set of dampers to control the amount of exhaust air and the amount of fresh air, and the mixing of return air and fresh air. All commercial buildings are required to bring in outside air at a minimum of 17 cubic feet per minute per

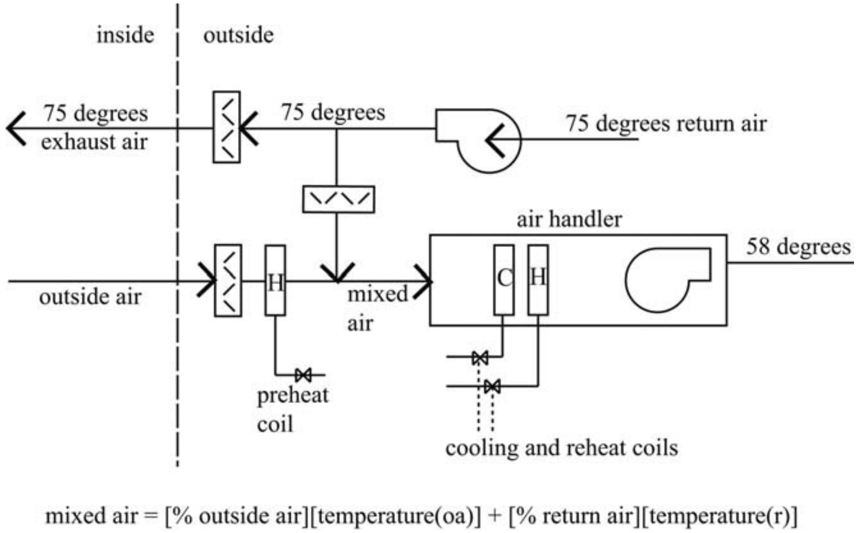

FIGURE 23.2 The configuration of a typical air handler unit with its accompanying return fan and dampers to control exhaust air, recirculated air, and outside fresh air.

person. This air can be at or below freezing during the winter months so a preheat coil is necessary to ensure that freezing air does not reach the cooling coil and freeze the water in the coil. The fresh air is then mixed with a portion of the return air before being drawn into the air handler. The air handler first cools the air down. This results in saturated air at about 45 degrees. If this air was delivered into the rooms the result would be cool but very humid spaces. The reheat coil then heats the air up to about 58 degrees, which also lowers the relative humidity of the air to about 50 percent. This air is then delivered to the rooms needing cooling. The slope of the line on the psychrometric chart between the delivered air and the room air is determined by the ratio of sensible and latent load in the receiving rooms (Figure 23.3). A steep line represents a situation where there is more latent load than sensible load. The slope of the line shown on the chart represents a latent load of about 30 percent and a sensible load of about 70 percent.

The simplest HVAC system is a single zone constant volume system (Figure 23.4). Air is delivered to the room at a constant volume flow rate. The temperature of the air is changed to respond to heating or cooling needs. This is a good system for large rooms like auditoriums.

Where a building has many spaces and multiple exterior orientations, the HVAC system needs to be able to respond to different needs for heating and or cooling in different rooms in the building. A variable air volume HVAC system is used in this case (Figure 23.5). The air handler delivers cool air into the supply duct system. At each room there is a variable air volume box that allows cool air into the rooms that need cooling. The temperature of the delivered air is set to meet this cooling load. In the zones where the cooling load is smaller, the variable

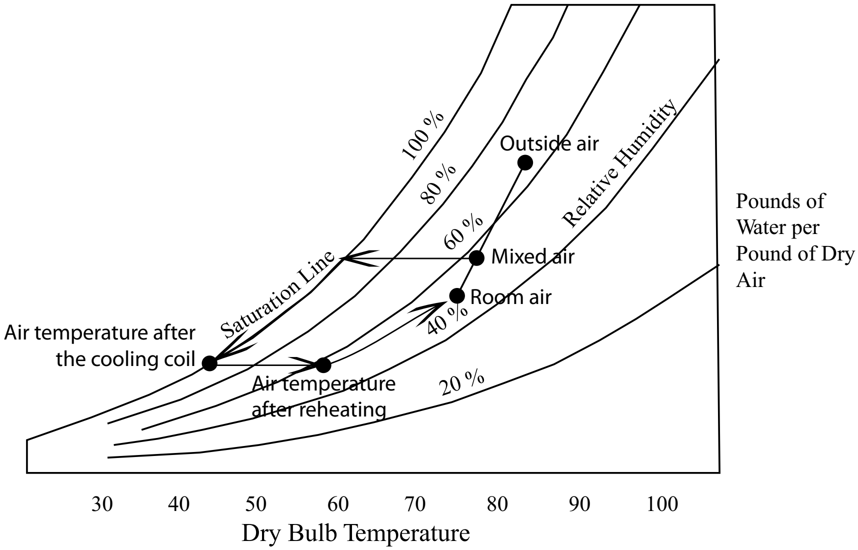

FIGURE 23.3 A plot on a psychrometric chart of the temperature and humidity characteristics of the air as it flows through the mixing dampers and the air handler unit to distribution into the conditioned space.

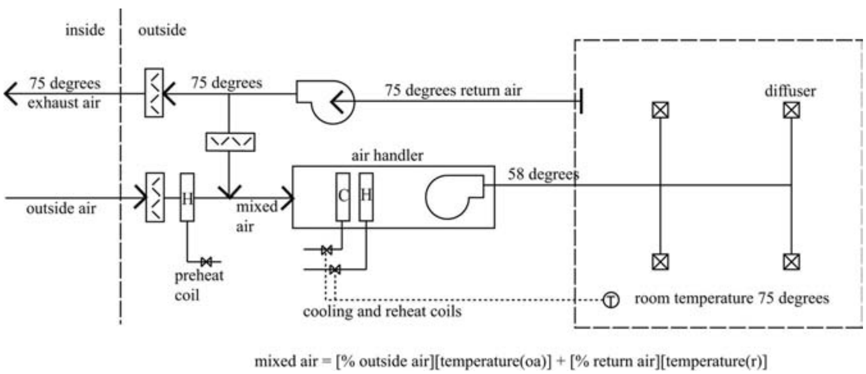

FIGURE 23.4 A single zone constant volume HVAC system.

air volume box reduces the amount of cool air delivered to the space, thus reducing the amount of delivered cooling. Where a room needs heating, the variable air volume box shuts air flow from the supply duct down to a minimum, usually about 25 percent of full flow. Then the air is heated with a hot water coil located downstream of the variable air volume control. This is called reheat.

Since interior zones are in need of cooling all year long, a variable air volume HVAC system without reheat works well in these interior zones responding to modest variation in the amount of cooling necessary. Heating is not necessary. Exterior zones need reheat because they will need heating during colder months.

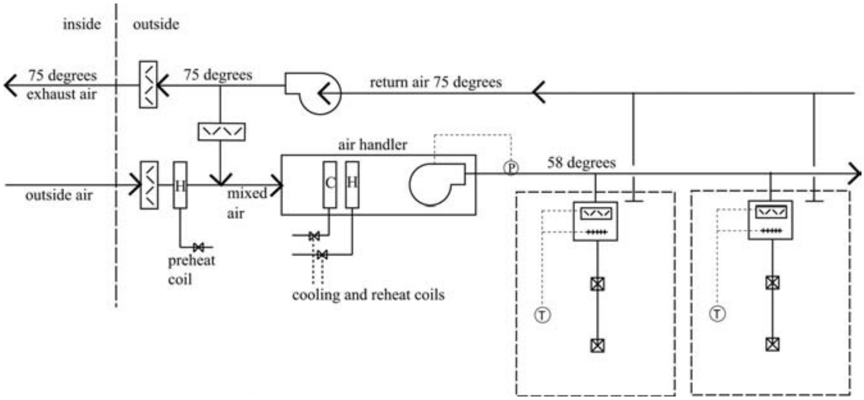

FIGURE 23.5 A variable air volume HVAC system.

Ideally each exterior orientation has its own variable air volume system so the delivered air can be set to the appropriate temperature for that exposure, thus minimizing the amount of reheat.

Variable air volume HVAC systems save energy in two ways. First, they minimize reheating by lowering the volume of air delivered before reheating it. Second, since most of the time there are a large number of variable air volume boxes reducing the air flow to the spaces they serve, the pressure in the supply duct will increase. A pressure sensor tells the fan in the air handler to slow down, thus saving on electricity used to drive the fan.

Exterior zones can also be served by a four pipe induction system. In each exterior office there is a unit with a cooling coil and a heating coil large enough to do the heating or cooling of the office. Fresh air in the required amount is tempered in a central air handler and delivered at high velocity to the induction unit with its coils. The fresh air stream is blown across the coils inducing room air to go along for the ride. The coils do the heating and cooling.

Another system that is used in office buildings is a chilled beam system. In this case a large portion of the cooling needs of the office space is delivered by panels mounted on the ceiling that have chilled water cooling them down. The chilled beams provide radiant cooling as well as cooling air that passes near the chilled beam. The air delivered into the spaces needs to be carefully dehumidified so that condensation does not form on the chilled beams.

There are various systems to reduce the amount of energy that an HVAC system uses. They can be organized into categories: systems that save energy through the difference in temperature and humidity of the exhaust air and the outside air, systems that recapture and store heat that the chiller would normally exhaust to the environment, and systems that store cool in the form of chilled water or ice.

One of the most common energy saving systems is an economizer (Figure 23.6). An economizer takes advantage of the fact that when the outside air is cooler than the return air from the zones being served it requires less cooling to throw away

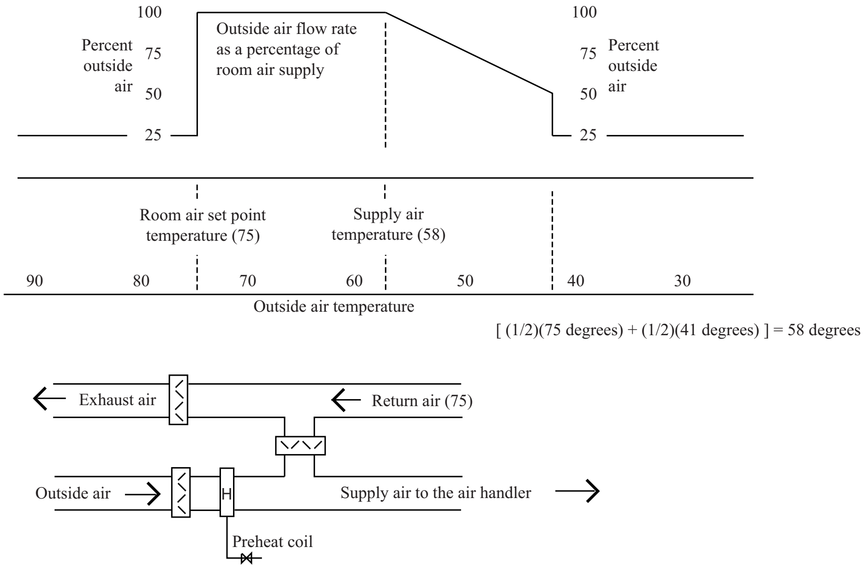

FIGURE 23.6 An air economizer system along with its operational temperature range.

100 percent of the return air and bring in 100 percent fresh outside air. Consider the situation where it is 58 degrees outside. The design delivery temperature for the air handler is 58 degrees. The economizer will bring in 100 percent outside air at 58 degrees and the air handler will not have to cool the air since it is already at the appropriate temperature. As the temperature gets colder than the delivery temperature, the economizer will slowly shut down the amount of outside air to the minimum amount for fresh air. Actually it is not quite this simple since humidity is also involved in the control systems of economizer systems. When temperature and humidity are considered, the economizer is enthalpy controlled.

In the situation where it is not possible to have 100 percent exhaust and fresh air streams, it is possible to achieve a similar result with a system called free cooling (Figure 23.7). In this system the cooling tower is used to directly chill the chilled water when it is cold enough outside to do this. The chiller is bypassed and turned off.

A run around coil places a coil with an antifreeze liquid solution in the exhaust air stream and in the supply air stream (Figure 23.8). A pump moves the liquid between the coils. This recaptures heat in winter and cool in summer.

An energy transfer wheel is a honeycomb made up of a light weight material like aluminum and has a desiccant on the surface of the aluminum (Figure 23.9). The wheel turns between the exhaust air stream and the outside air stream. In the winter the aluminum recaptures heat and the desiccant recaptures humidity from the exhaust air stream. The heat and humidity are then put into the fresh outside air stream warming it and humidifying it. In summer the aluminum recaptures coolness and the desiccant is dried out by the low interior humidity. The coolness

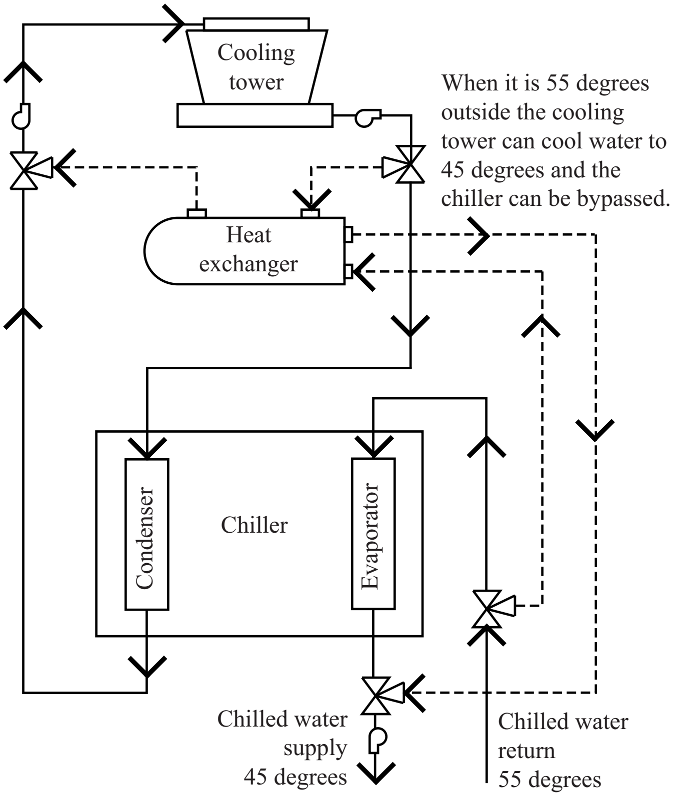

FIGURE 23.7 A cooling side economizer system often called free cooling.

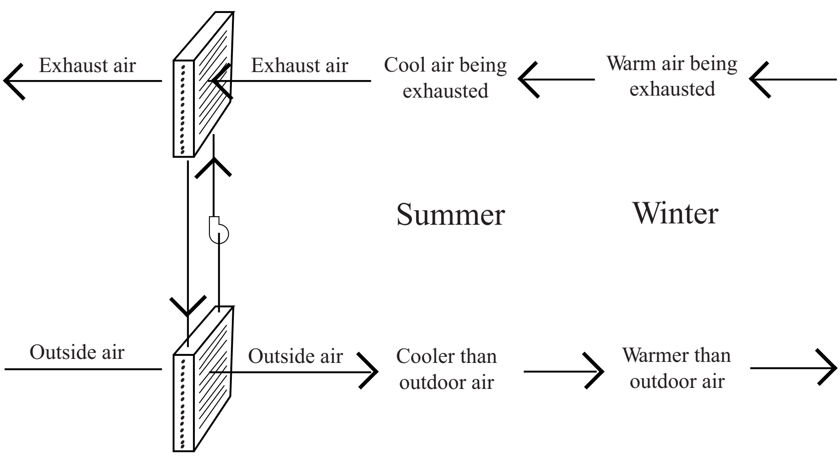

FIGURE 23.8 A run around coil system to recover heat or cold from the exhaust air and deliver it to the supply air.

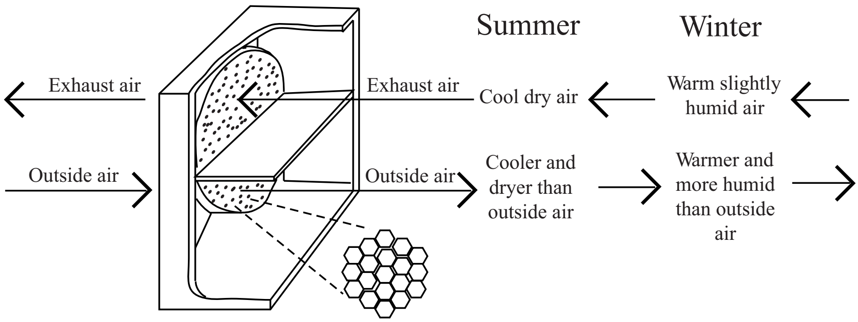

FIGURE 23.9 An energy transfer wheel can capture both heat and humidity from the exhaust air and deliver it to the supply air.

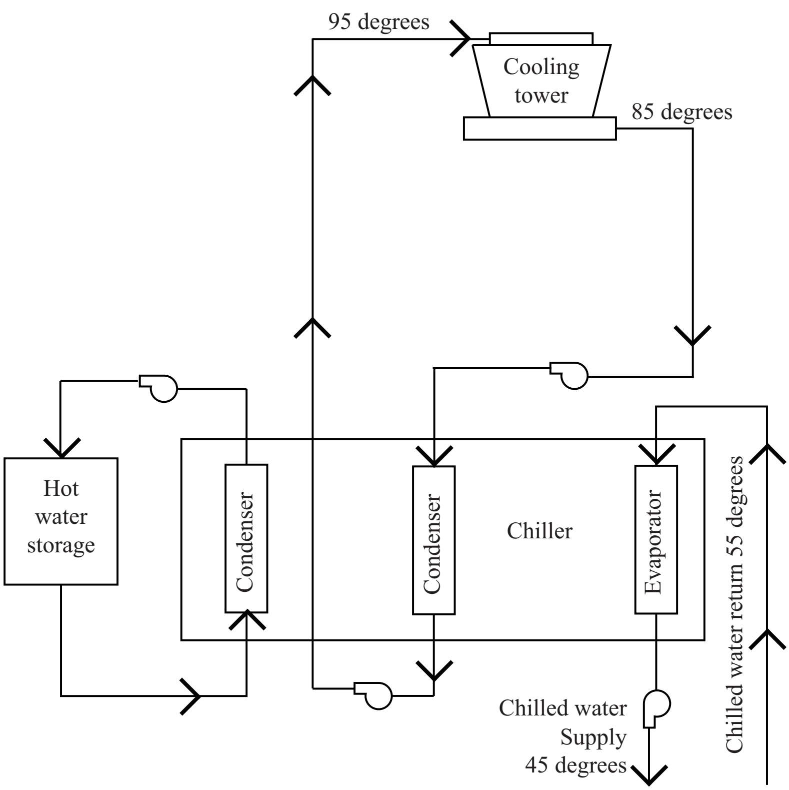

FIGURE 23.10 A dual condenser chiller captures some of the heat that would be rejected to the cooling tower for use in the building.

and lower humidity levels are then put into the fresh outside air stream being brought into the building.

The chiller takes heat out of the chilled water that is used to cool air in the air handlers. The chiller then exhausts the heat to the atmosphere through the cooling tower. A dual condenser chiller can capture some of the heat that is going to the cooling tower and store it as hot water to be used in other building conditioning systems (Figure 23.10).

The peak cooling needs of a building generally happen in the early afternoon, and the highest peak cooling happens in late summer. The electric utility companies have to deliver electricity on demand. There is no good way to store electricity. It is expensive for the utility companies to have standby electric generation capacity so they charge commercial customers for their energy use, and for their peak use. To reduce peak demand, a building's chillers can be used at night to store chilled water or ice. There are two advantages: peak demand is lowered saving money, and the chillers run more efficiently because it is cooler at night than during the day, saving energy and money.

24

INDOOR AIR QUALITY

The majority of the work environment is served by mechanical HVAC systems. These systems are designed to provide a comfortable temperature and humidity range throughout the year. They are also designed to bring in fresh outside air. Fresh air is drawn in and mixed with return air. An equal amount of air is exhausted to the outside. If the fresh outside air is not sufficient, carbon dioxide will accumulate in the building. Carbon dioxide is an indicator for indoor pollutants since it is directly related to the number of people in the building. If carbon dioxide levels are too high there is not enough ventilation air. Sources of indoor air pollution include biological organisms, outgasing from building materials and furnishings, outgasing from cleaning materials, ozone from copy machines, and pesticides. Control of indoor pollutants is two pronged. First, it is important to control and or eliminate the pollutants. Second, it is important to have enough fresh outside air to dilute the remaining pollutants. It is also important to have local exhaust from problem areas like copy machine rooms, areas where solvents are used, and bathrooms (EPA 1990, 1–2).

In 1984, the World Health Organization reported that up to 30 percent of buildings were the subject of complaints about indoor air quality. The problem was most often the result of poor maintenance and operation of the buildings. Sick building syndrome (SBS) is the situation where occupants experience discomfort and health issues related to time spent in a building. People report headaches, fatigue, dizziness, nausea, and eye, nose, or throat irritation. The symptoms are relieved when not in the building, but the cause of the symptoms is not known and usually very hard to pin down. The solution is usually to take a careful look at indoor air pollutants and to increase outside air ventilation rates. Indoor pollutant sources can be chemical, volatile organic compounds (VOCs) that come from almost everything inside a building. Indoor pollutants can also come from biological sources like mold, pollen, and bacteria. Another source of indoor air contamination is chemical or biological contaminants coming in with the fresh air being drawn into the building. This includes vehicle exhaust, and building exhausts as a result of badly located fresh air intakes. Building related illness (BRI) is where there is a specific cause for cough, fever, chills, and muscle aches. An example of BRI is Legionnaires' Disease, which is caused by a bacterium that grows in poorly treated cooling tower water. The aspirated water from the cooling tower then finds its way into the building through poorly located outside air intakes (EPA 1991, 1–2).

In a commercial building there are many different thermal zones. The dominant HVAC system responding to this multiple thermal zone problem is the variable air volume system (VAV). A VAV system supplies cool air through a supply duct. The temperature of the cool air is set to handle the largest cooling problem in the building. Other zones that do not need as much cooling reduce the amount of cool air entering the zone through a VAV box. If a zone needs heating, first the amount of cool air is reduced; then the air is reheated to provide the needed heat. As the air flow to individual zones is reduced, a pressure sensor in the supply duct tells the supply fan to reduce its air flow rate. As a result of this control scheme, most of the time the VAV system is operating at less than the design air flow rate. If the fresh air damper system is fixed to provide the proper amount of fresh air at the design air flow condition, most of the time there will not be enough fresh air entering the building. The difference between the design and actual amounts of fresh air gets larger as the weather gets colder (EPA 2000, 7).

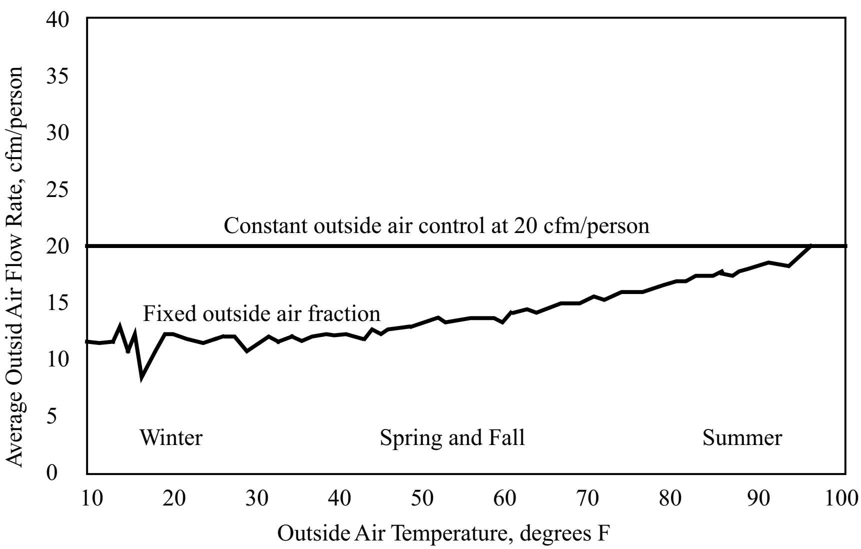

FIGURE 24.1 Fresh outside air quantities supplied by a variable air volume HVAC system with constant (adjustable) outside air control compared to systems with fixed (unable to adjust) outside air control.

Source: EPA 2000.

In a VAV system the fresh air amount needs to be adjusted so that the correct amount of fresh air is introduced into the building independently of the volume air flow rate that the air handler is pushing into the building. One mode of controlling this is by measuring the carbon dioxide level in the return air as the indicator of what volume of fresh air is necessary. ASHRAE Standard 62–1999 calls for 20 cubic feet per minute (cfm) per person to be introduced into the building independent of the air flow rate from the air handler into the building (EPA 2000, 7–8).

Buildings have interior and exterior zones. Interior zones are surrounded by conditioned space and therefore have no heat losses; thus an interior zone is a cooling all year long zone driven by the internal heat of people, lights, and equipment. The exterior zones on the east, south, and west can have large cooling loads as the sun moves through the sky. The north zone is more stable in its thermal needs. The exterior zones also have heating needs in cold weather. On average, the air flow in a building is about 1 cfm per square foot of building. The interior zone with its less demanding thermal requirement only needs about 0.5 cfm per square foot. The north zone needs about 1 cfm per square foot, and the east, south, and west zones need about 2 cfm per square foot. If there is one large VAV system supplying all these zones, the interior zone does not get its fair share of the 20 cfm per square foot that the air handling system is bringing in, and the east, south, and west zones get way more than their fair share of the fresh air (EPA 2000, 11). The solution to this problem is to have a separate VAV system for the interior zones, and ideally separate VAV or induction systems for each of the exterior zones. All the zones will then receive their fair share of the fresh outside air.

An economizer system compares the outside air temperature and humidity to the return air temperature. When the outside air is cooler than the return air temperature and not too humid, the economizer brings in up to 100 percent outside air and exhausts up to 100 percent of return air. As the outside air drops below the supply air temperature the economizer slowly adjusts the percentage of outside air down to the 20 cfm per person rate. During the time the economizer is in operation there is less to no need to cool the supply air. This saves energy. Also, while the economizer is operating, the amount of fresh outside air entering the building is vastly increased, which improves indoor air quality (EPA 2000, 8).

ASHRAE Standard 66–1999 calls for 15 cfm per person for education and auditorium occupancies. The high occupancy capacity of these venues results in a large outside air flow rate. This can make it difficult to control humidity when the outside air is warm and humid. An answer to this problem and to the energy use caused by large amounts of outside air is to install an energy recovery system that transfers both latent and sensible heat from the exhaust air to the outside air taken into the building (EPA 2000, 9–10).

Building designers and operators are always looking for ways to reduce energy use. Some of the methods used do not hurt indoor air quality and some can even improve indoor air quality. In general the energy savings schemes that are compatible with indoor air quality do not reduce the fresh outdoor air flow rate.

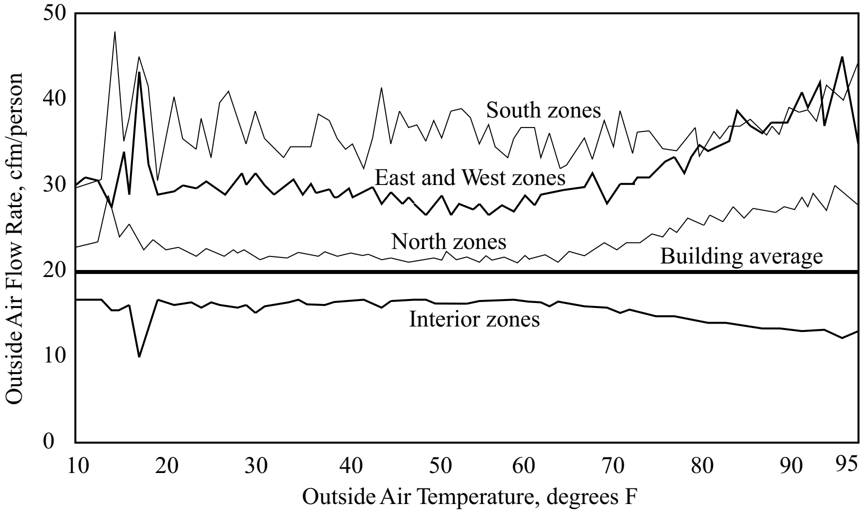

FIGURE 24.2 Fresh outside air quantities supplied by a VAV HVAC system to exterior and interior zones of a building.

Source: EPA 2000.

Increasing the thermal resistance of the building shell, reducing lighting energy use and improving the efficiency of HVAC equipment does not affect indoor air quality. An economizer, and night pre-cooling, both bring in more fresh outside air than the required minimum amount and thus improve indoor air quality. Carbon dioxide controlled fresh air ventilation improves indoor air quality by insuring the proper amount of fresh air at all times. Reducing HVAC operating hours, reducing outside air ventilation rates, and using a fixed outside air flow rate with a VAV system will lower indoor air quality by reducing the fresh air flow rate below necessary levels (EPA 2000, 33–34).

25

GREEN ROOFS

Green roofs provide many benefits. They reduce cooling loads, by reducing the temperature of the roof surface by shading it and by evapotranspiration. The surface of a green roof, and thus the air directly above the green roof, will be significantly cooler than the surface of a traditional roof and the air above the traditional roof. This reduces the heat island effect seen in urban areas (Figure 25.1). A green roof protects the roof membrane from damage caused by sun and storms, and a green roof can create a park-like environment for people to use directly or use by looking onto the greenery.

Evapotranspiration is the process where plants draw water up through their roots, transpiration, and then evaporate the water as vapor from their leaves. The water is used along with carbon dioxide to create the molecules that the plant uses to construct itself. The waste product in this process is oxygen. The water evaporating into the air above the plants reduces the air temperature. On a Chicago roof with temperatures in the 90s, a green roof's surface temperature ranged from 91 to 169 degrees Fahrenheit. A dark conventional roof on a nearby building was 169 degrees Fahrenheit. Also, the air temperature slightly above the green roof was 7 degrees Fahrenheit cooler than the air above the conventional roof (Hogan et al. 2008, 3).

Green roofs are classified into two categories. Extensive green roofs are not very deep and have hardy plants that can thrive on a roof top and can survive through low water times. Once established these roofs do not need much maintenance, and since the growing medium is only two to four inches thick, the structural weight of an extensive roof is not great. Extensive roofs can be located on sloped roofs up to about a 30 degree slope. Intensive green roofs have a growing medium that is somewhat deeper to a lot deeper than an extensive green roof. The depth of growing medium allows an intensive green roof to be more like a garden on the ground. The depth of growing medium also creates a considerable structural

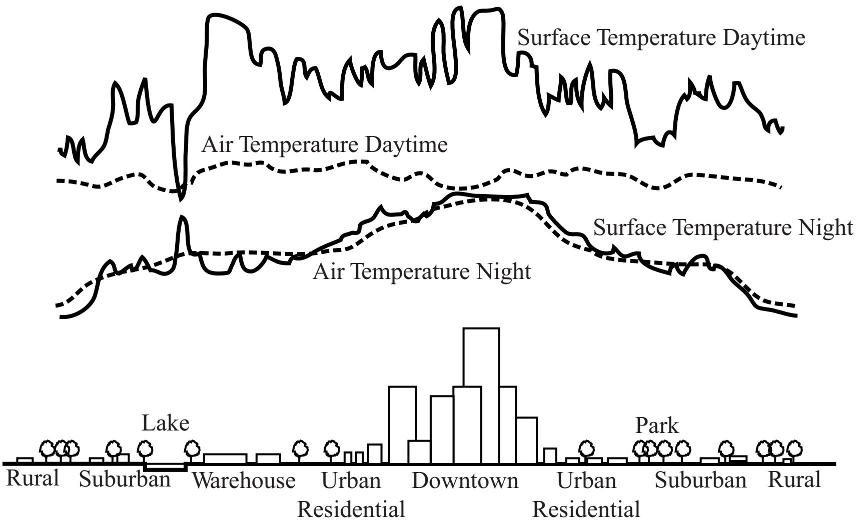

FIGURE 25.1 The heat island effect over an urban area.

Source: United States Environmental Protection Agency, Heat Islands. www.epa.gov/heatisland.

load, and there is more maintenance involved taking care of the plantings. Irrigation may be necessary.

Green roofs reduce energy use in buildings. In the summer, when the air is hot and the Sun is beating down, a green roof reduces the part of the cooling load that comes through the roof. This is enhanced when the growing medium is wet. The thermal mass of the green roof provides a slight reduction in the heating load through the roof, but the reduction in cooling load through the roof is more prominent, approaching a 75 percent reduction. Green roofs take in carbon dioxide and give off oxygen, and can make modest reductions in air pollutants like particulate matter, NO*x*, SO*x*, CO, and ground level ozone. A 1,000 square foot green roof can absorb the particulate matter produced by 15 cars over a year's time. Green roofs aid in storm water management. Green roofs absorb rain water and hold on to it for a while. More water is contained in a deeper intensive green roof than in a thin extensive green roof. Evapotranspiration puts some of the water back into the atmosphere. Depending on the green roof type 50 to 100 percent of the water falling on the roof is retained on the roof. Even if a green roof cannot contain all the water that falls on it, the roof delays the runoff, which reduces peak runoff while also filtering the runoff. Finally green roofs provide improved quality of life. Intensive green roofs can provide outside green spaces for people in tall buildings. Both intensive and extensive green roofs often are coordinated with outside decks so occupants can enjoy the green outdoor space even if walking on the roof is not advisable. Green roofs can also provide habitat for species in threat (Hogan et al. 2008, 5–10).

The California Academy of Sciences building in Golden Gate Park in San Francisco, designed by Renzo Piano, is a LEED Platinum building. It has a 2.5

FIGURE 25.2 The green roof on the California Academy of Sciences Building in Golden Gate Park, San Francisco, California. The architect was Renzo Piano, and the green roof was designed and installed by Ran Creek in 2008. Photo by Carl Bovill.

acre green roof designed by Ran Creek. The green roof is a mix of native annual and perennial plants designed to provide habitat for butterflies (Wels 2008, 66–75). The building produces 50 percent less waste water than the old building. Rainwater is used for irrigation. There are 60,000 photovoltaic cells mounted on an overhang that surrounds the building and 90 percent of the occupied areas are naturally illuminated. Recycled steel and concrete were used in the construction and the insulation was made from scraps of denim (Wels 2008, 58–63).

A green roof costs more than a conventional roof but the owner of the building needs to consider the energy savings associated with the green roof, and the municipality should provide a storm water management benefit to the building because of the green roof. Then there are the habitat benefits and the heat island benefits that are difficult to put a value on.

The structure of a green roof starts with the growing medium, which is mostly inorganic material with only 20 percent soil. Extensive roofs have 6 inches or less, and intensive roofs have 8 inches or more. Below the soil is a membrane designed to let water through but hold back the growing medium. The next layer is a drainage matt so excess water can drain away. Below that is a root barrier to keep invasive plant roots from penetrating the roof membrane. Closed cell thermal insulation is the next layer. And finally the roof membrane is applied on top of the structural deck. Ideally the roof membrane is adhered to the roof deck so that any future roof leak problems can be located easily. If the roof membrane is not adhered to the roof deck or is located above the roof insulation water from a leak can travel underneath the membrane before finding a path into the building below. Finding the cause of the leak is then much harder. Extensive green roofs require plants that have shallow roots, that are self-propagating, and that can withstand the extreme temperature, sun, and wind conditions on a high roof. Succulents meet all these criteria and are drought resistant. Intensive green roofs with their deeper growing

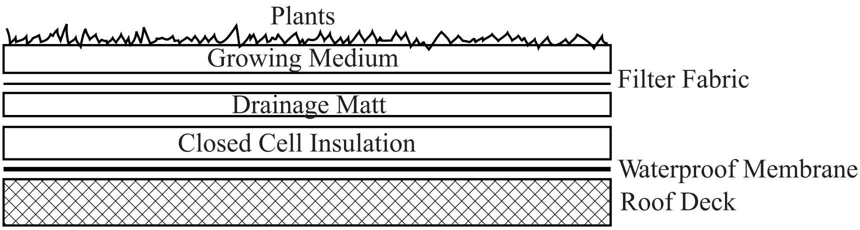

FIGURE 25.3 A cross section through a typical green roof.

medium can have a wide variety of plants from grasses, through shrubs, to trees (Hogan et al. 2008, 15–16). Roofmeadow is a green roof company located in Philadelphia, PA. Their website (www.roofmeadow.com) has a wealth of information on detailing green roofs.

Some maintenance is necessary. During the first year or two, as the roof is establishing itself, weeding will be required. After that a slow release fertilizer is often necessary. Extensive green roofs may need irrigation as they mature but should be designed to live off the natural rain supply. Intensive green roofs can require irrigation depending on the climate. As with planted gardens on the ground replanting will be needed at times. Dry plant materials on a roof can pose a fire safety problem. An irrigation system can mitigate this and fire breaks approximately 2 feet wide will contain the spread of a fire if one gets started (Hogan et al. 2008, 16–18).

The U.S. Green Building Council LEED green rating system provides points for the benefits that green roofs provide.

26

MATERIAL CHOICES

The greenness of a material is a complex issue. The problem can be broken down into a series of questions but even those questions can create questions. As an example consider the question. Is it hazardous? The question is when it might be hazardous. Is it hazardous installed, or during installation, or during mining, manufacturing, or transportation, and was there a hazardous substance used or discarded into the environment? Using local materials reduces transportation energy use. What happens if most of the material is local but some of it is not? Using recycled materials is a good thing, but what if the recycling facility is far away, or a toxic glue is used to bind the recycled material together. The question of energy intensity is simple, but what energy source is used? Coal puts far more carbon dioxide into the air than natural gas. After use, is a product capable of being recycled? There are levels of recycling. Steel can be recycled as steel. Concrete cannot be recycled as concrete. Concrete gets down-cycled to rubble. Green is a fuzzy term, but that does not mean that we should not push the concept (Spiegel and Meadows 2006, 33).

A set of questions following a product from raw material source, through production, shipping, installation and use, to resource recovery can help determine the level of greenness of a material by tracing its life cycle. Is a raw material from a renewable or certified source? Is it recycled pre- or post-consumer? And, finally, is it toxic or is part of the extraction process toxic? In production, the questions involve how much energy is consumed, how much water is consumed, and how much waste is produced. Is the waste recycled, and is the water reused? Shipping is a fairly straightforward issue. How far is the material shipped from raw source to production, and finally to the site. Local materials are obviously greener than materials from across the world. Installation and use bring up questions about hazards to workers and product durability and maintenance. Also does the product or the finishes necessary for the product produce VOCs? Finally there are questions about what happens to the product when its useful life is over. Can it be recycled or reused, and if it becomes part of the waste stream is it biodegradable (Mendler and Odell 2000, 140)?

The three main construction materials are concrete, steel, and wood. Concrete is gravel and sand held together with Portland cement. In building construction it is reinforced with steel bars. The mining of the sand and gravel can create environmental problems. Portland cement is a mixture of lime, iron, silica, and alumina, which are crushed and ground and then heated to 3,000 degrees Fahrenheit in a furnace to produce clinker, which then is ground into cement. This process uses a large amount of energy. Concrete is usually a local product since the raw materials are widely available. Concrete is also durable and does not give off any VOCs, but it is not recyclable as concrete and often ends up in landfills as rubble. Steel is an alloy of iron with less than 2 percent carbon. Iron mines are locally destructive. Steel production from iron ore uses large amounts of energy derived from coal, which translates into greenhouse gases. Steel is produced in a limited number of plants, and thus requires transportation to fabrication locations and then to the job site. Steel is strong, durable, and does not give off VOCs. Steel is highly recycled. The recycling process uses electric furnaces to make recycled steel back into steel. This is one of the best examples of an industrial material once produced from raw materials being continually reused rather than becoming part of the waste stream. Wood is a natural renewable product however it often comes from the clear cutting of forests. A large percentage of wood used in the United States comes from forests in Canada and the Pacific Northwest. This adds transportation costs to wood's environmental footprint. Wood is durable if detailed correctly so it does not remain wet after rainfalls. However wood is usually covered with stains, sealers, and or paint, which can outgas VOCs. Wood can be reused as framing, or recycled in the form of particle boards. The Forest Stewardship Council (us.fsc.org) certifies wood that is produced in a sustainable manner (Freed 2008, 86–89).

Three important secondary construction materials are brick, glass, and drywall. Brick has been around for a very long time. Brick is made from clay that is fired in a kiln, which uses a large amount of energy. Brick production is often local, so transportation costs are minimized. Brick is durable and an inert material so it does not outgas; however, brick is not often recycled because it is hard to collect in a demolition process. Glass is made from silica (sand), which is available everywhere. The silica is melted and floated on molten tin, which requires energy. Glass production is usually local. Glass is durable unless shattered by an object, and glass is inert, so there is no outgasing. Glass can be recycled, crushed and reheated back into glass. Drywall has an inner core of gypsum covered in paper on all sides. The gypsum is mined, which can be an environmental problem, and requires heat to turn it into gypsum plaster. Drywall production is often local, minimizing transportation issues, but installation on the job site creates significant drywall waste. If separated at the construction site, drywall waste can be recycled. Drywall requires paint to be durable, so the choice of a low VOC paint is important.

Demolition usually damages drywall and intermixes it with other materials, so it is hard to recycle at this end stage, but it is possible (Freed 2008, 88–91).

There are an almost infinite variety of products that are installed in commercial buildings. *The GreenSpec Directory*, published by Building Green (www.greenspec.com), is a comprehensive source of green material information. It follows the Master Spec format. Each section has an introduction to important green specification concepts followed by a list of manufacturers that produce green products.

Finally there is a growing list of certification programs that can help designers make green choices. The Carpet and Rug Industry has a Green Label Plus (www.carpet-rug.org). The Forest Stewardship Council (us.fsc.org) certifies that wood was sustainably harvested. Greenguard (www.greenguard.org) provides standards for low VOC materials. Green Seal (www.greenseal.org) tests paints, household cleaners, and window products for environmental quality. Ecologo (www.ecologo.org) certifies the greenness of a wide range of products. Ecologo and Greenguard are both backed with an Underwriters Laboratory (UL) seal of approval. Finally at ul.com/environment, there is a search space that provides a list of green materials and Greenguard certificates listing outgasing and other information.

PART V
The Urban Scale

Urban design provides probably the most important tool in the creation of a sustainable society. A green urban dwelling unit combined with the accompanying reduction in automobile miles traveled uses 25 percent of the energy of a suburban dwelling with its automobile miles traveled. The United States Green Building Council's LEED rating system for neighborhood development provides a good overview of the important features to consider, such as not building on ecologically sensitive sites, and reinforcing compact walkable urban layouts connected by urban transit. These features echo the concepts of New Urbanism. Urbanism starts with a walkable neighborhood connected to the city at large with rail and bus transit systems. The city is then connected to other city centers in the region with a rapid transit system. San Francisco provides a good example of a compact city made up of neighborhoods connected by streetcars and buses to the city center, which is connected to the region through the Bay Area Rapid Transit system.

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27

URBAN EXAMPLE

San Francisco

San Francisco city and county occupy the same land area at the end of the San Francisco peninsula (Figure 27.1). The land area is about 47 square miles with a population of approximately 800,000 people, which is the most densely populated city in California (SF Genealogy 2014). San Francisco was founded in 1776 by the

FIGURE 27.1 San Francisco is surrounded on three sides by the Pacific Ocean and San Francisco Bay.

Source: Wikimedia, San Francisco. Public Domain. Photo by Paul.h. 2006.

Spanish, who set up a fort and a mission named for Saint Francis of Assisi. The Spanish name for the city was Yerba Buena. At the start of the Mexican American war, Commodore John Sloat sailed into Monterey Bay to claim California for the United States, and Captain John Montgomery arrived in San Francisco a few days later. The city was given the name San Francisco at this time. Sloat and Montgomery are the names of major streets in San Francisco. The gold rush of 1849 caused a population surge, and California was admitted as a state

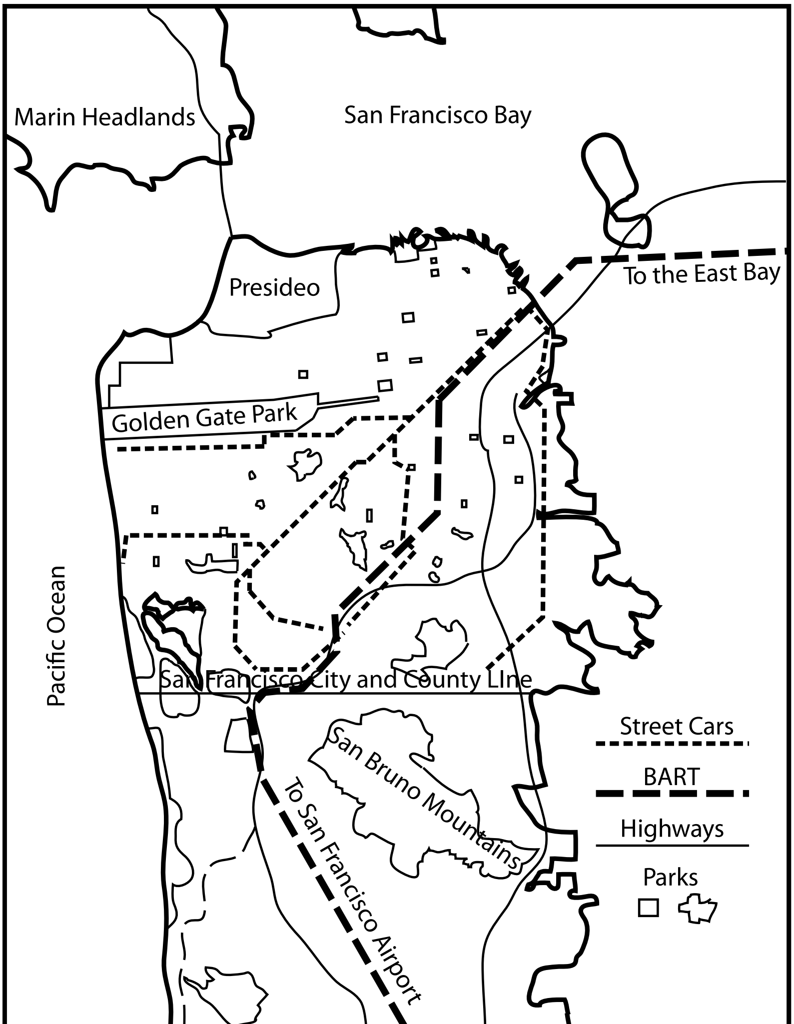

FIGURE 27.2 San Francisco City and County showing parks, street car lines, major highways, and the Bay Area Rapid Transit system.

FIGURE 27.3 Neighborhoods center around shopping areas often related to and served by the street car lines.

(San Francisco 2014). The wealth of the gold rush created other business opportunities. Wells Fargo and the Bank of America created a banking industry, Levi Strauss sold dry goods, and Ghirardelli started making chocolate. By 1890, the population was 300,000, and the city was known for its open attitudes, for the arts, and for wealth displayed by large houses (SF Genealogy 2014).

At 5:12 am on April 18, 1906, the San Andreas fault ruptured causing a great earthquake. Three quarters of the city was either collapsed by the earthquake or burned by the fires after the earthquake. San Francisco was rebuilt on the existing city grid. In the early part of the twentieth century the municipal railway system was developed. The J, L, K, N, and M streetcar lines still operate today, moving people from the neighborhoods into the city center (SFMTA 2014). World War II brought a large flow of people and goods through the port of San Francisco and, after the war, many of the people decided to stay. San Francisco's open attitudes spawned the beat generation in the 1950s, the hippie summer of love in the mid-1960s, and the gay renaissance in the 1970s. The personal computer industry developed around Stanford University in what is now called Silicon Valley in the 1970s and 1980s, followed by the dot-com companies in the 1990s. This created an entrepreneurial environment that feeds on itself creating many diverse startup companies, which are a mainstay of employment in the Bay Area (San Francisco 2014).

The city of San Francisco has the ultimate in urban boundaries (Figure 27.2). There is water on three sides. The Pacific Ocean is on the west, with the San

Francisco Bay to the north and to the east. Lake Merced and the San Bruno mountains create barriers to the south. The City and County of San Francisco are the same geographic entity. These hard urban boundaries focus development toward density. San Francisco has many neighborhoods that surround neighborhood retail centers that are often located at prominent street car line stops (Figure 27.3). This creates a situation where people walking to and from transit lines that take them into the city center can shop for food and other items on their everyday transit journey. The urban neighborhoods display a variety of street sizes, from residential

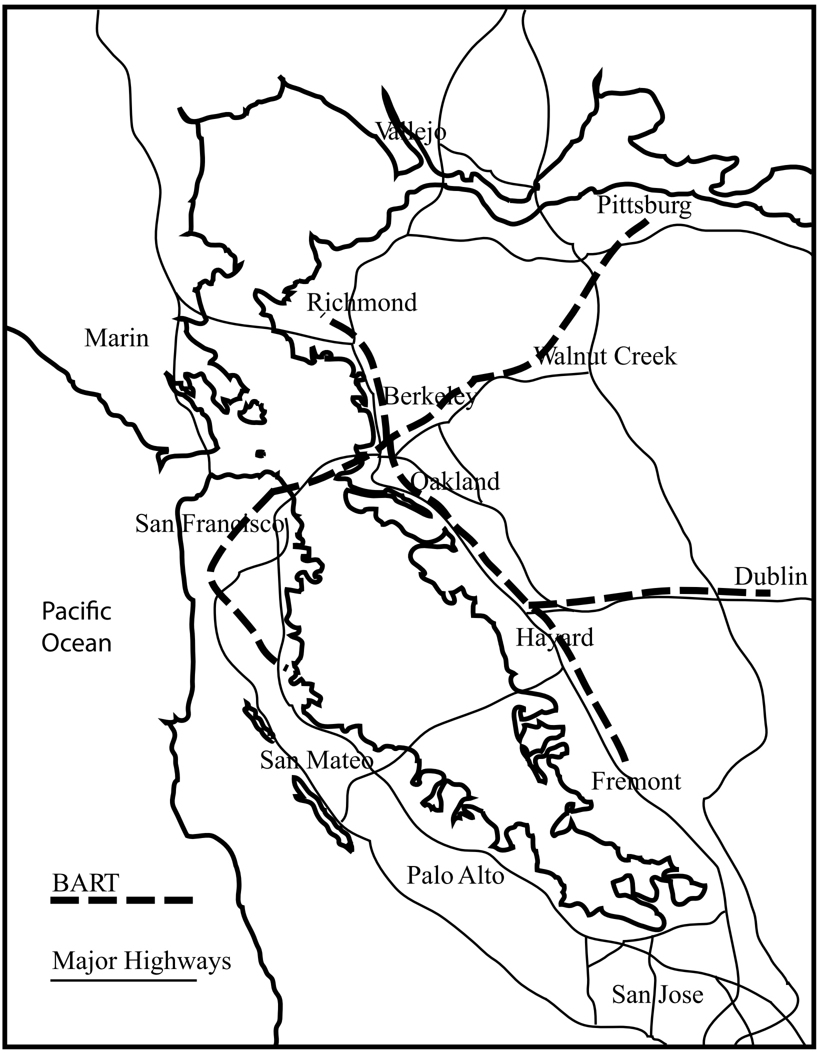

FIGURE 27.4 City centers and residential areas surrounding San Francisco Bay are connected by the Bay Area Rapid Transit system (BART).

streets that, with parallel parking on both sides, provide tight driving space for cars, to urban boulevards that move people between neighborhoods and around the city. The city is a grid of streets that create many paths to get from one place to another.

The density of the city calls for urban parks. There are parks of all sizes, from small and medium sizes to Golden Gate Park, which stretches across a large area of city from the ocean almost to City Hall. These parks provide outdoor recreation spaces for a dense population. There are open grass spaces, woodlands, tennis courts, baseball fields, and golf courses. In Golden Gate Park, surrounding a music concourse, are the De Young Art Museum, The California Academy of Sciences, and the Japanese Tea Garden.

The Bay Area Rapid Transit (BART) system connects San Francisco with the East Bay Area (Figure 27.4). And Caltrans trains connect San Francisco with the peninsula south of the city. The BART trains run under Market Street, through the commercial center of the city.

In summary San Francisco with urban boundaries of ocean and bay to the west, north, and east, and Lake Merced and the City and County line on the south, developed into a dense walkable urban center. Multiple neighborhoods are connected, by a street grid and a municipal transit system of streetcars and buses, to each other and to the city center. Urban parks from small to large provide open space. And, the city is connected to the surrounding Bay Area through the BART rapid transit system, and the Caltrans rapid transit system.

28

LEED FOR NEIGHBORHOOD DEVELOPMENT

LEED is a rating system developed by the United States Green Building Council. The rating system outlines important sustainable design features that neighborhood developers should incorporate, and provides a scoring system to rank success. The rating system is available on the USGBC website, www.usgbc.org/Leed/Rating-systems. LEED for Neighborhood Development has three major parts to it. "Smart Location and Linkage" provides guidance on choosing sites. "Neighborhood Pattern and Design" provides guidance on town layout. "Green Infrastructure and Buildings" provides guidance at a smaller scale. Finally there is also an allowance for "Innovative and Exemplary Performance".

"Smart Location and Linkages" steers development away from ecologically sensitive areas such as wetlands, agricultural land, floodplains, and steep slopes. It steers development toward denser infill areas that can provide jobs closer to housing, resulting in reduced automobile use. Finally the guidelines give credits for restoration and long-term conservation of habitat, wetlands, and bodies of water.

"Neighborhood Pattern and Design" provides credits for most of what is considered good new urban design. Compact design is reinforced with a call for a walkable, tree-lined street network serving diverse neighborhoods. Access to transit, recreation, local schools, and civic spaces echoes transit oriented development.

The "Green Infrastructure and Design" part of the LEED guidelines points the builder toward energy and water efficient buildings and landscaping. It also calls for site design features to use natural landforms to manage rainwater, to minimize solid waste with recycling, and to minimize wastewater. Solar orientation receives a credit along with minimizing site disturbance during construction.

Finally there are credits to be gained from innovative concepts that are not part of the formal credit system.

29

URBANISM

Peter Calthorpe in *Urbanism in the Age of Climate Change* (2011) makes a convincing argument that urbanism needs to be a major component of society's efforts to control greenhouse gas emissions. He compares high density city environments with moderate density, close-in suburbs, and finally with further-out, low density suburbs. The annual carbon emissions per household are 6 metric tons in the city, 10 metric tons in the close-in suburbs, and 21 metric tons in the low density suburbs (Calthorpe 2011, plates 4 and 5).

A suburban house can be made greener and the cars used to get around can be made more efficient, reducing energy use by about 30 percent (Table 29.1). A townhome in a close in neighborhood with public transit uses 38 percent less energy than a low density suburban house, even without solar panels or a super-efficient car. With a greener house and car, a close-in household uses 58 percent less than a suburban household. If an urban living unit is made more energy efficient and a more energy efficient car is used, the green urban existence uses 74 percent less energy than a suburban house (Calthorpe 2011, 19). These are significant reductions in energy use and, therefore, greenhouse gas reductions. The smaller energy use of urban living also translates into smaller utility bills and fewer new power generation plants. Urbanism reduces carbon footprint and is less expensive for the people living there and for the society as a whole (Calthorpe 2011, 10).

The current population of the United States is 296 million people, and we emit 23 metric tons of carbon per person per year. The population is growing at a rate that will add an additional 130 million people by 2050. Climate science suggests that we need to reduce energy use to 20 percent of our 1990 levels by 2050 to control greenhouse warming. This reduction, combined with population growth, means we need to reduce our per capita energy use to 12 percent of our current energy use (Calthorpe 2011, 8). If policy changes could move more of the population toward green urban living we would be well on our way to the

TABLE 29.1 Household energy use for the outer suburban sprawl, the inner compact suburbs, and the urban core in MBtu/year

	Cars	*House*	*Total*	*Percent*
Suburban	237	152	399	100
Green Suburban	158	113	271	69.4
Compact Suburb	119	126	245	61.4
Green Compact Suburb	79	88	167	41.8
Urban	71	80	151	37.8
Green Urban	47	56	103	25.8

Source: Calthorpe 2011, plate 3.

12 percent goal. Green urban living uses 25.8 percent of the current energy use of suburban living. Urban growth patterns can take us halfway with efficiencies in other sectors of the economy filling in the other half (Calthorpe 2011, 116).

To create a new urban way of life it is necessary to rethink how zoning and policy direct our attention to forms. Neighborhoods are the core concept with their interconnected walkable streets leading to a commercial core. Town and city centers are the next scale up and are connected to the neighborhoods by light rail and bus transit systems. Corridors connect the region together. Corridors are roads, regional and local transit, rivers, and power distribution. Preservers set aside natural features of the region, and, finally, districts collect large entities like airports and big box stores (Calthorpe 2011, 64). Human scale, from how houses and streets interact to how people get around the neighborhood and city, should be the guiding design principle. Diversity of building types at the residential and retail commercial scale provides a more usable community close at hand. Conservation calls for greener buildings that use fewer resources along with saving historical fabric and natural features (Calthorpe 2011, 53–55).

Human scale, diversity, and conservation as overreaching concepts can be applied at the neighborhood, city, and regional scales. Walkable streets at the neighborhood level become light rail and bus transit at the city scale and regional rapid transit at the regional scale (Figures 29.1 and 29.2). Clustered urbanism forms around the transit stops at a variety of appropriate scales (Calthorpe 2011, 56). This is a fractal concept. Fractal geometry is the study of self-similar shapes. Learning how to see with a fractal eye opens up a deeper awareness of the structure of natural and man-made systems. See Chapter 8 on nature's geometry.

Urbanism starts with the neighborhood. A neighborhood is a collection of housing with convenience retail and commercial business at its core. The size of a neighborhood is defined by Andres Duany as a 5 minute walk (Duany et al. 2010, 6.1). Others set the size at a 10 minute walk (Calthorpe 1993, 56). Either way, a neighborhood is more defined by its center than by its outside edge (Duany et al. 2010, 6.2). Actually at the outside edge there will be a fuzzy border between different neighborhoods. Housing density and diversity are important components for the support of a retail center that can provide at least some of the daily shopping

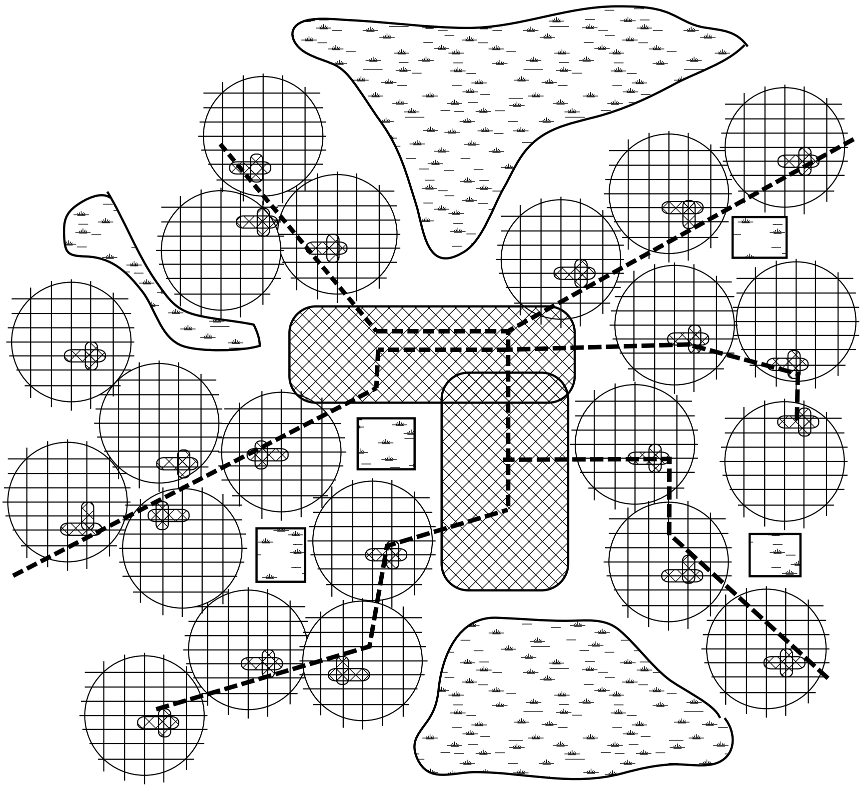

FIGURE 29.1 Neighborhoods connected together by a transit system become towns and cities less dependent on the automobile.

needs of the community. Schools are a very important component of neighborhood. The grammar schools are the glue that connects the parents of the children together, often creating lifetime friendships. Middle and high schools usually collect from multiple neighborhoods and thus provide cross neighborhood connections. A dense neighborhood needs a collection of small parks of about one-quarter acre (Duany et al. 2010, 6.3). Related to these parks and possibly encompassing them, the natural features of an area should be preserved. This should include water drainage streams and wetlands, stands of trees, and high and low points of the site (Duany et al. 2010, 4.1–4.8). The street structure should provide multiple connections and multiple paths between the parts of the neighborhood. This usually means some form of a grid of streets and modest block size. The grid should also have multiple connections to other neighborhoods and the region (Duany et al. 2010, 7.1–7.4).

In and around neighborhoods there are typically three street types (Figure 29.3). Streets designed for easy flow of traffic, with parallel parking on both sides and two 10 foot wide travel lanes striped for clarity, are connecting streets between neighborhoods. Inside neighborhoods, there are two street sizes, streets that still provide

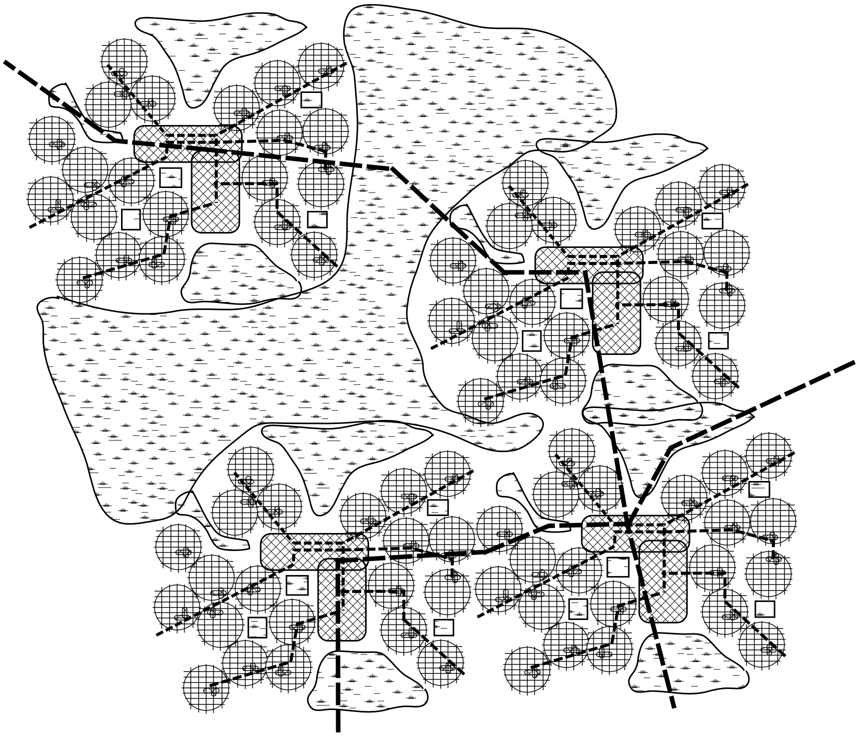

FIGURE 29.2 The cities and towns of an urban area connected together by an urban transit system reduce strain on the highway system and reduce the energy footprint of the urban dweller.

FIGURE 29.3 Dense neighborhoods in San Francisco demonstrate the mix of street sizes from connector streets to narrow neighborhood streets. Photo by Carl Bovill.

enough room for cars traveling in both directions, with parallel parking on both sides but with 8 foot travel lanes, which slows the traffic down, and streets serving the lower density housing in the neighborhood, providing only room for one car to pass if cars are parallel parked on both sides of the street (Duany et al. 2010, 8.9–8.11). Sidewalks sheltered from the moving cars with parallel parked cars and/or street trees are important to street life. In commercial areas, sidewalks should be 15 to 25 feet wide without obstructions (Duany et al. 2010, 9.1–9.6). A range of building types from apartments through to condos, townhouses, and small lot to larger lot houses needs to be provided to accommodate a diverse population (Duany et al. 2010, 12.2–12.8).

30

TRANSIT ORIENTED DEVELOPMENT

Transit oriented development (TOD) has overlapping goals with New Urbanism. However, transit oriented development is more focused on how the transit system relates to the development. The guidelines call for commercial and employment uses located near the transit stop, so that the rider gets off the light rail in a town center. The residential development around the town center needs to have enough density to support the town center and the transit stop. The average density is 18 units to the acre made up of a mix of 26, 16, and 10 dwelling units per acre with the higher density near the commercial core. All of this is located within a 10 minute walk to the transit stop (Figure 30.1). It is envisioned that there is a range of TODs with the more urban TODs along the main transit line with a relatively large commercial core, down to neighborhood TODs with a smaller commercial core and a higher percentage of residential development. The neighborhood TODs would be located on feeder transit lines. The TODs are a high density area, so public parks are a necessary part of the mix. Small and medium size parks need to be sprinkled around the development. The urban core should have civic buildings. Secondary areas, extending out about one mile from the commercial core of the TOD, contain mostly single family houses. This additional population helps support the commercial development and the transit stop (Calthorpe 1993, 56–61). The TOD, at 20 units per acre, has about 2,800 households. The secondary area, at 10 units per acre, has about 20,000 households.

Neighborhood TODs should have a mix of 10–15 percent public spaces, 10–40 percent core commercial, and 50–80 percent housing. Urban TODs should have 5–15 percent public spaces, 30–70 percent core commercial, and 20–60 percent housing. The neighborhood TODs located on feeder transit lines should be located so that the transit time to the urban TOD, where the main transit line is located, is about 10 minutes, which is about 3 miles. In order to achieve the residential density necessary to populate the TOD with enough households and provide choices

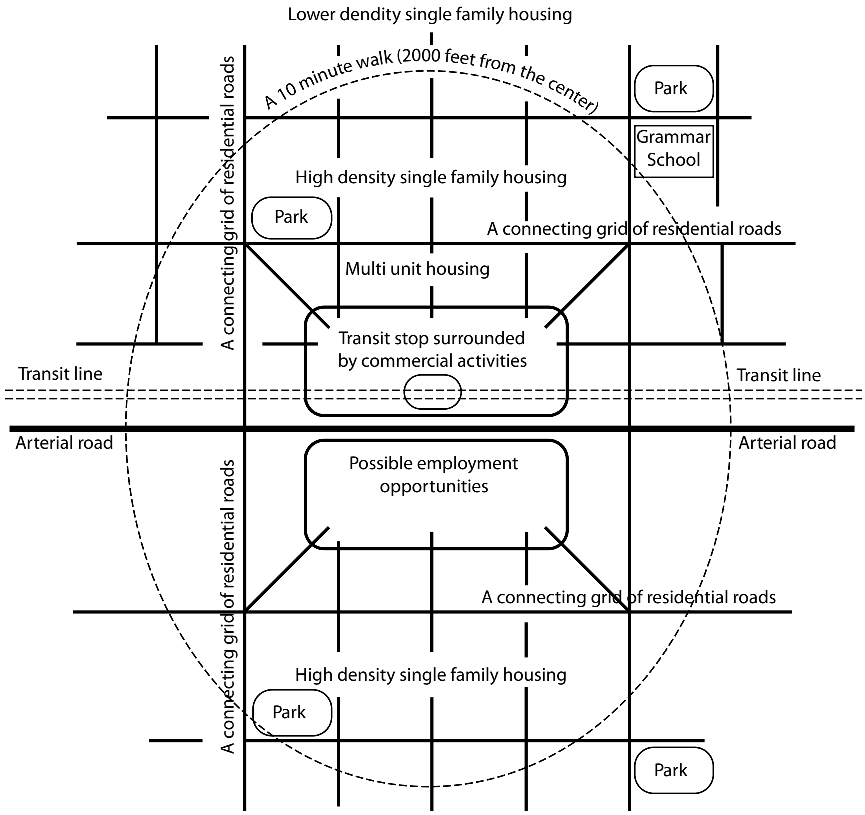

FIGURE 30.1 Transit Oriented Development (TOD) creates a walkable neighborhood around a commercial core with a transit stop at its center.

Source: Calthorpe 1993.

for the residents, a mix of residential units is necessary. The mix should include apartments and condominiums, townhouses, duplexes, and single family houses. The street pattern in the TOD needs to be a grid of some sort providing multiple paths to the core commercial area and transit stop. This grid needs to extend out into the secondary area surrounding the TOD. Buildings both commercial and residential should create a streetscape. Commercial buildings need to face directly onto the street, with parking on the street and parking lots if necessary in the center of blocks (Figure 30.2). Residential units should also create a street presence, with small front yard setbacks and porches to create a friendly community environment. In order to reinforce the vitality of the core commercial areas of the TODs it is necessary to space them out at least one mile apart, and the zoning should not allow strip commercial development along the arterial roads that connect the TODs.

Existing landscape drainage, wetlands, and creeks need to be respected and can be incorporated into the open space of the development (Figure 30.3). Indigenous plantings create a pleasant and easily maintained landscape (Calthorpe 1993, 62–75).

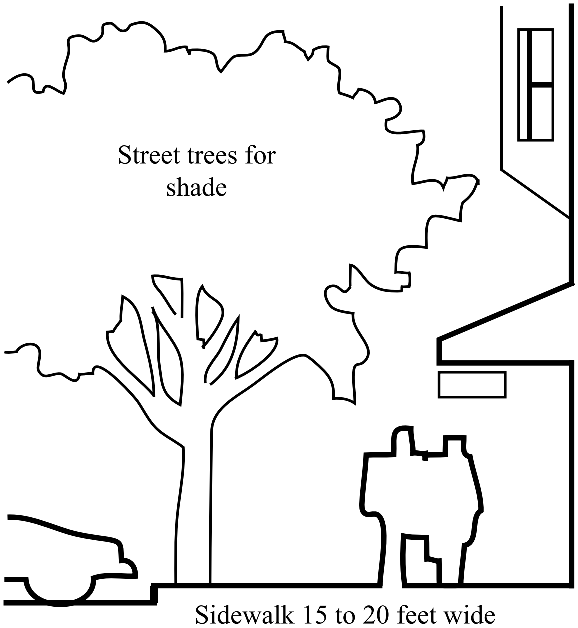

FIGURE 30.2 In the commercial core of the TOD the buildings need to front on the street with generous sidewalks and street trees.

Source: Calthorpe 1993.

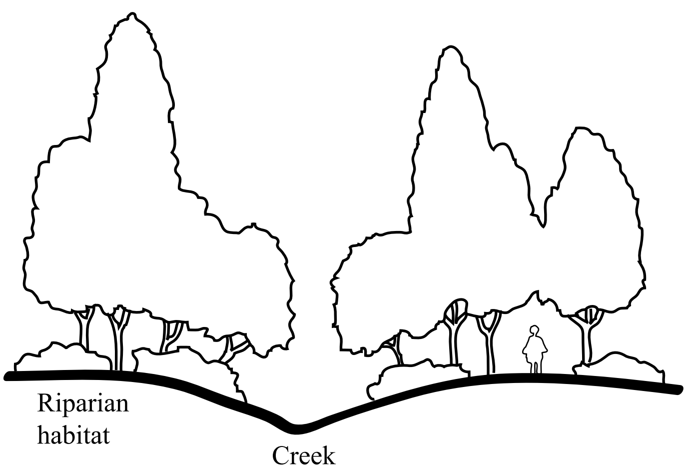

FIGURE 30.3 The urban layout of the TOD needs to respect drainage land and drainage patterns. Creeks and wetland areas can be part of the park open space needs of the community.

Source: Calthorpe 1993.

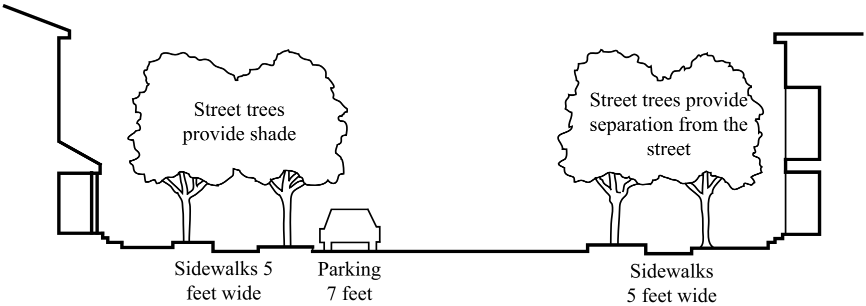

FIGURE 30.4 Sidewalks protected by street trees and parallel parked cars create a pleasant walking environment.

Source: Calthorpe 1993.

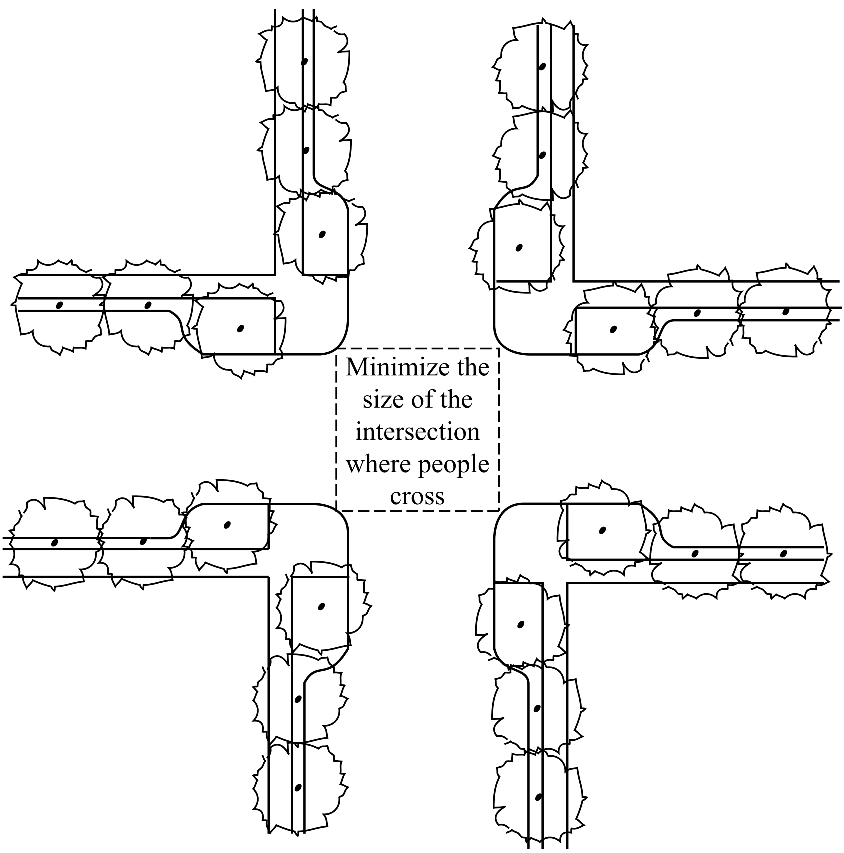

FIGURE 30.5 At corners, sidewalks need to widen out to the parallel parking line to minimize the size of the intersection. This makes crossing the street easier and slows cars down.

Source: Calthorpe 1993.

Parks of 1 to 4 acres need to be placed within a few blocks of everyone living in the TOD. Streets should be narrow enough to slow traffic. Street trees, spaced so that their canopies touch, create shade in summer, and, located between the sidewalk and the road, provide security for the sidewalk. Sidewalks should be a minimum of 5 feet wide, which lets two people walk side by side. On street parallel parking provides another buffer between the pedestrian and the moving cars on the street (Figure 30.4). At intersections, the sidewalk should widen out to the depth of the on street parking so that pedestrian crossing distance at the intersection is minimized (Figure 30.5). Larger parks with playing fields should be located on the boundary between the TOD and the secondary area. This boundary zone is also a good location for schools. A village green and a transit plaza should be about 2 acres in size and be located at the locus of the transit stop and the core commercial area. The transit stop needs to let residents off at the transit plaza with the core commercial shops in near proximity. Parking lots next to the transit stop are inappropriate. The intent is to create a walking environment. If parking is required it needs to be placed in the center of blocks away from the transit plaza. Kiss and ride drop-offs also need to be located away from the transit stop to avoid excess automobile traffic disrupting the pedestrian intent of the transit plaza and core commercial area (Calthorpe 1993, 87–106).

The overarching intent of transit oriented development is to create a denser living environment coordinated with an urban transit system. Urban households use 71 million BTUs per year for transportation and 80 million BTUs for running the household. Compare this to a suburban household that uses 237 million BTUs for transportation and 162 million BTUs for running the household (Calthorpe 2011, plate 3).

PART VI
Energy Sources

Coal, oil, and natural gas provide the vast majority of the energy that society needs to fuel itself. Coal is primarily used to generate electricity. Oil transformed into gasoline provides the high energy per volume useful for transportation. Natural gas is used in industry, and in home heating. Per energy unit delivered, coal puts more carbon dioxide into the air than oil, with natural gas delivering the least amount of carbon dioxide per unit of energy delivered. These three fuels provide 83 percent of the energy needs of the United States. Nuclear energy provides 8 percent, and renewables provide 9 percent. Renewable energy includes hydroelectricity, biofuels, including wood, wind, geothermal, solar thermal, and photoelectricity. Wind is the fastest growing renewable energy source. These numbers indicate that a transition to renewable energy will require a vast reduction in energy use along with a vast investment in renewable sources. A tax on carbon could provide a policy path to both goals.

31

CONVENTIONAL ENERGY SOURCES

Wood was the primary energy source throughout most of human history and remained so up until the industrial revolution. Population increases in Europe reduced the forest cover from 95 percent during the Roman Empire to 20 percent at the start of the industrial revolution (Figure 31.1). The shortage of wood and the energy density of coal combined with the steam engine to usher in the age of fossil fuels (Gore 2009, 52).

Conventional fuels can be classified as solid fuel, coal, liquid fuel, oil, and oil byproducts, such as gasoline, and gaseous fuels, such as methane. Liquid fuels have very high energy content per volume and are easily moved through pipelines and tanker trucks to distribution points where vehicles can have their gas or oil tanks filled up. These characteristics make liquid fuels very useful for transportation. Oil is currently the fuel society uses the most (Gore 2009, 54). Natural gas is the next primary energy source after oil. Natural gas is used primarily in industry but also to heat homes. Natural gas is the cleanest of the conventional fuels because it has fewer impurities and it has a higher ratio of hydrogen to carbon (Gore 2009, 55). When a fuel is burned the fuel is oxidized. The atoms in the fuel are rearranged to a lower energy state with the accompanying release of heat energy. The energy comes from the rearrangement of the hydrogen (H) and the oxygen (O) atoms. Methane is CH_4, and oxygen is O_2.

$$CH_4 + 2(O_2) = CO_2 + 2(H_2O)$$

Sometimes there are other atoms in a fuel, such as sulfur and or nitrogen. Then the combustion process produces sulfur oxides and nitrous oxides, which create smog. These impurities can be significantly cleaned from the exhaust gases, but usually not completely so. An important concept to understand is that the complete combustion of a fuel produces carbon dioxide (CO_2) and water (H_2O). There is no way to combust a fuel without producing carbon dioxide.

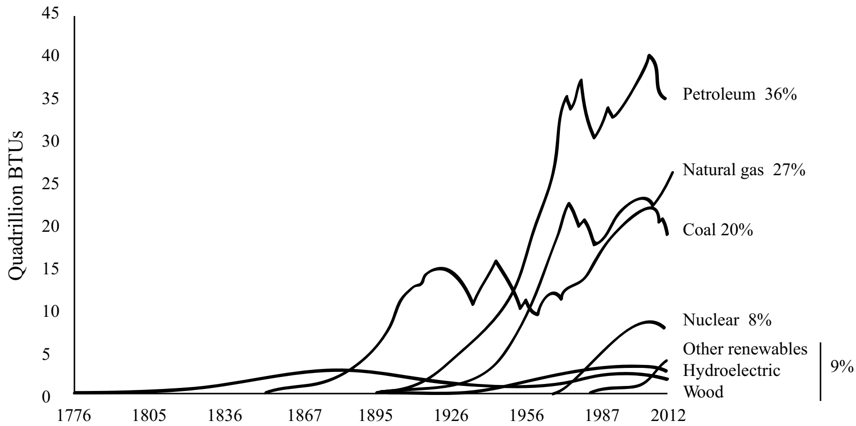

FIGURE 31.1 Energy use in the United States by fuel source.

Source: United States Energy Administration, Annual Energy Review 2011. www.eia.gov/are.

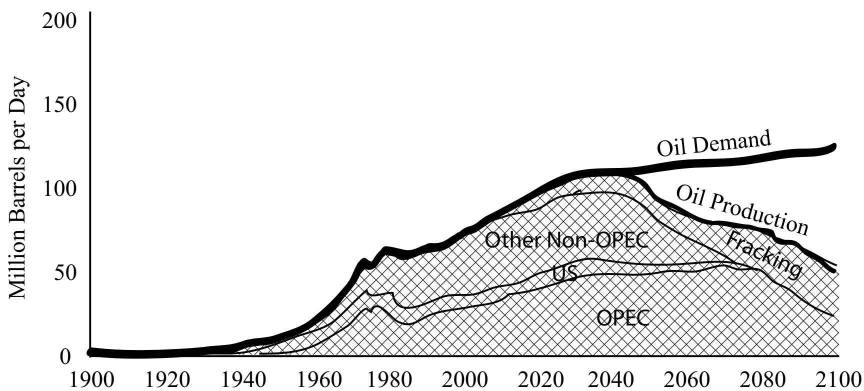

FIGURE 31.2 Projecting oil supply and demand through 2100.

Source: United States Energy Administration, Annual Energy Review 2011. www.eia.gov/are.

Burning natural gas results in 48 percent less carbon dioxide than burning coal, and 28 percent less carbon dioxide than burning oil (Gore 2009, 54–55). Natural gas produces less carbon dioxide per unit of energy because natural gas (CH_4) has a higher hydrogen to carbon ratio than coal or oil. Energy comes from the rearranging of the hydrogen and oxygen atoms. The carbon is along for the ride. In addition, oil and coal have significantly more impurities in them, with the resulting need to take the impurities out before or after combustion.

A rapidly approaching problem with the world's dependence on oil is that peak oil production will happen in the next few decades. Since demand for energy will continue to increase as the developing world expands, the price of the remaining dwindling oil supplies will increase quickly (Figure 31.2).

Nuclear energy is an option that does not burn a material to produce heat. Nuclear plants split uranium atoms, nuclear fission, which produces heat. Carbon rods in the reactor are used to control the chain reaction. Pressurized water is heated, which then creates steam that is used to turn turbines to create electricity. The accidents at Three Mile Island, Chernobyl, and Fukushima Daiichi after the tsunami have created a situation where there is considerable political opposition to nuclear power (Gore 2009, 164–165). In addition, there is the problem of what to do with the spent fuel, which needs to be isolated from the biosphere for longer than human civilization has existed.

Electricity is a very convenient energy carrier. It is produced by all of the fuels mentioned above. Coal, oil, or gas is burned and uranium is split to create heat that produces steam that turns turbines to produce electricity. Electricity is very useful to provide light and turn motors, so demand has grown. The United States generates electricity using coal (42 percent), gas (25 percent), nuclear (19 percent), hydro (8 percent), and other and renewables (6 percent). (U.S. Energy Information Administration 2011, 222) The dependence on coal for electricity is a major carbon dioxide problem. Another issue with electricity generation is that only about 35 percent of the energy content of the fuel burned to produce the electricity ends up as electricity; 65 percent of the fuel energy goes up the stack as waste heat.

Total energy, or cogeneration, systems generate electricity and then use the waste heat to create hot water for heating with heat exchangers and chilled water for cooling with absorption chillers. This process is used in situations where there is a consistent electricity demand coincident with a nearby heating and or cooling demand. Cogeneration can approach using 90 percent of the energy content of the fuel used.

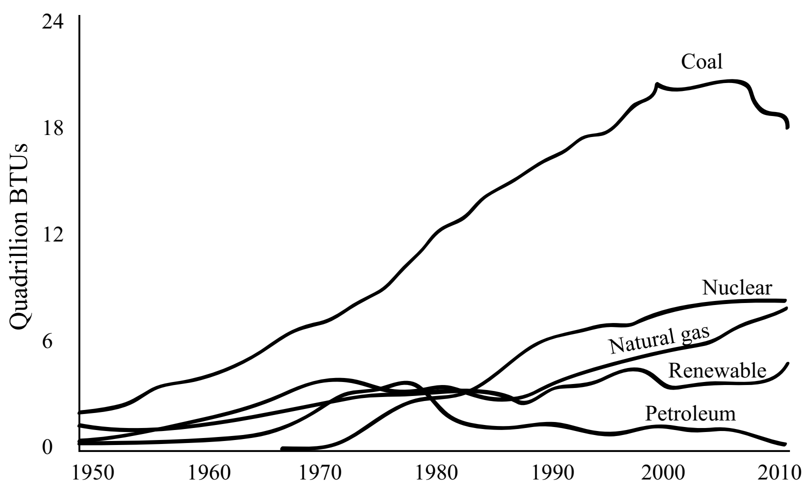

FIGURE 31.3 Electricity generation in the United States by fuel source.

Source: United States Energy Administration, Annual Energy Review 2011. www.eia.gov/are.

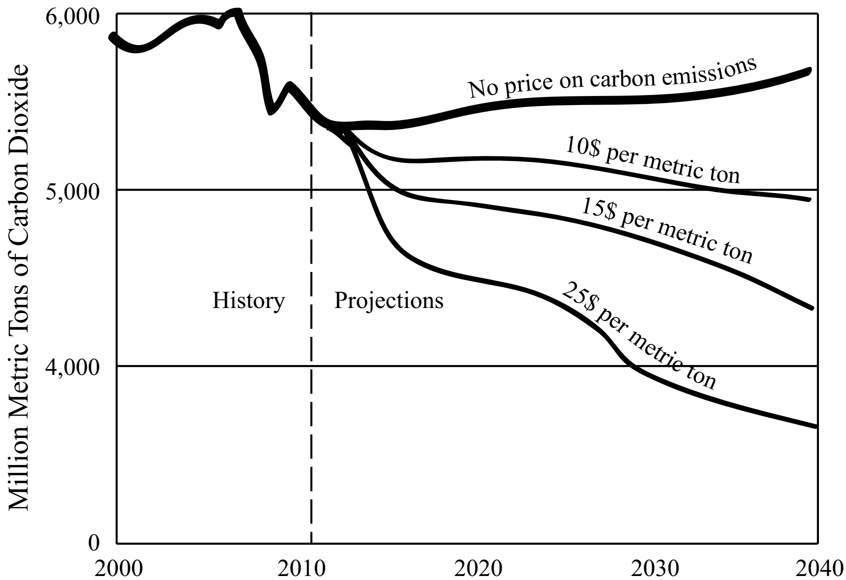

FIGURE 31.4 The reduction of carbon dioxide emissions resulting from a carbon tax of \$10, \$15, and \$25 per metric ton of carbon dioxide.

Source: United States Energy Information Agency, Annual Energy Review 2013. www.eia.gov/are

Taxing the use of fossil fuels through a carbon tax would have the dual benefit of raising revenue for the government and reducing the use of fossil fuels and thus carbon dioxide (Figure 31.4). A carbon tax would push users of coal toward natural gas, and in the long run cause a transition to wind, solar, and bio-fuels. The revenue generated by the tax could be used to facilitate the transition to alternative energy sources.

32

ALTERNATIVE ENERGY SOURCES

The amount of energy available from the Sun is almost unimaginable. One hour of sunlight falling on the earth has enough energy to power the entire earth for a year. If engineers can capture 1 percent of this energy, the energy to power the earth for a year could be captured in 100 hours. Assuming 8 hours per day collection time, it would take 12.5 days of captured solar energy to power the earth. Even if only one-tenth of this amount can be captured, it would only take 125 days of captured solar energy to power the earth. Solar energy also drives the winds and ocean currents. A month's worth of energy captured from wind could power the earth. There is also the geothermal energy of the earth itself. As fossil fuels get more expensive and harder to find, alternative fuels will become more and more affordable. Remember that coal replaced wood as society's fuel as the industrial revolution was beginning partially because wood became scarce (Gore 2009, 52–57).

Electricity can be generated from sunlight using mirrors to concentrate solar energy to heat a fluid, which then creates steam to turn a turbine to produce electricity. Electricity can also be generated directly from photovoltaic panels.

Concentrated solar thermal energy plants are large utility owned installations. There are three varieties. One has a large array of two axis tracking mirrors that reflect solar energy onto a receiver mounted on a tower (Figure 32.1). The high temperature fluid is then used to create steam to drive electric generators (Gore 2009, 64). The Ivanpah Valley, California solar tower power plant has 173,500 computer controlled mirrors focusing solar energy on a receiver at the top of a 46 story tower. Water is heated to 1,000 degrees Fahrenheit, creating steam to generate electricity. Enough electricity will be generated to power 140,000 homes (Bernstein 2014). Another method of concentrating solar energy is an array of linear parabolic reflectors that focus the Sun's energy on a pipe filled with a specially

FIGURE 32.1 A solar tower power plant in Daggett, California.

Source: Wikimedia Commons, Attribution-Share Alike 3.0, Photo by Kjkolb 2003.

designed fluid. This heat is then used to generate steam in a heat exchanger. The steam is used to generate electricity. The parabolic trough can be a smooth parabolic mirror or it can be made from many flat mirrors arranged in a parabolic shape. The third method involves a parabolic dish mirror that tracks the sun focusing solar heat on a receiver attached to the mirror dish. The heat generated is used by a Stirling Engine to generate electricity (Gore 2009, 64).

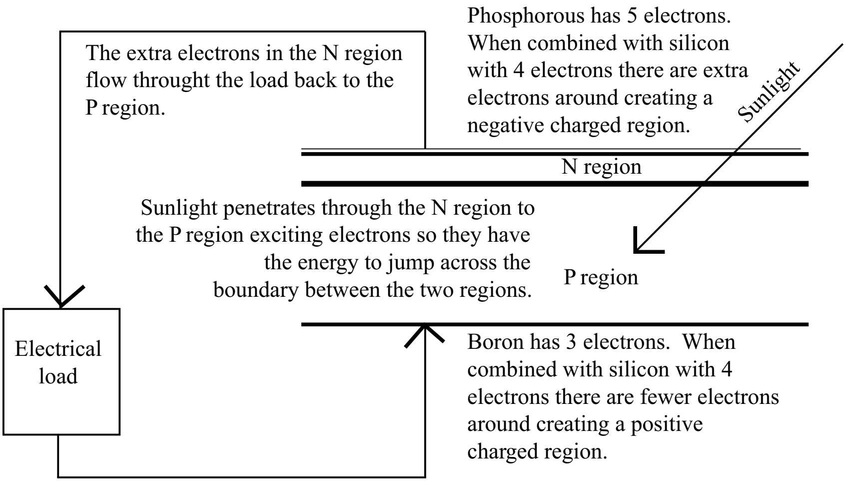

FIGURE 32.2 Photovoltaic panels produce electricity directly from the Sun by exciting electrons in the photovoltaic material.

There are concentrated solar thermal plants that were built in the Mojave Desert 25 years ago. They have a combined size of 2 million square meters of mirrors, and have operated continuously ever since (Gore 2009, 74).

Traditional photovoltaic panels are made from silicon (Figure 32.2). A thin top layer has a small amount of phosphorous in it, which supplies extra electrons. Silicon has four valance electrons. Phosphorous has five valance electrons. A thicker lower layer has a little boron in the silicon. Boron has three valance electrons. Thus the upper level has a slight negative charge and the lower level has a slight positive charge. Because of the slight deficit of electrons in the lower level, the electrons have more room to move around and have slightly more energy than the electrons in the upper level. Where the two layers join together there is a resistance to the passing of electrons. Sunlight comes through the thin upper layer and excites the electrons in the lower layer enough so they can jump across the boundary between the two layers. This creates an excess charge in the upper layer, which is collected and sent through circuits to provide electricity to a use (Strong and Scheller 1993, 15–18). Photovoltaic panels produce direct current. Most household and commercial appliances and the utility grid use alternating current; thus, a solid state controller is necessary to produce alternating current.

Photovoltaic panels lend themselves to distributed use. They can be mounted in small, medium, or large arrays almost anywhere (Gore 2009, 68). When a utility grid is available the most straightforward method of storing excess electricity production during the day is to send the extra electricity back into the electric grid. If the utility grid is not available, then batteries are necessary to store electricity generated during the day for use at night or during cloudy weather. Batteries are sized by determining the amp hours they need to deliver. Amp hours are calculated by dividing the watt hours of energy required by the building per day by the voltage of the system and battery bank. Often this is 24 volts. The amp hours per day are multiplied by the number of days of storage required and by a 1.2 discharge factor since batteries can only discharge 80 percent of their total charge (Grondzik et al. 2010, 1342).

Another form of photovoltaic panel is thin film amorphous silicon. These panels are less expensive and less efficient. Traditional silicon cell panels are from 10 to 15 percent efficient depending on their temperature. Amorphous silicon panels are from 5 to 7 percent efficient also depending on temperature. The efficiency is highest when the panels are cool, 50 to 60 degrees Fahrenheit, and least efficient when they are in the range of 110 to 120 degrees Fahrenheit (Humm and Toggweiler 1993, 99). Thus, it is important to mount photovoltaic panels so that they can ventilate away heat. It is also important to mount photovoltaic panels so that they are not shadowed at all during most of the day. Even a small amount of shadowing drastically reduces output.

Photovoltaic panels of either type come with a voltage and a current rating. Connecting the panels in series adds individual panels' voltages together so that it increases the voltage of the array of panels. Connecting the panels in parallel adds the individual panel's current together so that it increases the current output of the array of panels. Most photovoltaic arrays are connected in a combination of parallel and series connections to provide the voltage and current required (Figure 32.3).

FIGURE 32.3 Nellis Air Force Base 15 megawatt photovoltaic power plant.

Source: US Air Force photo, public domain.

The National Renewable Energy Laboratory (NREL) provides a website (www.nrel.gov.rredc/pvwatts) that calculates the power output of a solar array anywhere in the world. The array size is inputted in kilowatts. Each photovoltaic panel is rated for voltage and amps. (Watts = volts × amps.) Multiplying the watts produced by a single panel by the number of panels will give the watts produced by the array. A kilowatt is 1,000 watts. The tilt and azimuth of the array can also be inputted. A tilt equal to the latitude provides maximum power over the entire year. A lower angle will provide more power in summer, and a higher angle will provide more power in winter. There is a version 1 and a version 2 of the program. They both perform the same calculation.

Wind is created by uneven heating, which causes air to flow from hotter areas to colder areas. Wind is a widespread resource with the capacity to provide vast supplies of electricity. History credits Persia with the first windmills, which then spread to China. Windmill technology came to Europe with the crusaders where it found widespread use to pump water, grind grain, and saw wood. Until coal and the steam engine replaced them, windmills were an important technology used to create turning motion (Gore 2009, 86).

Modern windmills have three blades designed like airplane wings to generate efficient lift as the wind blows over the blade. The blades are typically 100 feet long and are mounted on 300 foot high towers. They each produce an average of 1.5 megawatts of electricity, enough for 400 homes. These large windmills are generally located in groups owned by utility companies and connected to the utility grid. Windmills are currently the least expensive source of solar energy (Gore 2009, 80).

A wind turbine cannot take all the kinetic energy out of the wind since the wind flows through and past the turbine. The maximum theoretical power extraction is 59 percent. This is Betz's law, developed through calculations on an ideal wind turbine by Albert Betz, a German physicist in 1916. Real wind turbines have friction losses that reduce their output to about 75 percent of the maximum possible output. Thus a well-designed wind turbine can expect to harvest 44 percent of the kinetic energy available from the wind (Grogg 2005, 7–10). The wind power density (WPD) is a measure of the average annual power per square meter of area the windmill blades swing through. The wind power density increases with height. The National Renewable Energy Laboratory (NREL) publishes maps of the United States classifying wind sites. The ratings range from Class-1 through Class-6 with Class-6 having the highest winds. Commercial wind farms are generally located on sites with high wind power densities (NREL, Wind Resources 2014).

Most commercial wind turbines are horizontal axis machines. Wind turbines can have their blades upwind of the tower or downwind of the tower. When the blades are downwind of the tower the wind naturally keeps the blades perpendicular to the wind, but the tower then is upwind of the blades, which creates turbulence in the air stream which reduces power output. This turbulence is avoided if the blades are kept upwind of the tower. To keep the blades upwind, aimed into the wind, large turbines use a wind sensor connected to a motor. Large commercial wind turbines rotate at 30 to 60 revolutions per minute. A gear box is used to increase the rotational speed of the electrical generator, which is a coil of wires rotating in a magnetic field. The power created needs to be generated at or converted by solid state circuits to alternating current at 60 cycles per second to interface with the electrical grid. All wind turbines have design features to keep them safe in very high winds. The individual blades can be rotated into the wind and breaks can stop or slow down the blades. These large wind turbines are generally grouped in wind farms (EERE, Wind Turbine 2014).

Utility scale wind turbines range from 1.5 to 7.5 MW at the high end, and from 500 kW to 1.5 MW at the lower end (Figure 32.4). They are usually grouped in wind farms, and require environmental and civic coordination along with aviation lighting. Commercial scale wind turbines ranging from 10 kW to 250 kW are suited to campuses, businesses, or communities. The mounting is not as high but still requires special permits. Residential scale wind turbines range from 2 kW to 10 kW. They can provide a healthy percentage of residential energy use, but careful consideration of location is necessary since the towers are not high and surrounding buildings create turbulence (EERE, What is Wind Power 2014).

There is a misconception that windmills kill large numbers of birds. Windmills cause the death of about 30,000 birds per year compared to 550 million killed by tall buildings, 130 million killed by power lines, 100 million killed by cats, and 80 million killed by cars (Gore 2009, 84).

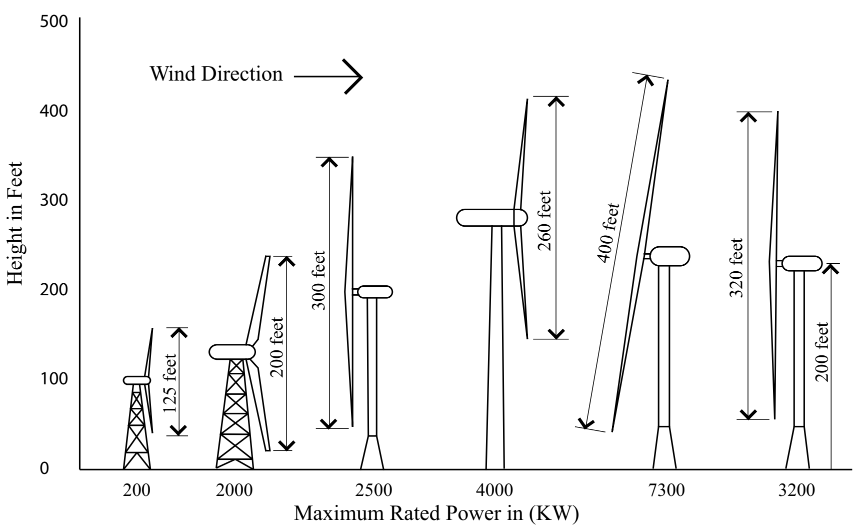

FIGURE 32.4 Wind turbines of varying size and capacity.

Source: NASA.

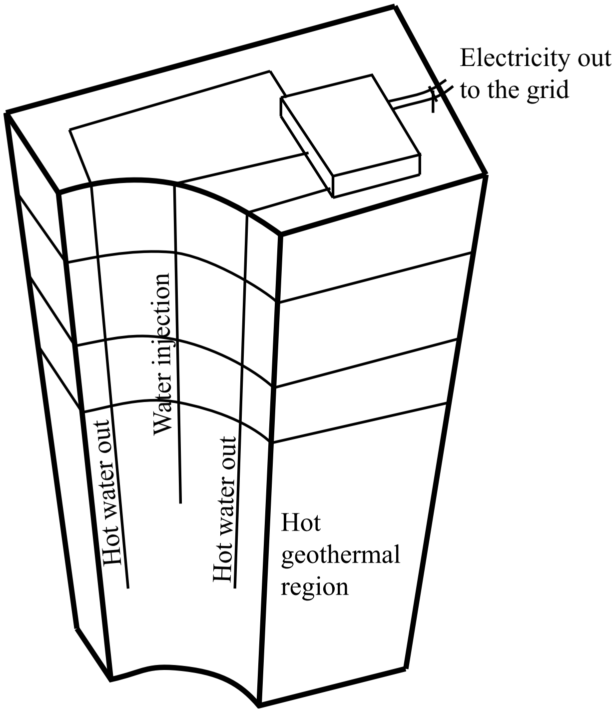

FIGURE 32.5 Geothermal electricity generation.

Wind energy and concentrated solar thermal have the problem of intermittent generation of electricity. Currently there is no good method of storing electricity. It needs to be generated as needed. The current electric grids do not respond well to intermittent sources when the amount of intermittent electricity exceeds 20 percent. The country needs to develop smart grids that can accept more intermittent power and can span across the country in order to integrate solar and wind power (Gore 2009, 91).

Geothermal power is the use of hot underground rock to heat water that creates steam to turn turbines that produce electricity (Figure 32.5). Numerous estimates of the potential of geothermal power suggest great promise. Geothermal power is also continuous, unlike the intermittent nature of solar and wind. But like solar and wind, geothermal creates electricity without any carbon dioxide emissions. Most current geothermal electricity production is located where there is geothermal heated water near the surface, which gives the impression that geothermal is not widely available. However, the ring of fire that surrounds the Pacific Ocean is ripe for geothermal development. There is also a hot zone that runs along the Mediterranean Sea and then across the upper Middle East into Iran, and another that extends down the red sea and along the riff valley of Africa. In addition to these hot areas related to plate movements, there are hot spots distributed around the earth. The Hawaiian Islands were created by one of these hot spots. Yellowstone is another example of a hot spot (Gore 2009, 94–95).

Geothermal power plants use steam created from hot water or hot rocks found a few miles below the surface. Geothermal plants come in three varieties: dry steam, flash steam, and binary cycle. Dry steam geothermal power plants have access to steam that comes from the well to the steam turbine, which turns the generator to create electricity. Access to underground steam of this type in the United States is limited to The Geysers in Northern California and Yellowstone National Park. The electrical generation at the Geysers provides a little over half the electrical power for the north coast of California. Flash steam plants are located where there is hot water at 360 degrees Fahrenheit or hotter and under pressure. A well brings the water to the surface where lower pressure causes steam to form. The steam is used to power turbines creating electricity. The excess water and condensed steam is put back into the ground creating a sustainable closed loop. This is the most common geothermal power plant. A variation on this process is used when the underground water is slightly cooler. The hot water is drawn up the well where it is run through a heat exchanger to boil a secondary fluid with a lower boiling point than water. The resulting steam is used to drive the turbines. The condensed secondary fluid is then recirculated back to the heat exchanger to be boiled again (NREL, Geothermal 2014). Where there is no water underground but there is hot rock, fracking can create permeable rock at the depth where there is enough geothermal heat, rock at 300°F to 400°F, to heat water pumped down and out of the hot zone. About 5 percent of the water is lost during this process (Gore 2009, 100). The United States Geological Survey estimates that there is enough geothermal potential in the western United States to supply close to half the electrical power needs of the country (Hendley 2008, 3).

A heat pump takes heat out of a cold source and then, using electrical energy, upgrades the quality and temperature of the heat so that it can be used to heat an interior space. There is a working fluid that can be compressed into a high temperature high pressure vapor. The high temperature vapor gives off heat, as it condenses to a liquid, to an air handler, which then delivers the heat to the interior spaces. The high pressure liquid then goes through an expansion valve that creates a low pressure, low temperature stream of liquid droplets. This low pressure liquid is colder than the outside air or the ground, so heat flows into the liquid, evaporating it, creating a low pressure vapor that is then compressed to create the high pressure vapor. The cycle thus pumps heat out of a colder source, the air or the ground, and then uses electricity to upgrade the temperature of the working fluid, by compressing it, so that the heat can flow into the building. Cooling is achieved by a valve that switches the hot condenser coil to the outside and the cool evaporator coil to the inside. Individual houses and modest commercial buildings can take advantage of the stable temperature of the earth through the use of ground source heat pumps. At 10 feet down, the earth temperature is fairly stable and near the average temperature for the year at that location. The result is ground temperatures of 50 to 60 degrees Fahrenheit. A ground source heat pump takes heat out of the ground to heat a building in winter and puts heat into the ground while cooling the building in summer. A yearly heat flow balance is maintained. The ground is warmer than the air in winter and cooler than the air in summer, so a ground source heat pump's coefficient of performance (COP) is higher than an air source heat pump's COP. The temperature difference the ground source heat pump works against is smaller than the temperature difference the air source heat pump works against. Moist ground is better than dry ground because moist ground conducts heat better. Finally, these systems are often called geothermal heat pumps, which is an incorrect use of the term geothermal. Ground source heat pump is a more descriptively correct term.

Biomass energy can be produced from trees, corn, sugarcane, switchgrass, mascanthus, and agricultural waste. These organic materials can be used to produce thermal energy for heating or the production of electricity. They can also be fermented into liquid fuels for use in transportation (Gore 2009, 114).

The use of biomass to generate energy is as old as fire. Burning wood is still the largest use of biomass. Burning biomass produces carbon dioxide and water just like burning fossil fuels. The difference is that the carbon in the biomass was recently taken out of the atmosphere. When it is burned the carbon dioxide is returned to the atmosphere. There is no net gain or loss of carbon dioxide in the atmosphere other than the energy it took to plant and harvest the biomass. Biomass crops are best grown on already cleared land since clearing forest land creates a carbon debt that takes decades to repay. Burning fossil fuels adds carbon dioxide into the atmosphere that was taken out of the atmosphere long, long ago; thus, burning fossil fuels increases the carbon dioxide in the current atmosphere (NREL, Biomass 2013).

A good example of biomass use is the production of ethanol from sugarcane in Brazil, which began in the mid-1970s. The sugarcane is grown on about 2 percent of Brazil's arable land. Sugarcane produces 650 gallons of ethanol per acre. Sugarcane works well in the tropical environment of Brazil but does not translate well to the northern climate of the United States. Corn grows well in the United States, but it is a food crop, and it yields less energy per acre than sugarcane. In addition, if the entire United States corn crop was made into ethanol it would only supply 13 percent of transportation fuel needs (Gore 2009, 118–122).

A more promising approach to biomass is the use of tall grasses like switch grass, fast growing trees, and left over waste from food crops. All these non-food crops have high cellulose content, which is good for the production of ethanol, but cellulose resists the bacteria of fermentation. As a result enzymes are being tested with a hydrolyzing steam process to break the cellulose down so it can be fermented into ethanol. Switch grass has the potential of producing 1,000 gallons per acre (Gore 2009, 122–124).

Ethanol can also be made in a gasification process where high temperatures combined with low oxygen create synthesis gas (hydrogen and carbon monoxide). This gas can then be chemically modified to create ethanol. The National Renewable Energy Lab (NREL) is exploring the use of algae to create the biomass input for biodiesel, gasoline, and jet fuel. Algae produces biomass at a high rate (NREL, Biomass 2013).

Biomass can be used to generate electricity. Most bioelectricity plants directly burn the biomaterial to create steam that is used to turn turbines to generate electricity. Cogeneration, using the waste heat from the electricity generation to heat buildings or do other jobs, greatly increases the overall efficiency of the process. Paper mills are the largest users of this form of electricity generation. Co-firing is the mixing of biomass with conventional fossil fuels, such as coal. Synthesis gas can be used like natural gas in a gas turbine driven electrical generation system. Biomass can be made into a liquid oil through a high temperature process without oxygen. The oil can then be burned to generate electricity. Landfills contain organic materials that decompose producing methane. The methane escapes into the atmosphere, which adds to the greenhouse effect. Methane is a much more potent greenhouse gas than carbon dioxide. Wells can be drilled into landfills to capture the methane to be used to generate electricity. This process keeps the methane out of the atmosphere and generates electricity. Methane can also be produced directly from organic matter through an anaerobic process. This process can scale

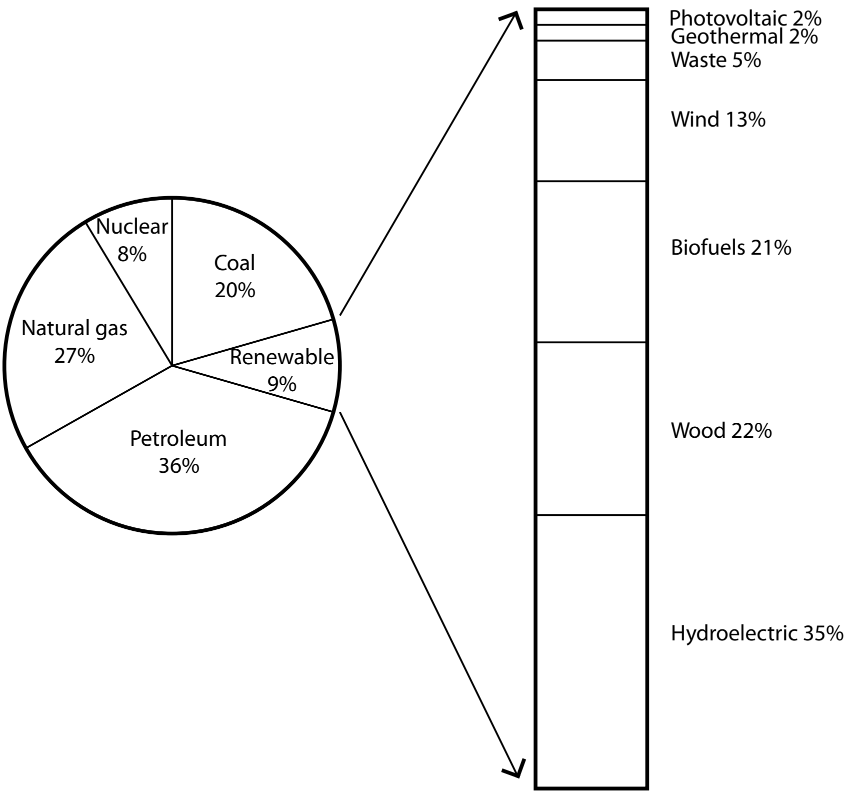

FIGURE 32.6 Renewable energy as a percent of total United States energy use.

Source: United States Energy Information Administration, Annual Energy Review 2011. www.eia.gov/are down to small digesters producing methane to be used in generators providing electrical power to remote sites (NREL, Biopower 2013).

Plastics and a wide range of products are made from fossil fuels. Fossil fuels are carbon and hydrogen. Biofuels are carbohydrates made from carbon, hydrogen, and oxygen. Both materials can be broken down into simpler chemicals that then can be recombined to create plastics and other products. The products made from biomass include plastics, glues, artificial sweeteners, textiles, and synthetic fabrics, wood adhesives, molded plastic, and foam insulation (NREL, Bioproducts 2013). Calvin Klein makes a sport coat from modal. Modal is a synthetic fiber made from cellulose from beech trees.

Biomass use is in a very early stage of development. If one considers how food crops such as wheat and corn were transformed from wild grasses with small amounts of edible material to their current state, it is certainly in the realm of possibility that biofuels from biomass could also make a dramatic change.

Currently renewable energy sources provide 9 percent of the energy use of the United States. With peak oil production projected to happen soon, there is an urgent need to invest in renewable energy technology development.

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APPENDIX A

SUN PATH DIAGRAMS

Appendix A provides Sun charts for 24, 28, 32, 36, 40, 44, and 48 degrees north latitude. The Sun charts were adapted from Fuller (1993).

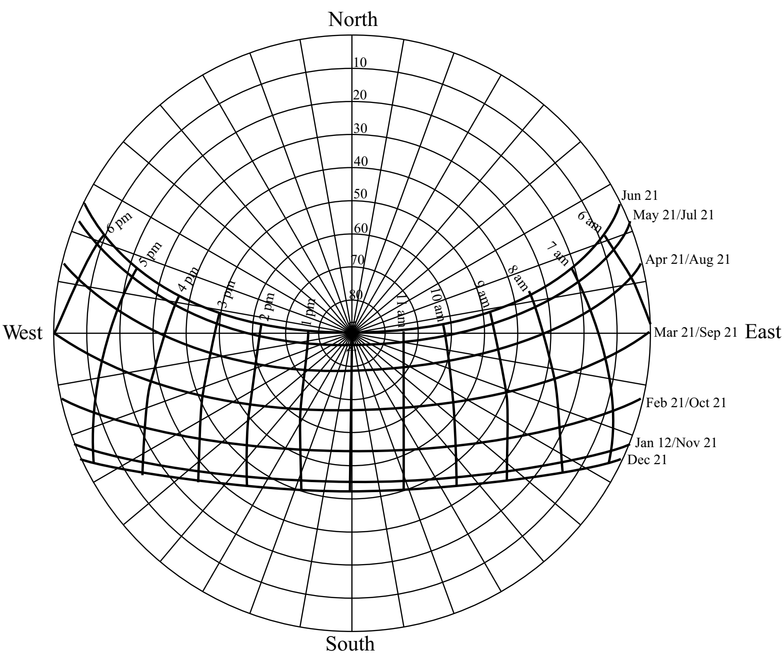

FIGURE A.1 Sun path diagram for 24 degrees north latitude.

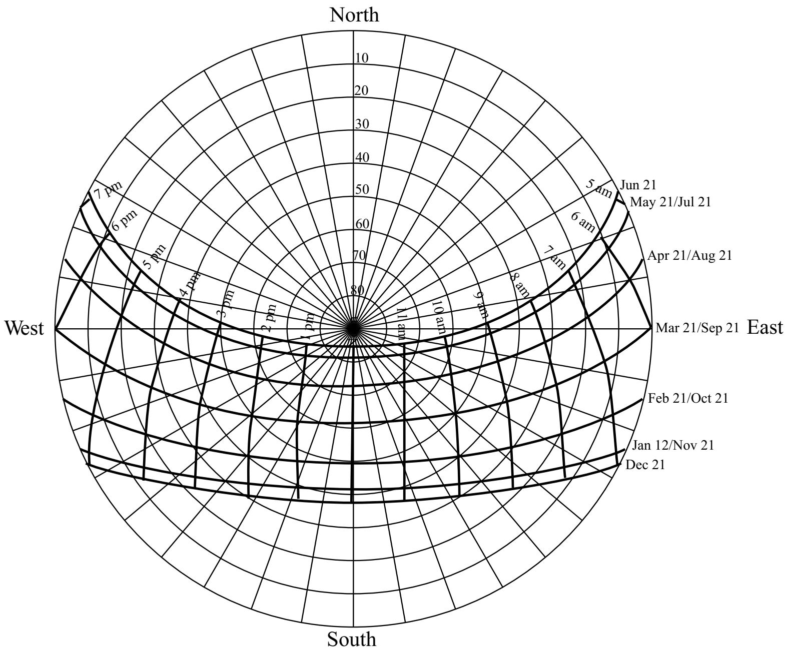

FIGURE A.2 Sun path diagram for 28 degrees north latitude.

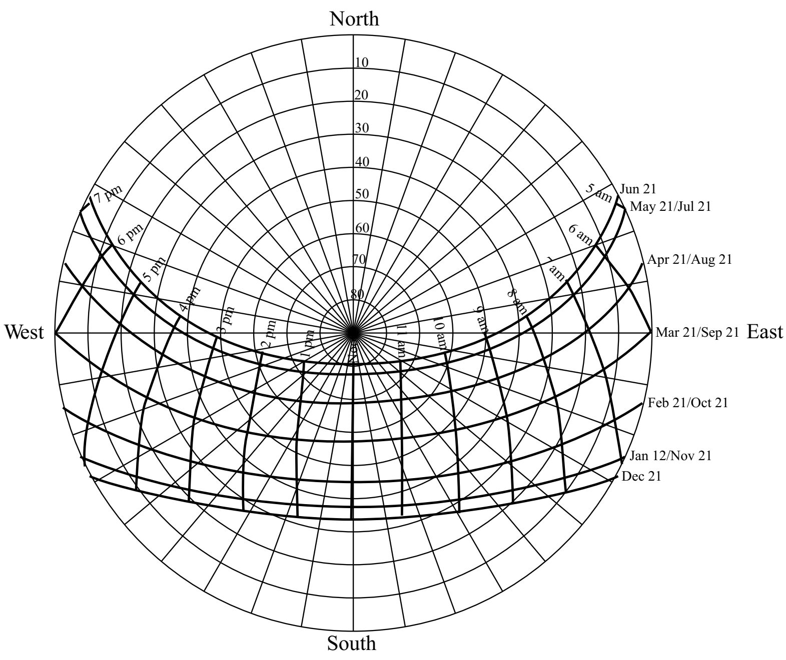

FIGURE A.3 Sun path diagram for 32 degrees north latitude.

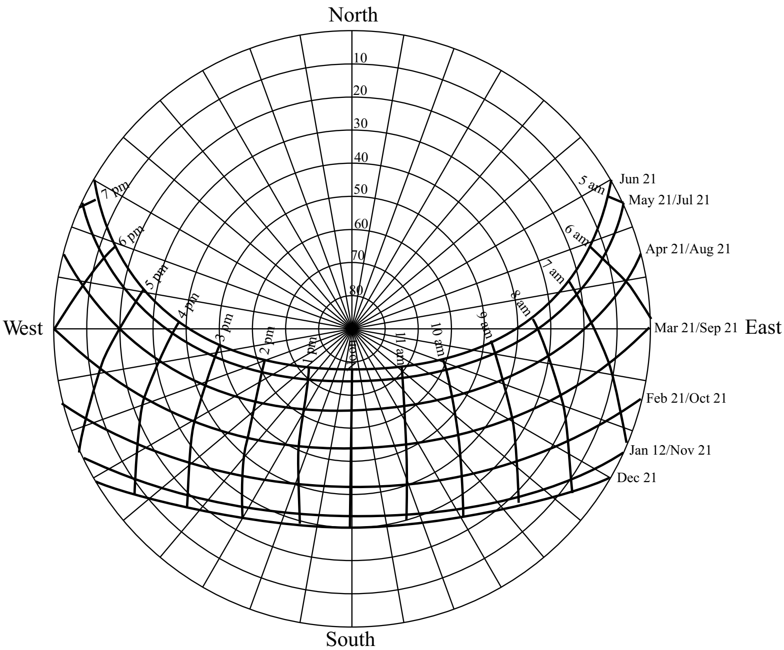

FIGURE A.4 Sun path diagram for 36 degrees north latitude.

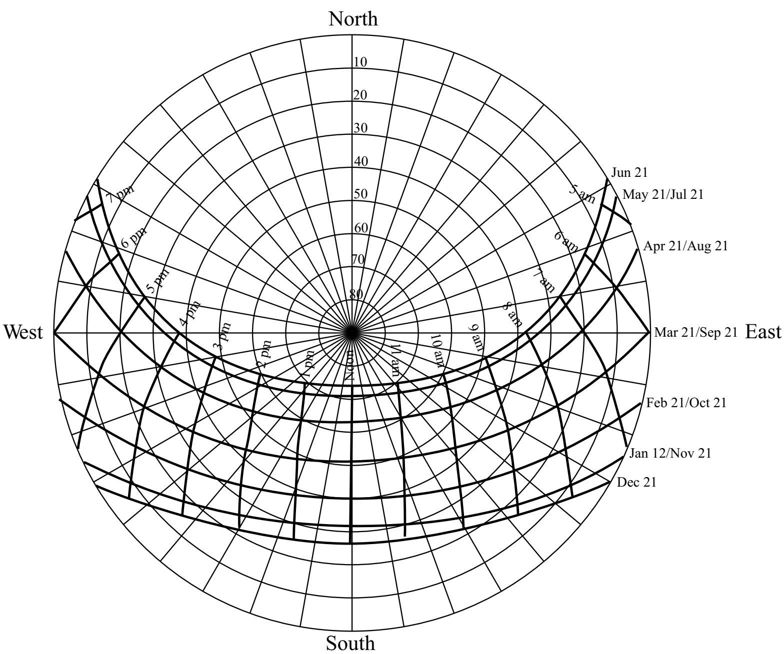

FIGURE A.5 Sun path diagram for 40 degrees north latitude.

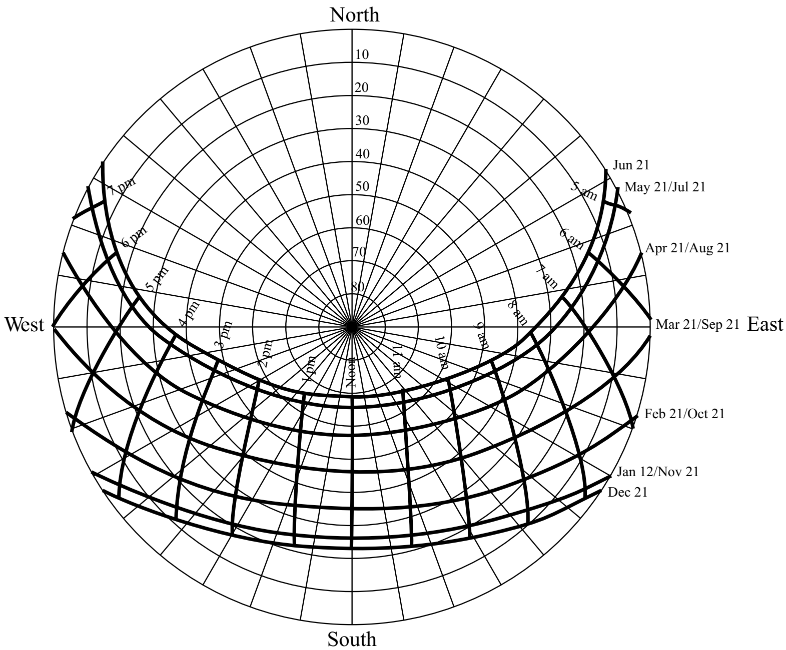

FIGURE A.6 Sun path diagram for 44 degrees north latitude.

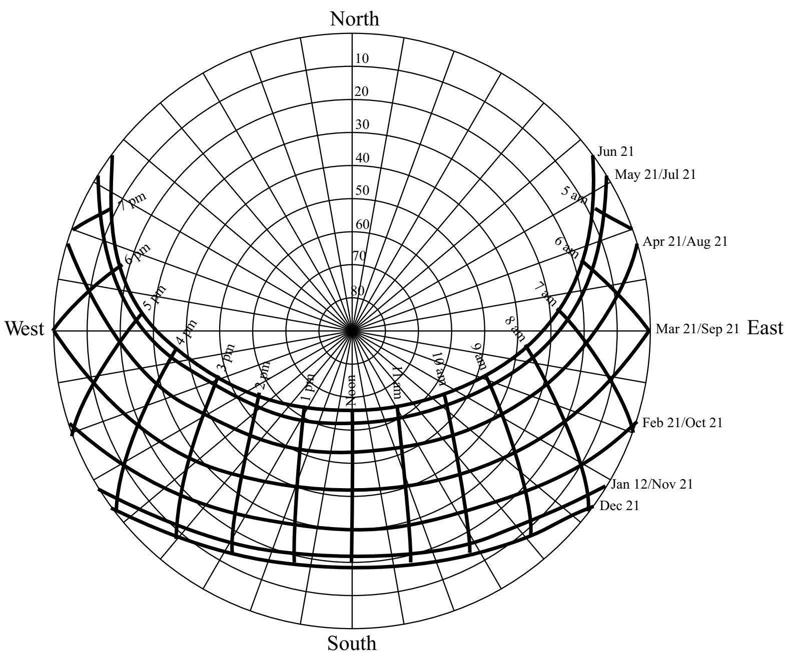

FIGURE A.7 Sun path diagram for 48 degrees north latitude.

APPENDIX B

ENERGY ANALYSIS SOFTWARE PROGRAMS

The information about the energy programs listed below came from their websites and from the *AIA Guide to Integrating Energy Modeling in the Design Process* (The American Institute of Architects 2012). Google the program name for detailed information and availability.

DOE-2-Based Computer Programs

DOE-2 is an energy modeling program developed by the Lawrence Berkeley National Lab. It models most commercially available HVAC systems along with lighting and daylighting. There are two versions, DOE-2.1E and DOE-2.2. Input is through building display language, which requires some skill. Doe-2.2 extensively upgrades HVAC analysis especially in the central plant descriptions.

EnergyPro is a front end for DOE-2.1E. It simplifies the input and output of information. It implements a wide range of the features available in DOE-2.1e. However, it is not free.

eQUEST is a menu driven interface to DOE-2.2. It builds a graphic model of the building. It has three levels of detail and runs parametric analysis, and runs very fast. There is a building creation wizard and an energy efficiency measure wizard. eQUEST is freeware.

PowerDOE has a complete set of DOE-2.2 features. Input and output is graphic including 2-D and 3-D display of the building. This program is in the final stages of pre-release testing.

VisualDOE is another interface to simplify input and output to and from the DOE-2.1E program. It creates a simple building model and there is a library of components and systems to choose from. It is not free.

EnergyPlus-Based Computer Programs

EnergyPlus is the Department of Energy's current energy modeling program, which goes beyond DOE-2. This program is well funded by DOE and its flexibility makes it capable of a wide variety of applications, but it is slower than other programs. It models heating, cooling, lighting and water use. It is freeware but hard to use without an interface.

Open Studio comes from the National Renewable Energy Lab. It provides access to EnergyPlus and Radiance, and has a SketchUp type modeling interface. It is cross platform (Windows, Mac, Linux). The program is a collection of software tools. System Outliner creates HVAC systems. Model Editor creates generic interfaces. Run Manager sets up the simulations, and Results Viewer creates graphic output. It is an open source project to facilitate community development. It is free.

DesignBuilder is a user friendly interface for EnergyPlus but is limited to traditional HVAC systems that has some advantages since you do not have to input too much information to get the simulation going. The input involves building a building model in the program. There is no input feature to bring in outside models. It is not free.

Simergy is another front end program feeding into EnergyPlus. It provides access to many of the features of EnergyPlus and has libraries of features to aid the designer including drag and drop components. Building geometry can be imported. Laurence Berkeley National Lab is the developer. It is free.

Ecotect-Based Computer Programs

Ecotect is designed as a concept through detail energy analysis tool. It can aid in designing for thermal performance, energy usage, water usage, solar radiation availability, daylighting, and shadows and reflections. It is an Autodesk product and is not free.

Vasari is a cloud-based system to provide building energy modeling. It is aimed at conceptual design with geometric and parametric modeling. It is an Autodesk product and is not free.

Other Energy Analysis Computer Programs

Hourly Analysis Program (HAP) is Carrier's HVAC sizing and energy analysis program. It is aimed at engineering system sizing. It has components for peak load and system design, building energy analysis, mechanical design, and economics. It is not free.

TRACE 700 Load Design Software is from the Trane Air Conditioning Company. It is primarily used to determine the loads on HVAC systems, especially the peak load, which can be hard to determine in multiple zone systems. A large number of systems and energy saving features like economizers are available. There is a built-in LEED guide and baseline building creator. The program can also estimate building energy use. It is not free.

Energy-10 was developed by DOE to model buildings of approximately 10,000 square feet. It is based on the CalPas computer program and automatically sets up a two zone rectangular building. It calculates heating, cooling, daylighting and photovoltaic energy with minimum input, and provides graphic output. It is not free, and there are problems running the program on current windows operating systems.

Transient System Simulation Program (TRANSYS) is a program language that can simulate almost any thermal system. It includes components that can be put together to create a system and has the ability to create new components. It is primarily used as a research tool.

APPENDIX C

ONLINE RESOURCES

The information about the energy programs listed below came from their websites, from the *AIA Guide to Integrating Energy Modeling in the Design Process*, and from www.2030palette.org. Google the program name for detailed information and availability.

www.myfootprint.org

This site calculates a person's footprint in the number of earths that would be necessary for everyone on earth to live the same way.

www.ipcc.ch

This is the website of the International Panel on Climate Change. This organization is a primary source of data and analysis about climate change and the consequences that may follow from climate change.

www.architecture2030.org

This site makes a documented argument that reducing the carbon footprint of the built environment to carbon neutral by 2030 is doable and can reduce global warming by a significant amount.

www.climatenetwork.org

"CAN is a network of NGOs working on climate change from around the world. These members are autonomous and independent. Many of these members have their own forms of organization and their own national or regional rules."

www.biologicaldiversity.org

"The Center for Biological Diversity works through science, law and creative media to secure a future for all species great or small, hovering on the brink of extinction."

www.newdream.org

"The Center for a New American Dream helps Americans to reduce and shift their consumption to improve quality of life, protect the environment, and promote social justice."

www.zwia.org

"The Zero Waste International Alliance has been established to promote positive alternatives to landfill and incineration and to raise community awareness of the social and economic benefits to be gained when waste is regarded as a resource base upon which can be built both employment and business opportunity."

www.earth-policy.org

"The Earth Policy Institute is dedicated to planning a sustainable future and providing a roadmap of how to get from here to there."

www.habitat.noaa.gov

"The NOAA Fisheries Office of Habitat Conservation protects, restores, and promotes stewardship of coastal and marine habitat to support our nation's fisheries for future generations."

www.noaa.gov

The National Oceanic and Atmospheric Administration is divided into the following groupings: National Environmental Satellite Data and Information Service, National Marine Fisheries Service, National Ocean Service, National Weather Servic , Office of Oceanic and Atmospheric Research, Office of Program Planning and Integration.

www.epa.gov/hiri

The Environmental Protection Agency site covers information on the heat island effect and ways to mitigate the problem.

heatisland.lbl.gov

"The Heat Island Group at Lawrence Berkeley National Laboratory works to cool buildings, cities, and the planet by making roofs, pavements, and cars cooler in the sun."

www.epa.gov

The Environmental Protection Agency website covers a wide range of topics. A partial list includes air, chemical toxics, emergencies, greener living, health and safety, land and cleanup, waste, and water.

www.ccrm.vims.edu

"The Center for Coastal Resources Management (CCRM) at the College of William and Mary develops and supports integrated and adaptive management of coastal zone resources. To fulfill this mission, the Center undertakes research, provides advisory service, and conducts outreach education."

www.sustland.umn.edu

"The goal of the SULIS is to provide sustainable landscape information to the public and to the horticulture/landscape industry. By utilizing SULIS concepts, homeowners, business owners and related industry personnel will be able to create outdoor spaces that are functional, maintainable, environmentally sound, cost effective and aesthetically pleasing."

www.ctod.org

The Center for Transit Oriented Development publishes information on the design and benefits of transit oriented development. There are numerous PDFs to download.

www.reconnectingamerica.org

"Reconnecting America advises civic and community leaders on how to overcome community development challenges to create better communities for all. Reconnecting America develops research and innovative public policy, while also building on-the-ground partnerships and convening players needed to accelerate decision-making."

www.cclr.org

"The Center for Creative Land Recycling (CCLR or "see clear") is a nonprofit organization founded on the belief that intelligent, innovative land use is the key to ensuring a healthy future for both our communities and our environment. Our mission is to enable communities to develop sustainably and equitably through land recycling—restoring underutilized, blighted sites to productive use."

www.transect.org

"The Center for Applied Transect Studies (CATS) promotes understanding of the built environment as part of the natural environment, through the planning methodology of the rural-to-urban transect. CATS supports interdisciplinary research, publication, tools, and training for the design, coding, building and documentation of resilient transect-based communities."

www.asla.org/sustainablelandscapes

This American Society of Landscape Architects site provides case studies and educational information related to the design of sustainable landscapes.

www.epa.gov/smartgrowth

This Environmental Protection Agency site provides information and publications about smart growth. Try www.epa.gov/smartgrowth/pdf/ptfd_primer.pdf.

www.smartgrowthamerica.org

"Smart Growth America advocates for people who want to live and work in great neighborhoods. We believe smart growth solutions support businesses and jobs, provide more options for how people get around and make it more affordable to live near work and the grocery store. Our coalition works with communities to fight sprawl and save money. We are making America's neighborhoods great together."

www.sustainablesites.org

"The Sustainable Sites Initiative (SITES(tm)) program was created to promote sustainable land development and management practices that can apply to sites with and without buildings."

www.wbdg.org/resources/lidtech.php

This is one of the websites of the Whole Building Design Group of the National Institute of Building Sciences. "Low Impact Development (LID) is an alternative site design strategy that uses natural and engineered infiltration and storage techniques to control storm water where it is generated. LID combines conservation practices with distributed storm water source controls and pollution prevention to maintain or restore watershed functions. The objective is to disperse LID devices uniformly across a site to minimize runoff."

www.wbdg.org

The Whole Building Design Group of the National Institute of Building Sciences provides a wide range of building design information.

www.igra-world.com

The basic idea of IGRA is the support of the Green Roof market on an international level by sharing knowledge and experiences in the field of Green Roof technology and public relations. In this context, the IGRA secretariat will serve as a global networking and co-ordination center. Typical activities of IGRA include workshops, conferences, publications and newsletters.

www.roofmeadow.com

This is the website of a green roof design firm. There are multiple case studies and extensive and intensive green roof details.

www.ranacreekdesign.com

"Rana Creek is a renowned ecological design firm specializing in environmental planning, landscape architecture, habitat restoration, and native plant propagation. Staffed by professional ecologists, biologists, landscape architects, researchers, contractors, arborists, horticulturists and landscape restoration specialists who believe passionately in our mission to restore biodiversity and preserve healthy ecosystems through an integrated design/build process, reconnecting the human experience with nature." There are many projects to look through.

www.patternguide.advancedbuildings.net

"New Buildings Institute in partnership with the University of Idaho and University of Washington has developed a freely available interactive tool for the design of proven daylighting strategies in a variety of building types. Users will be introduced to the Daylighting Pattern Guide while exploring the inter-relationship of sky, site, aperture, and space planning. The guide uses a combination of built examples and advanced simulation to set the stage for substantial reductions in lighting power consumption and overall energy use through successful daylighting design."

www.daylighting.org

"The Daylighting Collaborative was initiated by the Energy Center of Wisconsin and its sponsoring members as a source of why-do and how-to information for daylighting using windows. With the growing interest in the energy savings benefits and research on the other non-energy related benefits, the Daylighting Collaborative and its website were re-focused to not only provide information but act as a gateway to other existing information on daylighting."

www.energy-design-tools.aud.ucla.edu

"All our Energy Design Tools are fast, easy to use, highly graphic, and free. Each has a built in demonstration. Each has an automatic INSTALL routine or a READ.ME file explaining how to use it. You are welcome to publish the output and share copies provided that the Regents Copyright and Terms of Use remain unaltered."

www.nrel.gov/buildings/sunrel

"SUNREL® is a hourly building energy simulation program that aids in the design of small energy-efficient buildings where the loads are dominated by the dynamic interactions between the building's envelope, its environment, and its occupants. The program is based on fundamental models of physical behavior and includes algorithms specifically for passive technologies, such as Trombe walls, programmable window shading, advanced glazings, and natural ventilation. In addition, a simple graphical interface aids in creating input files."

www.architecture.com/sustainabilityhub

"The Sustainability Hub has been set up by the Royal Institute of British Architects (RIBA) in order to provide a growing, central resource on all aspects of sustainable design in architecture." This site has a well-documented set of design strategies, and case studies.

sustainabilityworkshop.autodesk.com

This site provides design ideas and guidance along with examples of using Autodesk products to provide information.

www.aiatopten.org

This is a website of the American Institute of Architects. The AIA has a yearly juried review of submitted green sustainable buildings. They choose ten winners. The winning buildings are documented on this website. There are multiple years of well-documented award winning buildings to look through for ideas.

www.2030palette.org

"The 2030 Palette is a free online platform that puts the principles and actions behind low-carbon and resilient built environments at the fingertips of design professionals worldwide. Since planning and designing the built environment is primarily a visual activity, the 2030 Palette is structured as a visual network of interrelated elements called Swatches. Swatches present highly complex and multi-dimensional information in a readily accessible format organized by category—Region, City/Town, District, Site and Building. Each Swatch contains a written recommendation, rule-of-thumb, images and graphics representing the physical application of the recommendation, as well as more detailed information for its successful application." There is a vast amount of information on this website.

GLOSSARY

Adobe: A traditional southwest building material made from clay, straw and water dried into bricks.

Air infiltration: Air from outside, driven by wind pressure, leaks in through gaps in construction around doors and windows and at top and bottom plates.

Air motion cooling: Air flow across a person's skin evaporates moisture which causes a cooling sensation.

Air source heat pump: A heat pump that takes heat out of the outside air during the winter and upgrades its temperature before delivering it to the inside. In summer it takes heat out of the interior and rejects it to the outside air.

Albedo: The ratio of light reflected to light falling on a surface.

Altitude angle: The vertical angle showing how high in the sky the sun is.

Amphibians: Ectothermic (cold-blooded) tetrapod vertebrates, which have a gilled aquatic larval stage followed by a terrestrial lung-breathing adult stage. The class includes frogs, newts and salamanders. Most amphibians live in terrestrial, arboreal or freshwater aquatic ecosystems. There is a not well-understood die off of amphibians.

Anasazi: An ancient people of the southwest United States who build dwellings oriented to solar positioning in winter, spring, summer, and fall.

Angkor Wat: An ancient civilization in Cambodia that harnessed the storage of water to magnify the ability to grow rice.

Azimuth angle: The angle along the horizon defining the position of the sun.

Baroque: An architectural style beginning in 16th century Italy that created exuberant forms and daylighting methods.

Barrel staves: The wooden boards used to make the vertical sides of barrels.

Bioclimatic chart: A plot of the zone of human comfort in relation to temperature, humidity, wind speed, mean radiant temperature, and water vapor.

Bioclimatic design: This procedure uses climate information about temperature and humidity to plot human comfort ranges and suggest residential design forms to achieve the comfort.

Biomass: Any organic matter that is renewable and can be converted to liquid or gas fuels.

British thermal unit (BTU): The amount of heat necessary to raise one pound of water one degree Fahrenheit. Approximately equal to burning one wooden match.

Carbon dioxide: The gas produced by combustion that is the primary driver of global warming.

Carbon footprint: The amount of carbon dioxide that can be attributed to a person's life style.

Carrying capacity: The area of land necessary to support an animal.

Cistern: A cistern is a tank used to collect rainwater.

Climate: The long range average weather conditions for a region.

Coastal wetlands: Shallow areas near the shore covered with grasses.

Collapse: If a species exceeds its resources by a large amount the species population will rapidly decline.

Color rendering index (CRI): A number between 0 and 100 that compares the color rendering of a lamp to the color rendering of a glowing black body at the same color temperature as the lamp.

Complex numbers: There is no solution to the square root of (–1). Mathematics creates a solution as (i). Thus complex numbers have a real and a complex part ($x + iz$).

Complex plane: Complex numbers ($x + iz$) can be plotted on a plane where the horizontal axis is the real axis and the vertical axis is the imaginary axis.

Continental climate: A climate with large daily and seasonal temperature swings but with only modest amounts of snow.

Convection coupled thermal mass: This is thermal mass that is heated by the air in the room. The air in the room is heated by solar radiation heating other surfaces in the room.

Convection currents: Air motion caused by temperature difference. Warm air rises and cold air drops.

Cool towers: A vertical tower with water sprayed into the top where it evaporates creating a cool down flow of air.

Coral reefs: Reefs are created by coral animals that secrete calcium carbonate. They provide habitat for a wide range of sea life.

Cross flow heat exchanger: Two fluids, usually one hot and one cold flowing past each other in opposite directions exchanging temperature across a surface.

Daylighting: Daylighting uses sky light to illuminate interior spaces. Direct sunlight is normally bounced so it does not penetrate into the space directly.

Degree day: The difference between the average temperature for a day and 65 degrees Fahrenheit. This difference is then added up for all the winter days to arrive at monthly and yearly degree day numbers. Better insulated houses might use a degree day base of 60, 55, or 50.

Desert climate: A climate where extreme heat and lack of water is the main driving force.

Desiccant: A material that attracts water molecules to its surface thus reducing the humidity levels. Heat is then used to dry the desiccant out so it can be used again.

Direct gain solar system: Sun is admitted to a room where thermal mass is used to avoid a large temperature swing and to store thermal energy for the night.

Direct glare: A bright light in the field of view.

Double glazing: Two panes of glass with an air gap between them and usually sealed together at the edges.

Echo-tech construction: Buildings that have elaborate technical movable multi-layered skin systems to control daylight and ventilation.

Ecological footprint: The area of land necessary to supply the resources necessary for survival.

Economizer: A system where up to 100 percent outside air can be brought into a building when the outside air is at a temperature that is at or below the return air temperature. An enthalpy controlled economizer considers both temperature and humidity.

Ecosphere: The combination of the living and non-living features of the earth that support life.

Ecosystem: The interacting living and non-living features of an area of the earth that maintains the balance of nutrients necessary for life to exist.

Efficacy: Efficacy is the term used to define the lumens of visible light in relation to the watts of electricity used (lumens/watt).

Electrical grid: The distribution system for electricity from power plant to users.

Embodied energy: The energy to mine, produce, deliver to the site, and install a product.

Energy efficiency ratio (EER): The efficiency of cooling equipment defined as the BTU/hr of cooling divided by the watts of electrical energy used. (SEER) is a seasonal average of this same number.

Estuaries: The inlets and bays that connect rivers with oceans. They are very productive.

Eutectic salts: A material that is designed to melt at a defined temperature. Thus solar energy can be stored in less material because of the large amount of energy stored in the phase change of the material.

Evaporative cooling: Warm dry air can be cooled by the introduction of water droplets that evaporate taking energy out of the air thus cooling it. The humidity of the air increases.

Exponential growth: Growth that is proportional to the size of the population ($dN/dt = rN$). Exponential growth is characterized by a constant doubling time ($t = 0.69/r$) where r is the rate of growth.

Extensive green roof: An extensive green roof is not very deep. It has 2 to 3 inches of growing medium.

Externality: Social and environmental costs of producing a product that are not part of the producers' directly paid costs of production.

Feng Shui: A system of organizing building forms and interiors to be in balance with the environment.

Fermentation: The decomposition of organic material by yeast or bacteria to produce alcohol, methane, etc.

Foot candle: A foot-candle is a lumen of light spread over a square foot of area.

Forest buffers: Forest areas surrounding rivers and estuaries provide a filtering of nutrient and sediment runoff.

Fractal dimension: A non-integer dimension that characterizes the roughness of what is being measured.

Fractal geometry: The study of self-similar and self-affine shapes.

Fuel cell: A device that uses electrochemical methods to convert chemical energy into electricity.

Galvalume: An Al–Zn coated sheet steel product used for roofing and siding.

Geothermal energy: Energy, usually electricity, produced by tapping geothermal heat. Heat taken from the underground source is used to turn turbines to produce the electricity.

Global warming: The atmosphere and oceans are slowly warming because of carbon dioxide and other gases that industrial society puts into the atmosphere.

Gray water: Gray water is water from sinks and showers that is only slightly dirty. It can be used for irrigation or to flush toilets.

Green materials: Green materials are reclaimed, recycled, sustainably harvested, rapidly renewable, have low volatile organic compounds, and have low embodied energy.

Greenhouse gases: Carbon dioxide is the primary greenhouse gas, but methane and other industrial gases also cause a greenhouse effect in the atmosphere.

Gross domestic product: The GDP measures all the goods and services that the economy uses.

Ground source heat pump: A heat pump that rejects heat in cooling mode and takes in heat in the heating mode from the earth rather than the outside air.

Habitats: The space in an ecosystem that a particular organism lives in.

Hadley cells: A large scale wind circulation system that moves heat and moisture from the tropics to the middle latitudes. Then other large scale circulation systems keep moving heat to the poles. These circulation cells create the trade winds.

Ice caps: The north and south poles are covered in ice because half the year there is little or no solar radiation.

Index of sustainable welfare: This index measures only the positive goods and services added to the economy.

Indigenous construction methods: Indigenous peoples used local materials and intimate knowledge of the local climate to create shelter and thermal comfort.

Indirect gain solar system: Solar energy is collected in a space other than the occupied room. The thermal energy is then stored in a thermal mass wall that transmits the heat to the room.

Industrial ecology: In ecosystems there is no waste. The waste of one organism is food to another. Industrial processes need to mimic this no waste concept.

Industrial revolution: Beginning around 1760, machines driven by steam engines powered with coal replaced human labor in the production process.

Intensive green roof: An intensive green roof has a deep growing medium which can support a diversity of plantings.

Iteration: A process where a shape is mapped on to itself over many scales.

Julia sets: The border between the bounded and unbounded numbers on the complex plane created by iterating simple equations like ($z(n + 1) = z(n)^2 + c$) where c is a complex number.

LEED: A rating system developed and maintained by the United States Green Building Council to provide a measurement of how green a building is.

Leeward: This is the downwind side of an island, mountain range or boat.

Low-e selective coating: A thin coating applied to glass surfaces that can selectively allow some wavelengths of electromagnetic radiation to penetrate while reflecting other wavelengths.

Lumen: A standard measure of light visible to the human eye. It is defined as the number of foot-candles of light one foot from a one candela light source.

Mandelbrot set: The border between Julia sets that are connected and Julia sets that are made up of separate unconnected pieces.

Marginal analysis: Each incremental change in a process is analyzed separately to look for an optimal point.

Marine west coast climate: This climate is dominated by air coming off the ocean and thus is relatively mild but cloudy and stormy.

Mean radiant temperature: The average temperature of all the surfaces of a space at a particular point in a room. Closer surfaces have a larger effect than surfaces further away.

Mediterranean climate: This climate has warm summers and mild winters which creates good indoor–outdoor living.

Mitigation measures: This is a broad description for steps taken to modify the end result of a process.

Mountain climate: This climate has mild summers and cold snowy winters.

Natural capital: Everything that the Earth provides to the human economy.

Negative feedback: This is feedback that reduces the size of the driving function.

Neolithic revolution: The transition from hunter gathers to agriculture is also called the agricultural revolution.

Net present value: The equivalent worth of all cash flows positive and negative brought back to the present time through interest rate calculations.

Niches: The space in an ecosystem that an animal or plant occupies.

Night ventilation cooling: Cool night air is ventilated through a house cooling down thermal mass. This cool thermal mass creates a cool environment inside the house during the day.

Nitrogen: Nitrogen is a mineral necessary for plant and animal growth. It is also one of the main molecules in the atmosphere.

Nonrenewable resource: Resources like iron, copper, coal, oil, etc. that exist in limited quantities on the earth.

Non-tidal wetlands: Interior wetlands that provide habitats for many plants and animals and filter runoff of nutrients and sediment into rivers.

Occupancy sensor: A sensor that turns lights off in a room using optical, ultrasonic, or infrared means to detect that there are no people in the room.

Overshoot and oscillation: This occurs when a population overshoots its resource base but does not destroy the resource base. The result is a die off and recovery oscillation that settles to a steady state after a number of oscillations.

Parallel strand lumber: This is timber sized lumber made from four to five inch long pieces of wood about the size of a finger glued together under high pressure. The pieces are all aligned in one direction.

Passive cooling: The use of natural means to minimize or avoid overheating of spaces in the warm periods of the year.

Passive solar heating: The sun is allowed to enter a living space where some of the heat is stored in thermal mass for later use.

Peak oil: At some point the world will reach a point where oil production peaks and then decreases. At that point oil prices will become increasingly higher.

Periodic behavior: Behavior that repeats itself on a daily or seasonal scale.

Phosphorous: A mineral necessary for plant and animal life.

Photosynthesis: Plants take in carbon dioxide and solar radiation and combine this with water and nutrients drawn up from the soil to produce the carbohydrates necessary to build the plant. The waste product is oxygen.

Population transition: Preindustrial societies have high birth and death rates. During industrialization the death rate drops because of public health and medicine but the birth rate stays high resulting in a large population increase. After this transition both birth and death rates become low resulting in a relatively stable population growth rate.

Positive feedback: Feedback that amplifies the driving function.

Private costs: Economic costs of production that are directly part of the production process.

Psychrometric chart: A chart that provides a map of the relationship between air and water vapor and also maps the energy content of the mixture.

Radiation coupled thermal mass: This is thermal mass that is directly hit by the solar radiation coming into the space.

Rain forest: A hot humid climate with generous amounts of rainfall supporting a lush tropical forest ecosystem.

Reflected glare: This occurs when an image of the light fixtures above is seen floating on top of what a person is trying to see or read on a desk surface.

Relative humidity: The relative humidity is the percent of the maximum amount of water vapor in air at a given temperature. Higher temperatures can hold more water in vapor form than lower temperatures.

Renaissance: The flowering of art, science, and literature which began in Florence, Italy, in the 14th century provided a foundation for modern society.

Renewable resource: Resources that grow like trees and fish. If used wisely they can supply society with resources indefinitely.

Replenishable resource: Resources like fresh water that are not alive but are replenished by the biosphere and if protected and used wisely they can continue as a resource indefinitely.

Resilience: The ability of a resource like an estuary to absorb an ecological shock and bounce back to health. A more diverse ecosystem is generally more resilient.

R-value: A measure of a material's ability to resist the flow of heat. The units are (hr, sq ft, F)/(Btu).

Savannas: A warm wet climate. This is the climate humans evolved in.

Self-affine: An object that presents similar but not exact copies of itself across many scales. Tree branching is self-affine.

Self-similar: An object that presents exact copies of itself across many scales.

Sigmoid growth: The smooth transition from one steady state to another steady state. This can happen when information is perfect, response is fast, and resources are not a problem.

Social costs: Economic costs to society like pollution from production processes that are not directly paid for by the producer.

Solar access: Zoning rules that guarantee some amount of solar access for all sites is a precondition to widespread use of solar energy.

Solar diagram: A map of the sky showing the path of the sun for each month of the year. The plot provides altitude and azimuth information and time of day information.

Solar time: Solar time is defined as time in hours where noon is placed at the time that the sun has traveled half way from sunrise to sunset.

Spaceship Earth: This is a Buckminster Fuller concept that was reinforced with pictures of the Earth floating in space taken by the Apollo missions to the moon.

Steppes: A hot dry climate with large daily and seasonal temperature swings but not quite desert.

Strong sustainability: Strong sustainability requires the protection of service flows from the ecosphere rather than only considering their value. It also values the right of other species to life and space.

Structural insulated panels: Panels with faces of plywood or oriented strand board bonded to a core of insulation. SIPs provide high insulation values and structural spanning capacity.

Subtropical climate: A climate that has warm to hot humid summers and mild winters.

Succession: After a widespread disturbance, an ecosystem will go through a succession of plant and animal varieties until it reaches the appropriate end state for the climate type.

Super insulated house: A house that has very high insulation levels and minimum air infiltration losses which minimizes heat loss so far that internal gains can provide most of the heat necessary to keep the house warm.

Sustainable yield: The amount of a renewable resource like trees or fish that can be harvested in a year without diminishing future harvests. Enough trees or fish need to be left to replenish the stock.

Swale: A linear depression in the ground surface designed to collect water and channel the water away.

Thermal mass: Concrete, brick, adobe or water that can store thermal heat for use after the sun goes down.

Tundra: A cold artic climate but with more plant and animal life than the ice caps.

Volatile organic compounds: Organic compounds that outgas from building materials and can cause distress for inhabitants.

Watt: A measure of electrical power: (watts) = (amps) × (volts).

Watt-hour: A measure of electrical consumption. One watt-hour is the use of one watt of power for one hour.

Weak sustainability: Weak sustainability is driven by economic value. There is no concern for sustainable flows from renewable resources.

Wind power curve: The power from the wind increases and decreases with the cube of the wind speed.

Windward: The upwind side of an island, mountain range or boat.

Zero population growth rate: A rate of growth where births minus deaths are equal to zero. Zero population growth is a precondition to a sustainable future.

Zoning: Zoning defines where various building types can be located and also defines the basic bulk, heights, and setbacks of allowed buildings.

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