CHAPTER 2

SUSTAINABLE DESIGN AND ENERGY SOURCES

We should be concerned about the future, because we have to spend the rest of our lives there.

Francis Kettering,
American investor, engineer, businessman, and philanthropist

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The United Nations World Commission on Environment and Development, the Brundtland Report, 1987

As we peer into society's future, we—you and I, and our government—must avoid the impulse to live only for today, plundering, for our own ease and convenience, the precious resources of tomorrow. We cannot mortgage the material assets of our grandchildren without risking the loss also of their political and spiritual heritage. We want democracy to survive for all generations to come, not to become the insolvent phantom of tomorrow.

President Dwight D. Eisenhower's Farewell Address, 1961

2.1 EASTER ISLAND: LEARNING FROM THE PAST

Easter Island has long mystified archaeologists. When the tiny, remote island 2,000 mi (3,200 km) from the nearest continent was "discovered" on Easter day in 1722, about two hundred mammoth stone statues, some more than 30 ft (9 m) tall and weighing more than 80 tons (73 metric tons), stood on the island [Fig. 2.1].

The island was a biological wasteland. Except for introduced rats and chickens, there were no animal species higher than insects. Only a few dozen plant species—mostly grasses and ferns—lived on the island, and nothing was more than 10 ft (3 m) in height. There was no obvious way that the island's 2,000 or so inhabitants could have transported and hoisted the huge statues.

Based on an analysis of ancient pollen, researchers have now established that Easter Island was a very different place when the Polynesians first arrived there around A.D. 400. In fact, it was a subtropical paradise, rich in biodiversity. The Easter Island palm grew more than 80 ft (24 m) tall and would have been ideal for carving into canoes for fishing, as well as into equipment for erecting statues. In addition to the rich plant life, there were at least twenty-five species of nesting birds.

We now believe that Easter Islanders exploited their resources to the point that they exterminated all species of higher animals and many species of plants. The island's ecosystem might have been destroyed in a cascading fashion; as certain birds were eliminated, for example, trees dependent on those birds for pollination could no longer reproduce. Denuded of forests, the land eroded, carrying nutrients out to sea.

Researchers believe that the island population had grown to a peak of 20,000 that lived in a highly organized structure. But as food (or the ability to get it) became scarce, this structure broke down into warring tribal factions. By 1722, the island's population had dropped to 2,000.

Why didn't the Easter Islanders see what was happening? Jared Diamond, in the August 1995 *Discover* magazine, suggests that the collapse happened "not with a bang but a whimper." Their means of making boats, rope, and log rollers disappeared over decades or even generations and either they didn't see what was happening or couldn't do anything about it.

Will humanity as a whole do better with planet Earth than the Polynesian settlers did with their Easter Island paradise? Many politicians and talk-show hosts claim that there are no limits to growth—that environmental doomsayers are wrong. But Easter Island shows us that limits are real. Let's not wait until it is too late to come to grips with these limits.

Shortened by permission from Alex Wilson, editor and publisher, Environmental Building News (EBN). *The full article appeared in* EBN *4, no. 5 (September–October 1995).* EBN *is a monthly newsletter for architects and builders committed to improving the sustainability of buildings and the built environment (see Appendix K). This material can also be found in Jared Diamond's* Collapse: How Societies Choose to Fail or Succeed, *2011.*

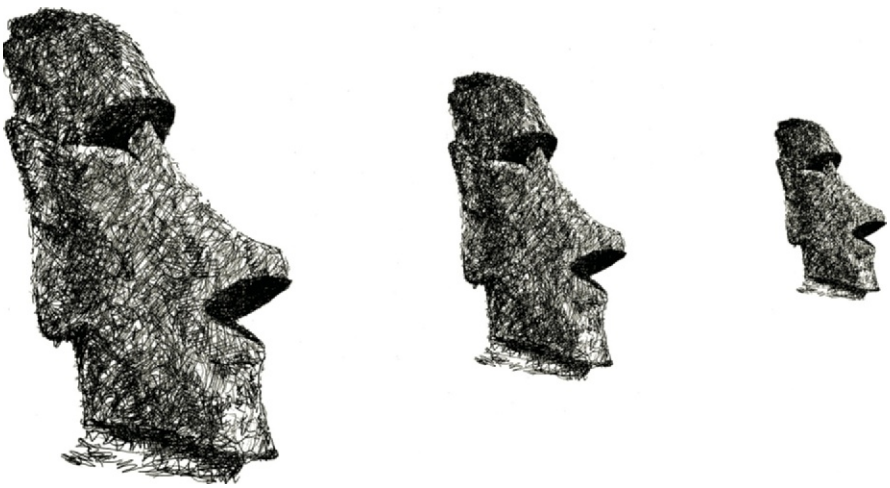

Figure 2.1 The mysterious stone heads of Easter Island. (Drawn by Ethan Lechner)

2.2 SUSTAINABLE DESIGN

In the long run, sustainable design is not an option but a necessity. Earth, with over 7.2 billion people, is rapidly approaching the same level of stress that 20,000 people caused to Easter Island. We are literally covering planet Earth with people (Fig. 2.2a). We are depleting our land and water resources; we are destroying biodiversity; we are polluting the land, water, and air; and we are changing the climate, with potentially catastrophic results.

In the short term, it may seem that we do not have to practice sustainable design, but that is only true if we ignore the future. We are using up resources and polluting the planet without regard to the needs of our children and our children's children (Fig. 2.2b).

Figure 2.2a Nighttime lights of the world as viewed from satellites clearly show how people are filling up the planet. Much of the dark land is uninhabitable (e.g., the Sahara and the Tibetan Plateau). (From NASA.)

Figure 2.2b Where a mountain once stood, a colossal hole now exists. Human beings are literally moving mountains to feed their appetite for resources. For a sense of scale, note the trains on the terraces on the far side. The tunnel at the bottom of this open-pit copper mine in Utah is for the trains to take the ore to smelters beyond the mountains.

Already in 1993, the World Congress of Architects in Chicago, said:

> Sustainability means meeting the needs of the current generation without compromising the ability of future generations to meet their own needs. A sustainable society restores, preserves, and enhances nature and culture for the benefit of all life present and future; a diverse and healthy environment is intrinsically valuable and essential to a healthy society; today's society is seriously degrading the environment and is not sustainable.

Many ways exist to describe sustainable design. One approach urges using the four Rs (Fig. 2.2c):

REDUCE
REUSE
RECYCLE
REGENERATE

This book will focus on the first R: reduce. Although the word "reduce" might evoke images of deprivation, it applies primarily to the reduction of waste and extravagance. For example, American houses have more than doubled in size since 1950, and since families are now smaller, the increase in size per person is about 2.8 times (Fig. 2.2d). Is that really necessary? Are Americans happier today than in 1950? Are "starter castles" and "McMansions" the route to happiness? Are Americans happier than the British or French who live in significantly smaller homes? The book *The Not So Big House*, written by the architect Sarah Susanka, was a national best seller. Many people have discovered that bigger is not better much of the time. Susanka believes that it is wiser to build a smaller,

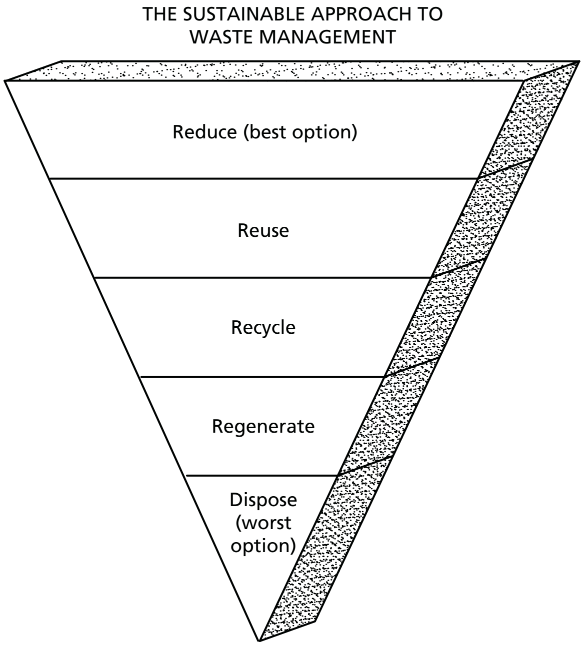

Figure 2.2c The size of each tapering block represents the relative importance of each approach to sustainability, with "reduce," as in smaller houses, being the best option.

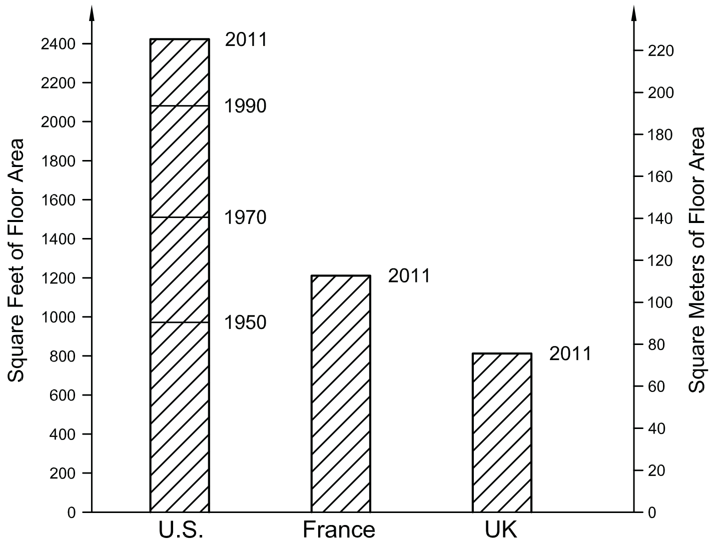

Figure 2.2d Contemporary houses in the United States are much larger than those in France, the United Kingdom, or larger houses in the United States of the 1950s. Unfortunately, not only are today's large less sustainable, but also there is no indication that larger houses have produced more happiness.

high-quality home than the more typical larger, low-quality one of the same cost. Furthermore, a small standard house is more sustainable than even a very energy-efficient large house, because it will have less embodied energy and a smaller surface area with fewer windows for heat gain and loss. Unfortunately, an incorrect use of the energy utilization index (EUI) and many other evaluation tools would show the larger house as more efficient and therefore more sustainable (see Sidebox 2.2).

Besides reducing the size of buildings, we can also reduce their energy appetite. Consider how inefficient a conventionally built home is, when a demonstration home in Lakeland, Florida, wastes 80 percent less energy (FSEC, 1998). Proven techniques in the areas of heating, cooling, and lighting can easily reduce energy use in buildings by 50 percent, and with a little effort 80 percent reductions are possible. We already have the knowledge, tools, and materials necessary to design ultra-low-energy buildings, and some of the known design strategies are equivalent to a free lunch. For example, strategies such as orientation and color can save much energy and cost nothing.

Although the primary focus of this book is "reduce" (i.e., make more efficient) by design, the building industry can also make use of the other three sustainability techniques, which will be briefly discussed in the next section.

SIDEBOX 2.2

The Energy Utilization Index (EUI), created by the U.S. government, is defined as the amount of energy used for heating and cooling per square foot per year.

$$\text{EUI} = \text{kBtu/ft}^2 \bullet \text{year}$$

where kBtu = 1000 British thermal units

The EUI is only useful for comparisons of buildings of the same type (e.g. offices, houses, schools) and of similar size. Furthermore, adjustments must be made for different climates.

Other measurement systems include:

Site energy used = utility-measured energy
Source energy = total amount of raw energy required to operate a building

2.3 REUSE, RECYCLE, AND REGENERATE BY DESIGN

Figure 2.3a shows a sight that is much too common: a building being demolished. Instead, it should in most cases be renovated and reused. According to one study, "in almost all cases, retrofit yields better environmental outcomes than demolition and new construction."[1] It takes from twenty to eighty years for a new energy-efficient building

[1]From a study coauthored by the National Trust for Historic Preservation and the Cascadia Green Building Council, *The Greenest Building: Quantifying the Environmental Value of Building Reuse*.

Figure 2.3a Buildings marked for demolition should be either reused through renovation or recycled through the process of deconstruction.

Figure 2.3b The Center for Regenerative Studies at Cal Poly Pomona was established to teach and explore how to restore the planet. The buildings are all oriented to the south, with few if any windows facing east or west. The roofs also face south to support active solar hot water collectors and future photovoltaic panels.

Figure 2.3c Fruit-bearing plants are used for shading at the Center for Regenerative Studies. (Photo by Walter Grondzik.)

to compensate for the environmental loss of the building it replaces. For most building types, it takes about twenty-five years before the savings in operating energy equals the energy required to build anew.

Although this book focuses on significantly reducing the operating energy required by buildings, it is almost as important to reduce the embodied (embedded) energy required to build new buildings because that energy has an immediate effect on global warming. A major tool for reducing the embodied energy is the technique of life cycle assessment (LCA), which tries to determine the environmental and resource impacts of a material, product, or even a whole building over its lifetime. A major part of the assessment is to determine the embodied energy. The green-building program LEED v4 includes life cycle assessment.

Also, as architect Carl Elefante has said, "New green buildings are not reducing global warming; they are only reducing the growth of global warming. Instead, fixing buildings can reduce global warming."

"The greenest building is the one that already exists!"

—Carl Elefante, architect

Even if the building in Figure 2.3a could not be saved, it could still be recycled. By a process of deconstruction, it could be taken apart, and its component parts could be either recycled (concrete, steel, lumber, etc.) or reused (windows, doors, bricks, etc.). Instead, most buildings end up as landfill, with their resources and embodied energy (see Section 3.23) completely lost.

The fourth R, regenerate, deals with the fact that much of the earth has already been degraded and needs to be restored. Since little is known about how to restore the earth, the Center for Regenerative Studies was established at Cal Poly Pomona through the pioneering work of John T. Lyle (Fig. 2.3b). Participating students from Cal Poly Pomona reside on-site to investigate how to live a sustainable and regenerative lifestyle. Built on a former landfill site, both the landscape and the architecture of the center were carefully designed to demonstrate and explore green and restorative techniques (Fig. 2.3c).

2.4 THE SUSTAINABILITY MOVEMENT

The issues related to sustainability are so all-encompassing that many feel that a different word should be used. The word "green" is often used because its connotations are flexible and it symbolizes nature, which truly is sustainable. For the same reason, many use the word "ecological." Still others prefer the phrase "environmentally responsible." The words might be different, but the goals are the same.

In "The Next Industrial Revolution" (*Atlantic Monthly*, Oct. 1998), architect William McDonough and scientist Michael Braungart suggest that sustainability is based on the following three principles:

1. *Waste equals food*—Everything must be produced in such a manner that, when its useful life is over, it becomes a healthy source of raw materials to produce new things.
2. *Respect diversity*—Designs for everything will respect the regional, cultural, and materials of a place.
3. *Use solar energy*—All energy sources must be nonpolluting and renewable, and buildings must be solar responsive.

The world community is becoming increasingly aware of the seriousness of our situation, and many important steps have been taken. The most successful so far has been the Montreal Protocol of 1987, through which the world agreed to rapidly phase out chlorofluorocarbons, which are depleting the ozone layer, thereby exposing the planet to more harmful ultraviolet radiation. Because the danger was clear and imminent, the world's resolve was swift and decisive.

Other important gatherings have addressed the need for environmental reform. In 1992, the largest gathering of world leaders in history met at the Earth Summit in Rio de Janeiro to endorse the principle of sustainable development. In 1997, representatives of many countries met in Kyoto to agree on concrete measures to address global warming. Other world summits on climate change were Bali 2007, Copenhagen 2009, and Warsaw 2013. Some countries, such as Germany, have decided to make sustainability a national goal for several reasons: it is the moral action that they owe to the children of the world, for their national security, and for economic reasons. In the United States, the American Institute of Architects has set up the Committee on the Environment (COTE) to help architects understand the problems and shape the responses needed for creating a sustainable world.

2.5 POPULATION AND AFFLUENCE

By the end of 2013, the population of the earth was more than 7.2 billion. There are various estimates on the rate of population growth, as seen in Figure 2.5a. It is appropriate to ask how many people the earth can hold. The answer to that question depends on the response to further questions. Is the capacity of the earth to be sustainable, and what is to be the standard of living?

The sustainable population or carrying capacity of the earth might already have been exceeded. Global warming is one indicator that we have exceeded the planet's carrying capacity.

Another indicator is the amount of freshwater available for the growing world population. Many parts of the world are using water faster than it is replenished. Figure 2.5b shows the problem in the American Southwest.

Scientists Paul Ehrlich and John Holden proposed the following relationship:

$$I = P \times A \times T$$

where

I = environmental impact
P = population
A = affluence per person
T = technology

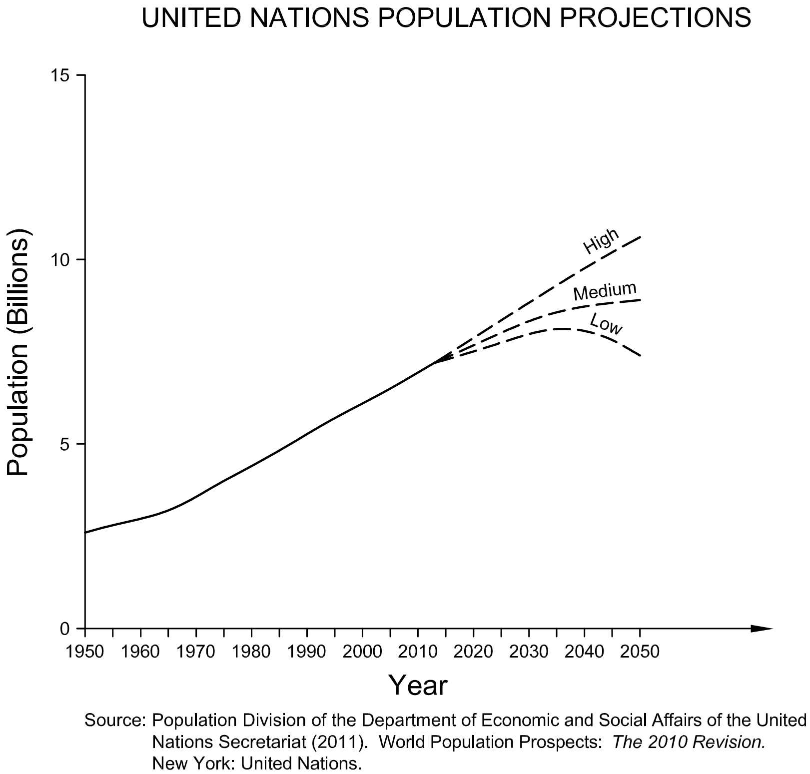

Figure 2.5a Since population growth cannot be predicted precisely, the United Nations publishes a projected range from high to low.

Figure 2.5b The "bathtub ring" visible in this view of Lake Mead indicates that water is being used up faster than the Colorado River can replenish it.

This relationship clearly shows that the greater the population, the greater the impact on the environment. It also shows that the more affluent a society, the greater the impact on the environment. For example, a family that lives in a 2500 ft^2 (225 m^2) house affects the environment far more than a family that lives in a 1000 ft^2 (90 m^2) house. Thus, it should be noted that for a given impact on the environment, the greater the population, the lower its affluence must be. Consequently, the higher a standard of living we want, the greater the need to stop population growth.

Technology also has a great impact on the environment. A person today will have a much greater impact on the environment than did a person a couple of centuries ago, when there were no automobiles, air travel, air-conditioning, electrical appliances, electrical lighting, etc. So far, most technology has had a negative impact on the environment. We can change that situation, and this book shows how to use technology that is more benign. Although not the purpose of this book, it must be recognized that sustainability cannot be achieved only by good technology; it requires us to change our values so that a high quality of life is not equated with high consumption. We also need to understand that trying to create a high standard of living for the inhabitants of the world without population control "is as though one attempted to build a 100-story skyscraper from good materials, but one forgot to put in a foundation" (Bartlett, 1997).

2.6 GROWTH

As we have seen, the growth of population, affluence, and technology places great stress on the planet by causing growth in the use of petroleum, wood, concrete, water, and just about everything else.

How is it, then, that we generally think positively about growth? Most politicians get elected by promising growth. Most communities think that 5 percent annual growth is a great idea, but do they realize that with steady 5 percent growth per year, the community will double in size every fourteen years? The doubling time for any fixed growth rate is easy to determine. See Sidebox 2.6.

Growth is popular for several reasons: many people make a good living based on growth, we generally think bigger is better, and we don't fully understand the long-term consequences of growth.

Let us look to nature for guidance on what kind of growth we want. Most living things grow until they mature. In nature, unlimited growth is seen as pathological. As the environmental writer Edward Abbey noted: "Growth for the sake of growth is the ideology of the cancer cell." Nature suggests that growth should continue until a state of maturity is reached, whereupon the focus should be on improving the quality and not the quantity.

A steady growth rate does not result in steady growth. This misconception is a major reason for our inability to plan properly for the future. For example, if the world population continues growing at its 1.9 percent rate (a small rate?) from 1975, it will grow to a size where there will be one person for every square meter (approximately a square yard) of dry land on earth in only 550 years (Bartlett, 1978). This is an example of the power of exponential growth.

SIDEBOX 2.6

To determine the doubling time for any fixed rate of growth, use the following equation:

$$T_2 = 70/G$$

where

T_2 = doubling time
G = growth rate in percent

2.7 EXPONENTIAL GROWTH

Since this book is about heating, cooling, and lighting, let us look at the growth of energy consumption over the last 10,000 years (Fig. 2.7). As in all exponential curves, growth is very slow for a very long time. Then, all of a sudden, growth becomes very rapid and then almost instantly out of control. Because the implications of exponential growth are almost sinister, it is important to take a closer look at this concept.

We have a very good intuitive feel for straight-line relationships. We know that if it takes one minute to

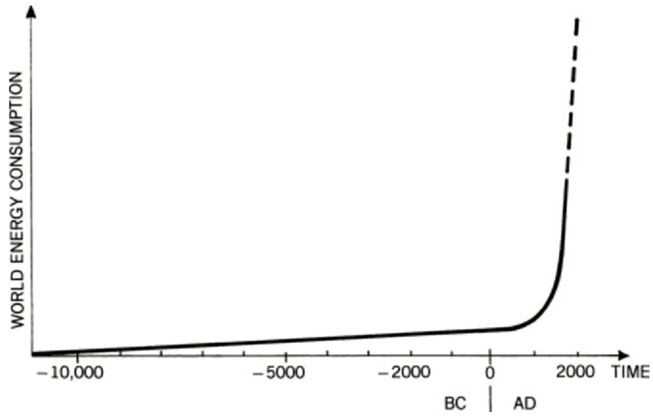

Figure 2.7 The exponential growth in world energy consumption and population growth are very similar.

fill one bucket of water, it will take five minutes to fill five such buckets. We do not, however, have that kind of intuitive understanding of nonlinear (exponential) relationships. Yet, some of the most important developments facing humankind involve exponential relationships. Population, resource depletion, and energy consumption are all growing at an exponential rate, and their graphs look very much like Figure 2.7.

2.8 THE AMOEBA ANALOGY*

Suppose a single-celled amoeba splits in two once every minute. The growth rate of this amoeba would be exponential, as Figure 2.8a illustrates. If we graph this growth, it yields the exponential curve seen in Figure 2.8b. Now let us also suppose that we have a certain size bottle (a resource) that would take the reproducing amoebas ten hours to fill. In other words, if we put one amoeba into the bottle and it splits every minute, then in ten hours the bottle will be full of amoebas, and all the space will be used up.

Question: How long will it take for the amoebas to use up only 3 percent of the bottle?

A. 18 minutes (3 percent of 10 hours)
B. about 1 hour
C. about 5 hours
D. about 8 hours
E. 9 hours and 55 minutes

Since each amoeba doubles every minute, let us work backward from the end.

Time	Percentage of bottle used up	
10:00	100	
9:59	50	
9:58	25	
9:57	12	
9:56	6	
9:55	3	Answer

For the amoebas, the space in the bottle is a valuable resource. Do you think the average amoeba would have listened to a doomsayer who at nine hours and fifty-five minutes predicted that the end of the "bottle space" was almost upon them? Certainly not—it would have laughed. Since only 3 percent of the precious resource is used up, there is plenty of time left before the end.

Of course, some enterprising amoeba went out and searched for

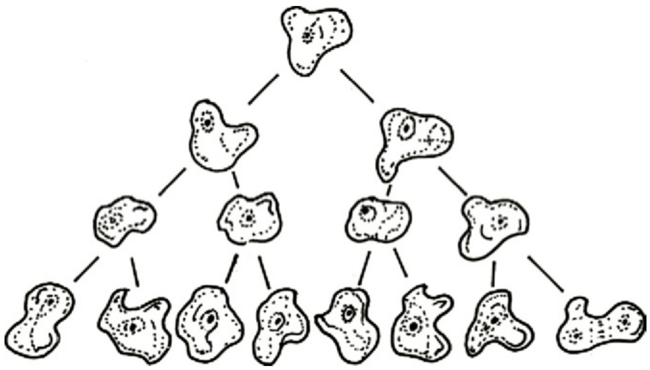

Figure 2.8a The exponential growth of an amoeba colony.

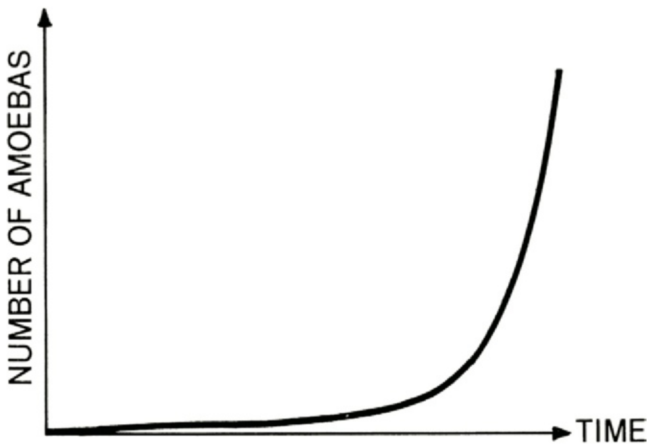

Figure 2.8b The theoretical exponential growth of an amoeba colony.

*Based on the work of Albert A. Bartlett (Bartlett, 1978).

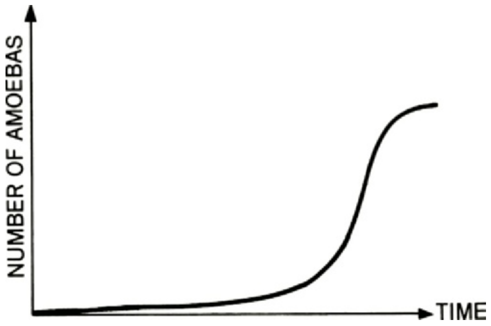

Figure 2.8c The actual growth of an amoeba colony.

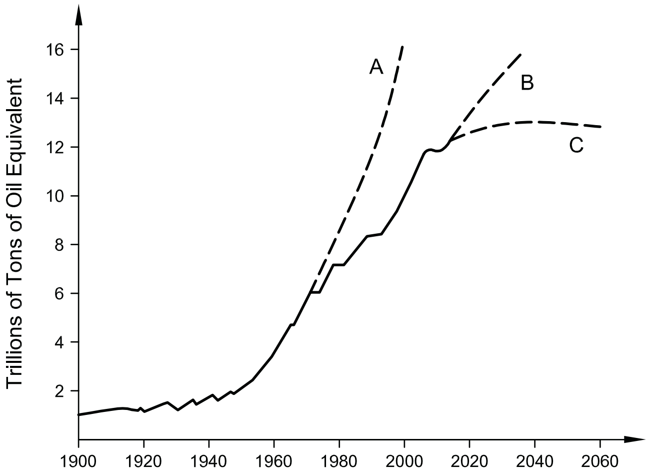

Figure 2.8d Alternate paths for future world energy consumption: (A) historical trend not followed because of the 1973 energy crisis; (B) trend if old wasteful habits return; (C) trend if conservation and efficiency guide our policies. (After "State of the World, 1999" and International Energy Agency, "World Energy Outlook," 2011.)

more bottles. If it found three more bottles, then the amoebas increased their resource to 400 percent of the original. Obviously, that was a way to solve their shortage problem. Or was it?

Question: How much additional time was bought by the 400 percent increase?

Answer: Since the amoebas double every minute, the following table tells the sad tale.

Time	Percent of the bottle filled
10:00	100
10:01	200
10:02	400

The amoebas gained only two more minutes by finding three more bottles. Obviously, it is hopeless to try to supply the resources necessary to maintain exponential growth at its later stages. What, then, is the solution?

In nature, there is no such thing as limitless exponential growth. For example, the growth of the amoeba actually follows an S curve. Although growth starts at an exponential rate, it quickly levels off, as seen in Figure 2.8c. The amoebas not only run out of food but also poison themselves with their excretions. Since humans are not above nature, they cannot support exponential growth very long either. If people do not control their growth willingly, nature will take over and reduce growth by such timeless measures as pollution, shortages, famine, disease, and war.

Until 1973, the growth of energy consumption followed the exponential curve A in Figure 2.8d. Then, with the beginning of the energy crisis of 1973, energy consumption followed an S-shaped curve. Initially the shortages and later the implementation of efficiency strategies dramatically reduced energy-consumption growth. Our attitude to the growth of energy consumption will determine whether we will follow another dangerous exponential curve B or a more sensible growth pattern, such as that indicated by curve C.

2.9 SUPPLY VERSUS EFFICIENCY

The laws of exponential growth make it quite clear that we can match energy production with demand only if we limit the growth of demand. In addition, it turns out that efficiency (conservation) is more attractive than increasing the supply from both an economic and an environmental point of view. The Harvard Business School published a major report called *Energy Future* (Stobaugh and Yerkin, 1979), which clearly presented the economic advantages of efficiency. The report concluded that conservation combined with the use of solar energy is the best solution to our energy problem. All the years since this report was published have shown that it was right on target.

The economic advantage of efficiency is demonstrated by the following example. The Tennessee Valley Authority (TVA) was faced with an impending shortage of electrical energy required for the economic growth of the valley. The first inclination was to build new electric generating plants. Instead, a creative analysis showed that efficiency would be significantly less expensive. The TVA loaned its customers the money required to insulate their homes. Although the customers had to repay the loans, their monthly bills were lower than before, because the reduced energy bills more than compensated for the increase due to loan repayments. As a consequence of reduced consumption due to efficiency, the TVA had surplus low-cost electricity to sell, the customers paid less to keep their homes warm, and everyone had a better environment because no new power plants had to be built.

Efficiency is a strategy where everyone wins. And as Amory Lovins, a hero of the planet, says, "If a building is not efficient, it is not beautiful."

2.10 SUSTAINABLE-DESIGN ISSUES

Creating a sustainable green building involves all aspects of design, which is more than one book can discuss in detail. There is, however, an important subset of issues that is discussed here, namely, energy (see Fig. 1.9).

Heating, cooling, and lighting are all accomplished by moving energy into or out of a building. As mentioned in the previous chapter, buildings use about 48 percent of all the energy consumed in the United States. Because of global warming and air pollution, the energy subset of all the sustainability issues is the most urgent to address.

The highly regarded *Environmental Building News* printed a list of what it believes are the eleven most important sustainable design issues. They are reproduced below. Note that the first issue is "Save Energy: Design and build energy-efficient buildings." Although this book covers only some of the issues, the whole list is reproduced.

Priority List for Sustainable Building*

1. Save Energy: Design and build energy-efficient buildings.
2. Recycle Buildings: Utilize existing buildings and infrastructure instead of developing open space.
3. Create Community: Design communities to reduce dependence on automobiles and to foster a sense of community.
4. Reduce Material Use: Optimize design to make use of smaller spaces and utilize materials efficiently.
5. Protect and Enhance the Site: Preserve or restore local ecosystems and biodiversity.
6. Select Low-Impact Materials: Specify low-environmental-impact, resource-efficient materials.
7. Maximize Longevity: Design for durability and adaptability.
8. Save Water: Design buildings and landscapes that are water-efficient.
9. Make the Buildings Healthy: Provide a safe and comfortable indoor environment.
10. Minimize Construction and Demolition Waste: Return, reuse, and recycle job-site waste, and practice environmentalism in your business.
11. "Green Up" Your Business: Minimize the environmental impact of your own business practices, and spread the word.

*Reprinted by permission from the *Environmental Building News*. See the September–October 1995 issue for a more thorough discussion of these issues, which are as relevant today as they were in 1995.

Note that only item number five does not have a direct impact on energy consumption in buildings. The design and location of a building determines the amount of energy needed for its operation, its embodied energy, the energy it takes to supply water, and the energy needed to commute.

Reducing energy consumption is 90 percent of sustainability!

2.11 CLIMATE CHANGE

Energy issues are directly related to global warming. That latest report (2013) of the Intergovernmental Panel on Climate Change (IPCC) is clearer than ever that the warming of the climate is unequivocal and most of it is caused by human-created greenhouse gases. It also states that before the end of this century (1) the earth's temperature will rise; (2) there will be more and greater droughts, heat waves, cyclones, and heavy rainfall; and (3) sea levels will rise. In 2010, the National Research Council (a branch of the US National Academies of Science) suggested that by the end of the twenty-first century, temperatures will rise 4°F to 11°F (2.2°C to 6.1°C) and the oceans will rise 22 to 79 in. (0.55 to 2 m). Such predictions assume that the present trends continue, but that is not certain. In 2013, the National Research Council warned again that the climate can tip and that it could happen very soon.

The cause of the global warming is no mystery when we note the corresponding increase of the greenhouse gas carbon dioxide (Fig. 2.11a). Humanity is also heating the planet by producing methane, nitrous oxide, chlorofluorocarbons, and some other minor greenhouse gases. Most of the heating, however, is due to the carbon dioxide produced from burning the fossil fuels coal, oil, and natural gas. The greenhouse effect will be explained in the next section.

Even small increases in global temperatures can have serious effects besides deadly hotter summers. Precipitation patterns will change, with a corresponding disruption in agriculture; some of the world's poorest and most heavily populated regions will be losers. There will be more droughts in some areas and floods in others. Diseases that thrive in warmer climates, such as malaria, will spread over more of the globe, and species extinction will have a further negative impact on the present ecology. And perhaps most important, there will be a rise in the sea level.

Although the high prediction of 79 in. (200 cm) by the National Research Council is bad enough, sea levels could rise much more than that, especially if the climate suddenly tipped. It is worth asking what the maximum sea-level rise could be if all the ice on Greenland and Antarctica melted, which is possible because it has happened several times in geologic time. The seas could rise as much as 240 ft (80 m). Even if only 20 percent of the ice melted, the seas would rise 48 ft (14.4 m).

When important decisions are made about the future, we must base them not only on likelihood but also on the severity of outcomes. For example, few people play Russian roulette, where a person spins the cylinder of a revolver loaded with only one bullet, aims the muzzle at his head, and pulls the trigger (Fig. 2.11b). Although the probability of dying is only a low one in six (17 percent), sane people don't play because the outcome is a disaster.

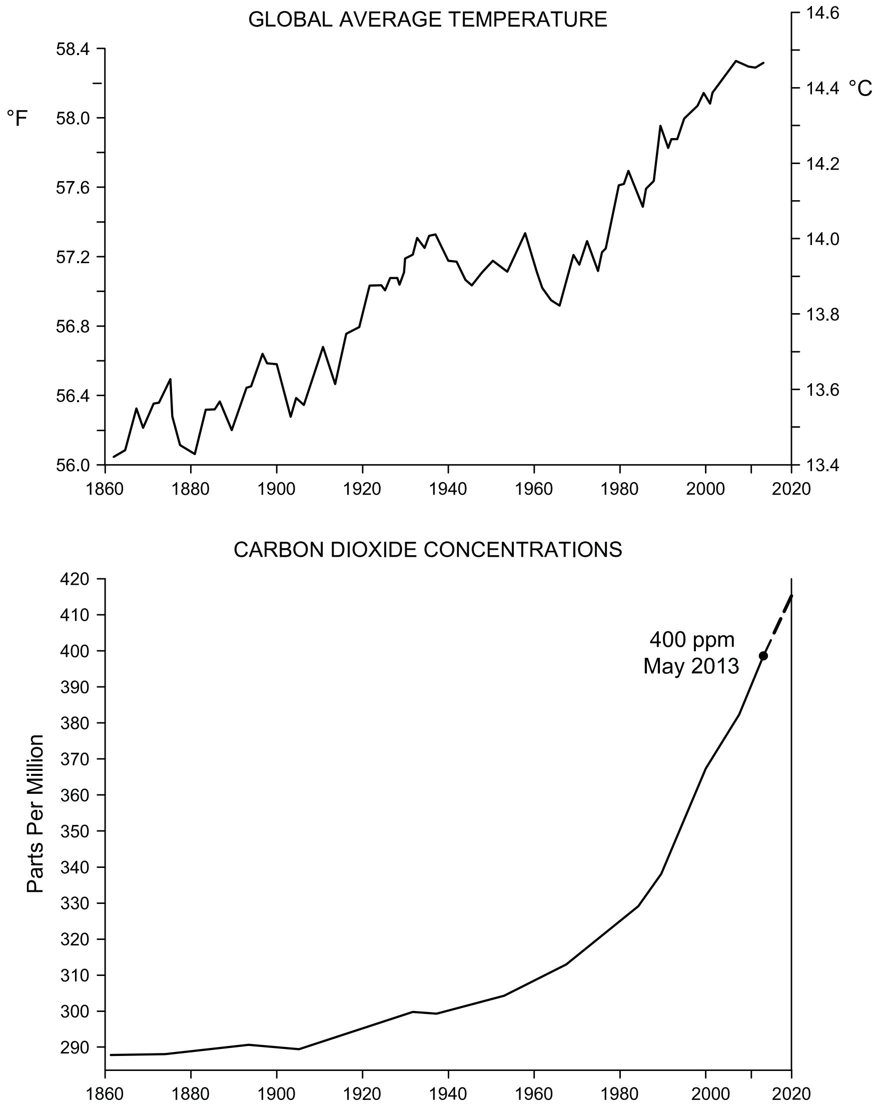

Figure 2.11a The upper graph represents the increase of the global average temperature, and the lower graph represents the increase of carbon dioxide during the same time period. (Sources: temperature data from Goddard Institute for Space Studies; carbon dioxide data from Scripps Institution of Oceanography, updated 2013.)

Similarly, we should not play Russian roulette with the planet, which we are clearly doing (Fig. 2.11c).

The fundamental and generally accepted "prudence principle" states: even if the probability is low, if the consequences are serious, then action should be taken. Thus, no matter what the probability of a global warming catastrophe, its seriousness requires us to take immediate action.

A major reason for the uncertainty of the of climate change is that the climate may suddenly tip like a tower that is leaning too far (Fig. 2.11d and e). We know of several phenomena that can cause the climate to tip, with the most obvious one being the changing solar reflectivity as ice melts in the Arctic and Antarctic. Snow and ice are about 90 percent reflective while land and open water are only 10 percent reflective. Thus, as more land and water are exposed, more sunlight is absorbed, increasing the temperature to melt more snow and ice—thereby exposing more land and water and a positive feedback loop is created.

A second known mechanism that can cause the climate to tip is the melting of the permafrost found in northern Canada, Europe, Russia, and Alaska. Huge amounts of organic material will decompose, giving off both carbon dioxide and methane, which is twenty-one times more powerful a greenhouse gas than carbon dioxide. Thus, a faster warming planet melts permafrost faster, which creates more greenhouse gases, and so on.

Another known tipping mechanism is the release of methane from a material called methane hydrate, also known as fire ice or flaming ice, because it consists of methane (natural gas) trapped within a crystal structure of water. A piece of methane hydrate, which looks like ice, will actually burn as the methane is released from the melting ice. Huge quantities of this material are found under sediments in oceans and lakes located in cold regions such as Siberia and northern Canada. Lakes in those cold regions can be set on fire in the summer as warm temperatures release the methane that then bubbles to the surface. Methane hydrates can also be found in permafrost. As the earth warms, methane will be released from the methane hydrate causing more warming releasing more methane—and so another positive feedback loop is created. Consequently, there are at least three vicious feedback cycles that can cause the climate to tip.

We must heed the warnings of Hurricanes Katrina and Sandy, super typhoons in Asia, major planetary heat waves, and unusual worldwide flooding by taking action immediately to minimize the severity of global warming. As the eminent physicist Albert A. Bartlett said, "We must recognize that it is not acceptable to base our national [planetary] future on the motto, 'When in doubt, gamble'" (Bartlett, 1978).

One of the main reasons for inaction is the mistaken belief that fighting global warming hurts the economy. The opposite is true. A major report in 2006 for the United Kingdom by Sir Nicholas Stern, a former chief economist with the World Bank, states that unless we

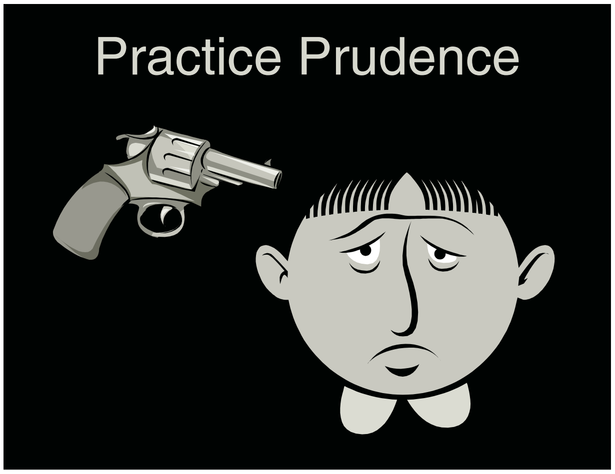

Figure 2.11b Russian roulette is unpopular not because of the odds but because the stakes are too high.

Figure 2.11c This generation has no right to play Russian roulette with the planet. It is immoral!

act soon, global warming will cause a worldwide economic depression. Furthermore, countries like Germany, which have made sustainability a national goal, are thriving economically.

Because of our tremendous appetite for energy, Americans produce more carbon dioxide per person than just about any other nation. Furthermore, because we have a long history of industrialization and because we have a large population, the United States has produced slightly under 30 percent of all the carbon dioxide in the atmosphere, which is by far the largest amount of any country (see Table 2.11). The recent abundance of oil and gas from fracking is a mixed blessing for the United States. It decreases our dependence on foreign energy sources,

Figure 2.11d Many phenomena exhibit a tipping effect whereby change is gradual until a point of instability occurs. Global warming could well be such a phenomenon.

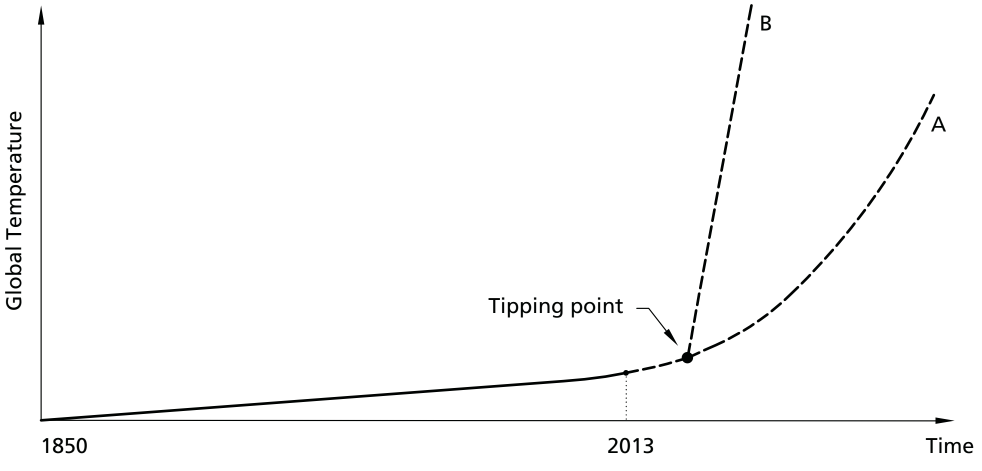

Figure 2.11e If or when the climate tips, changes to the environment would be very rapid rather than the more gradual changes we see today. A tipping climate greatly reduces the time available for taking corrective action.

Table 2.11 Contribution to Atmospheric Carbon Dioxide, by Country

Country	Percentage of World Total
United States	29.3
Russia	8.1
China	7.8
Germany	7.3
United Kingdom	6.3
Japan	4.1
France	2.9
India	2.2
Australia	1.1
Mexico	1.0
South Korea	0.8
Iran	0.6
Indonesia	0.5
Pakistan	0.2
Developed countries	76
Developing countries	24

Source: World Resource Institute

and the expanded use of natural gas is reducing our reliance on the most harmful fossil fuel, coal. Although natural gas is better than coal, it still adds significant amounts of carbon to the atmosphere, and its abundance and low cost delays our transfer to clean renewable fuels and takes the pressure off to make buildings more energy efficient.

2.12 THE GLOBAL GREENHOUSE

The greenhouse gases in the atmosphere act as a one-way radiation trap. They allow most of the solar radiation to pass through to reach the earth's surface, which then radiates increased amounts of heat back toward space in the form of long-wave infrared radiation, but the greenhouse gases trap some of this radiation (Fig. 2.12). Consequently, the earth warms up.

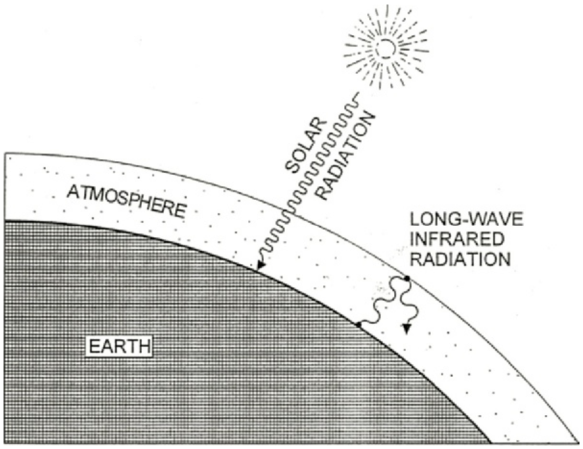

Figure 2.12 The atmosphere acts like a greenhouse by allowing most of the solar radiation to enter but blocking the long-wave infrared radiation from leaving the planet.

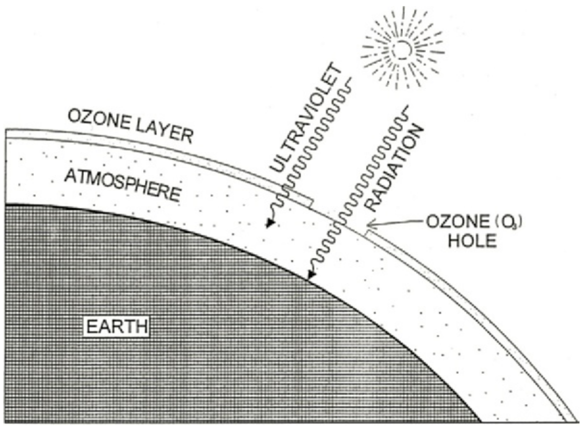

Figure 2.13 The depletion of the ozone layer allows greater amounts of the sun's harmful ultraviolet radiation to reach the earth's surface.

The present average global temperature is a consequence of the existing level of water vapor and other greenhouse gases mentioned above. The earth is about 60°F (35°C) warmer than it would be without these gases. When more greenhouse gases are added to the atmosphere, the equilibrium temperature increases and the earth gets warmer. The greenhouse effect is explained in more detail in Sections 3.10 and 3.11.

2.13 THE OZONE HOLE

The ozone hole is another example of a critical undesired change to the atmosphere. The air-conditioning of buildings has led indirectly to a hole in the ozone layer that protects the earth from most of the sun's harmful ultraviolet radiation (Fig. 2.13). The chlorofluorocarbon (CFC) molecules that were invented to provide a safe, inert refrigerant for air conditioners have turned out to have a tragic flaw, inertness, which ironically was considered their major virtue. When these molecules escape from air conditioners or are released as propellants in spray cans, they survive and slowly migrate to the upper atmosphere, which contains ozone. There, the CFCs deplete the protective ozone layer for an estimated fifty years before they themselves are destroyed. Consequently, the problems will be with us long after we eliminate all CFCs on the surface.

The 1987 Montreal Protocol, which the United States wholeheartedly supports, requires countries to phase out the production of CFCs. Although this is a classic example of how technological solutions can be the source of new problems, it is also a good example of how world cooperation based on sound science can respond quickly to a serious problem.

Regretfully, international cooperation has not succeeded as well in controlling greenhouse emissions. Progress is slow for various reasons, one of which is the shortsighted policies of some fossil-fuel and transportation industries.

2.14 EFFICIENCY VERSUS RENEWABLE ENERGY

When people discover that the consumption of fossil fuels is causing global warming, they commonly conclude that we should switch to clean, renewable energy from the sun, wind, or other sources. A less common reaction is the belief that we can greatly reduce the consumption of fossil fuels by reducing waste. Of course, we need to do both, but it must be clearly understood that by far the most important option is efficiency, since it is the easiest, quickest, and least expensive way to fight global warming. Efficiency is the low-hanging fruit (Fig. 2.14).

For example, optimized window design can reduce energy consumption and carbon dioxide production up to 40 percent. Although such a window system will cost more initially, it will not only reduce energy costs for the life of the building but will also reduce the first cost of the air-conditioning system thereby partially offsetting the cost of the windows.

Because most of this book discusses how to design energy efficient and solar responsive buildings, the remainder of this chapter discusses the various energy sources that are presently available mostly off-site to power buildings.

Figure 2.14 Efficiency is the low-hanging fruit. We should not put all our effort in going after the high fruits (photovoltaics, wind, hydrogen, etc.) until we have picked the low-hanging fruit (orientation, insulation, shading, etc.).

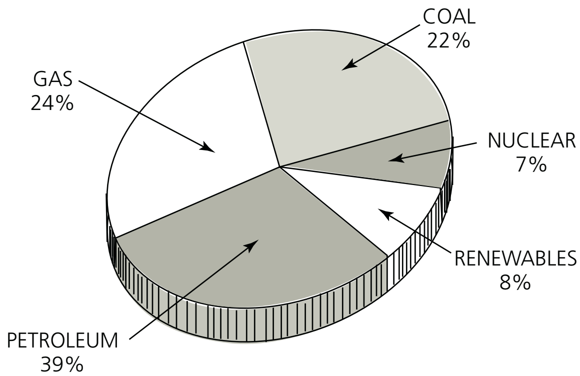

Figure 2.15 Energy consumption by source in the United States. Note that 92 percent is from nonrenewable sources.

2.15 ENERGY SOURCES

Which energy sources are available to power buildings, and which of these are sustainable? We can divide all of the sources into the two main categories: renewable and nonrenewable:

I. Renewable
   A. Solar
   B. Wind
   C. Biomass
   D. Hydroelectric
   E. Geothermal
II. Nonrenewable
   A. Fossil fuels
      1. Oil
      2. Natural gas
      3. Coal
   B. Nuclear
      1. Fission
      2. Fusion?

Figure 2.15 shows that we are using mostly nonrenewable energy sources. This is an unfortunate situation because not only are we using up these sources, but they are the very ones causing pollution and global warming. We must switch as quickly as possible from nonrenewable to renewable sources. Before we look at each source in terms of its ability to power buildings sustainably, let's look at a brief example of the history of energy use in buildings.

2.16 ENERGY USE IN ANCIENT GREECE

The role of energy in buildings was largely ignored in recent history until the energy crisis of 1973, when some of the leading members of the Organization of Petroleum Exporting

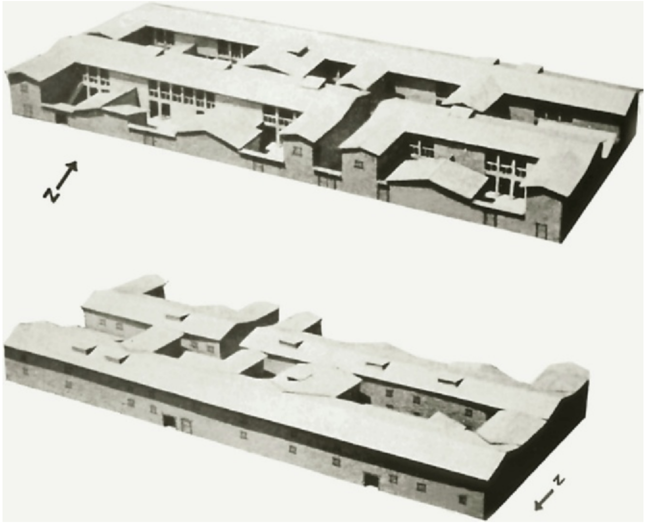

Figure 2.16 Solar buildings were considered modern in ancient Greece. Olynthian apartments faced south to capture the winter sun. Note that there are no east or west windows and only a few and small northern windows. (From *Excavations at Olynthus, Part 8: The Hellenic House*. © Johns Hopkins University Press, 1938).

Countries (OPEC) suddenly raised prices and set up an embargo on oil exports to the United States. The resulting energy shortages made us realize how dependent we were (and still are) on unreliable energy sources. We began thinking about how we use energy in buildings.

Before the energy crisis, a discussion of ancient Greek architecture would not have even mentioned the word "energy." The ancient Greeks, however, became aware of energy issues as the beautiful, rugged land on which they built their monuments became scarred and eroded by the clearing of trees to heat their buildings. The philosopher Plato said of his country: "All the richer and softer parts have fallen away and the mere skeleton of the land remains."

The ancient Greeks responded to their energy crisis partly by using solar energy. The philosopher Socrates thought that this was important enough to compel him to explain this method of designing buildings. According to the historian Xenophon, Socrates said: "In houses that look toward the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so that there is shade" (see Fig. 2.16). Socrates continued talking about a house that has a two-story section: "The section of the house facing south must be built lower than the northern section in order not to cut off the winter sun" (Butti and Perlin, 1980).

2.17 NONRENEWABLE ENERGY SOURCES

When we use nonrenewable energy sources, we are much like the heir living it up on an inheritance with no thought of tomorrow until one day he or she finds that the bank account is empty. Two major categories of nonrenewable energy sources exist: fossil fuels and nuclear energy.

Fossil Fuels

For hundreds of millions of years, green plants trapped solar energy by the process of photosynthesis. The accumulation and transformation of these plants into solid, liquid, and gaseous states produced what we call the fossil fuels: coal, oil, and natural gas. When we burn these, we are actually using the solar energy that was stored hundreds of millions of years ago. Because of the extremely long time required to convert living plants into fossil fuels, in effect they are depletable or nonrenewable energy sources. The fossil-fuel age started around 1850 and will last at most a few centuries more. The finite nature of the fossil-fuel age is clearly illustrated by Figure 2.17a.

Most air pollution and smog are a result of the burning of fossil fuels (see Fig. 2.17b). The use of fossil fuels also causes acid rain, mercury poisoning, and most important of all, global warming.

Natural Gas

Natural gas, which is composed primarily of methane, is a convenient source of energy. Except for the global-warming carbon dioxide it produces when burnt, it is a clean energy source. With the extensive pipeline system that exists, natural gas can be delivered to most of the populated areas of the United States and Europe. Once burnt

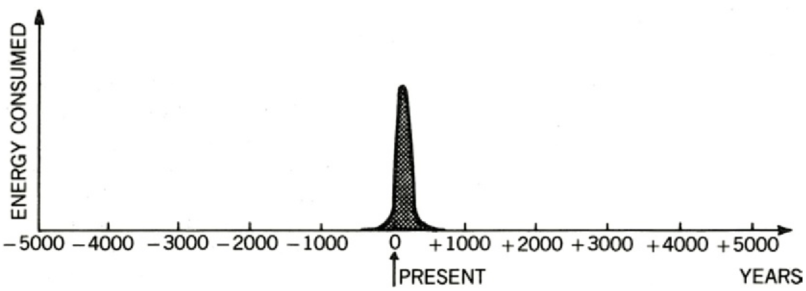

Figure 2.17a The age of fossil fuels in the longer span of human history. (After Hubbert.)

Figure 2.17b Air pollution covering New York City is not like this every day. Often the pollution is blown away to Connecticut or New Jersey.

Figure 2.17c Oil platforms for drilling underwater are very expensive, making the extracted oil also more expensive.

at the oil well as a waste by-product, it is in great demand today. Natural gas is again bountiful because of the recently developed "fracking" techniques of extracting gas from shale. As stated above, this new source of natural gas is a mixed blessing. On the plus side is its displacement of coal, but on the negative side, fracking causes ground and water pollution and may cause accidental release of significant amounts of methane, which is twenty-one times more powerful a greenhouse gas than carbon dioxide.

Oil

The most useful and important energy source today is oil. But the world supply is limited and will be mostly depleted by the end of this century. Unconventional sources of oil such as fracking and tar sands are creating a temporary reprieve in the rising cost of oil. Unfortunately, extracting oil by fracking and from tar sands not only pollutes land and water but also causes increased global warming, because more energy is needed in the extraction. A gallon of gasoline from these sources causes much more global warming than a gallon derived by more conventional methods.

Since much of the easily obtainable oil has already been pumped out of the round, we are now forced to use fracking, much deeper wells, deep sea wells (Fig. 2.17c), and go to almost inaccessible places, such as the north slope of Alaska. Difficult places to drill also increases the chances of serious oil spills like the BP Deepwater Horizon oil spill in the Gulf of Mexico in 2010.

Most important, however, is that no matter where the oil comes from, burning it produces carbon dioxide and thereby global warming.

Coal

By far the most abundant fossil fuel we have is coal, but significant problems are associated with its use. The difficulties start with the mining. Deep mining is dangerous to miners in two ways. First, there is the ever-present danger of explosions and mine cave-ins. Second, in the long run there is the danger of severe respiratory ailments due to the coal dust. If the coal is close to the surface, strip mining might be preferred. Although strip mining is less dangerous to people, it is quite harmful to the land. Reclamation is possible but expensive. Much of the strip mining occurs in the western United States, where the water necessary for reclamation is a scarce resource.

Additional difficulties result because coal is not convenient to transport, handle, or use. Since coal is a rather dirty fuel to burn and a major cause of acid rain and mercury in the environment, its use will likely be restricted to large burners, where expensive equipment can be installed to reduce air pollution. Even if coal is burned "cleanly," it still produces huge amounts of carbon dioxide and thereby much global warming.

To overcome some of the negative impacts, the coal industry has developed a technology called clean coal, and it has suggested that carbon dioxide emissions from power plants could be sequestered. However, using clean coal technology raises costs, and carbon-dioxide sequestering will raise costs even further to the point where coal will not be cost competitive.

All of these difficulties add up to coal being inconvenient, expensive, risky, and a major cause of global warming. Although plentiful, it is not the answer to our energy problems.

Nuclear Fission

In fission, certain heavy atoms, such as uranium-235, are split into two middle-size atoms, and in the process give off neutrons and an incredible amount of energy (Fig. 2.17d). During the 1950s, it was widely believed that electricity produced from nuclear energy would be too cheap to meter.

Even with huge governmental subsidies because of nuclear energy's defense potential, this dream has not become a reality. In fact, just the opposite has happened. Nuclear energy has become one of the most expensive and least desirable ways to produce electricity. One important factor in the decline of nuclear power is that the public is now hesitant to accept the risks. Nuclear power accidents, such as the ones that took place at Chernobyl in the Soviet Union in 1986 and Fukushima in Japan in 2011, spread deadly radiation over large areas. The nuclear accident at Three Mile Island, Pennsylvania, in 1979 might have been just as serious if a very expensive containment vessel had not been built. More than twenty years later, the reactor is still entombed, with a billion-dollar cleanup bill. The safety features needed to prevent accidents or minimize their impact have made the plants uneconomical. Even with all the safety features, the risks are still not zero, as Figure 2.17e shows.

The overall efficiency of nuclear power plants has not been as high as had been hoped. The initial cost of a nuclear power plant is high, the operating efficiency is low, and the problem of disposing of radioactive nuclear waste has still not been solved.

Since uranium is a rare element, unearthing it requires huge mines that create mountains of radioactive waste. Nuclear power plants also need huge amounts of cooling water. Plants that are located on rivers either

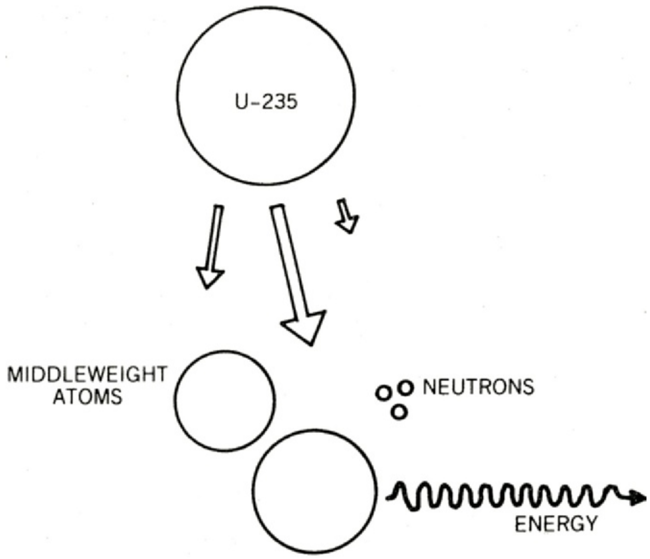

Figure 2.17d Nuclear fission is the splitting apart of a heavy atom.

Figure 2.17e Take this quiz: This sign refers to what kind of power plant? (A) photovoltaic, (B) wind, (C) biomass, (D) nuclear. (Courtesy of Southern Nuclear).

use or heat up the river. In 2003, during a heat wave and drought, France had to shut down some of its nuclear power plants because they were overheating the rivers that cooled them.

Lately, the nuclear power industry has argued that new technology is foolproof, yet they want the government to pass a law exempting them from all liability. Why is that necessary if their new systems are foolproof?

Thus, there are many excellent reasons not to go with the nuclear option besides the fact that it is much more expensive than renewable energy. As the business magazine the *Economist* said in its May 19, 2001, issue: "Nuclear power, once claimed to be too cheap to meter, is now too costly to matter." Although nuclear energy does not produce greenhouse gases, there are more economical options to displacing fossil fuels.

Nuclear Fusion

When two light atoms fuse to create a heavier atom, a process called fusion, energy is released (Fig. 2.17f). This is the same process that occurs in the sun and other stars. It is quite unlike fission, a process through which atoms decay by coming apart.

Fusion has many potential advantages over fission. Fusion uses hydrogen, the most plentiful material in the universe, as its fuel. It produces much less radioactive waste than fission. It is also an inherently much safer process because fusion is self-extinguishing when something goes wrong, while fission is self-exciting.

All the advantages, however, do not change the fact that a fusion power plant does not yet exist, and we have no guarantee that we can ever make fusion work economically. Even the greatest optimists do not expect fusion to supply significant amounts of power anytime soon.

Considering the shortcomings, perhaps the best nuclear power plant is the one 93 million mi (150 million km) away: the sun. It is ready to supply us with all the energy we need right now.

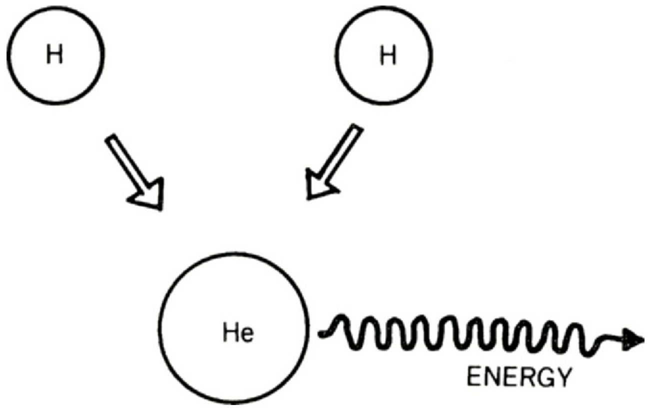

Figure 2.17f Nuclear fusion consists of the union of very light atoms. For example, the fusion of two hydrogen atoms yields an atom of helium as well as a great deal of extra energy.

2.18 RENEWABLE ENERGY SOURCES

The following sources all share the very important assets of being renewable and of not contributing to global warming. Solar, wind, hydroelectric, and biomass are renewable because they are all variations of solar energy. Of the renewable energy sources, only geothermal energy does not depend on the sun.

Solar Energy

The term "solar energy" refers to the use of solar radiation in a number of different ways. The building-integrated solar collection methods are all discussed at some depth in this book:

- Passive solar energy (Chapter 7)
- Photovoltaics and active solar energy (Chapter 8)
- Daylighting (Chapter 13)

The phrase "solar energy" is also used to describe large centralized systems that produce electricity either with solar electric systems (photovoltaics) or solar thermal systems that generate steam to power electric generators.

In one year, the amount of solar energy that reaches the surface of the earth is 10,000 times greater than all the energy of all kinds that humanity uses in that period. Why, then, aren't we using solar energy? This question can be explained only partly by the technical problems involved. These technical problems stem from the diffuseness, intermittent availability, and uneven distribution of solar energy. However, these problems are being resolved.

The main nontechnical challenge for solar energy is that most people equate it with photovoltaics (PV) usually called solar panels. When they discover that PV is expensive, they conclude that solar is expensive. Nothing is further from the truth. Figure 2.18a shows the solar-responsive design tree with the height of different fruits representing different solar strategies. Since "pick the low-hanging fruit first" is a wise policy, solar strategies such as building orientation, building color, and window distribution should be utilized first. These lowest-hanging solar strategies save huge amounts of energy and are free. The next higher ones are not free but are very cost-effective.

Solar energy consists of more than just photovoltaics (PV)!

Other nontechnical problems facing the acceptance of solar energy are primarily a result of people's beliefs that it is unconventional, looks bad, does not work, is futuristic, etc. On the contrary, in most applications, such as daylighting or the use of sunspaces, solar energy adds special delight to architecture. Interesting aesthetic forms are a natural product of solar design (see Fig. 11.6e and 11.6f). Solar energy promises to not only increase the nation's energy supply and reduce global warming but also enrich its architecture.

Besides being renewable, solar energy has other important advantages. It is exceedingly kind to the environment. No air, water, land, or thermal pollution results. Solar energy is also very safe to use. It is a decentralized source of energy available to everyone everywhere. With its use, individuals are less dependent on brittle or monopolistic centralized energy sources, and countries are secure from energy embargoes. China, Germany, Japan, and Switzerland have embarked on ambitious solar programs in order to become more energy-independent, while in the United States solar is underutilized.

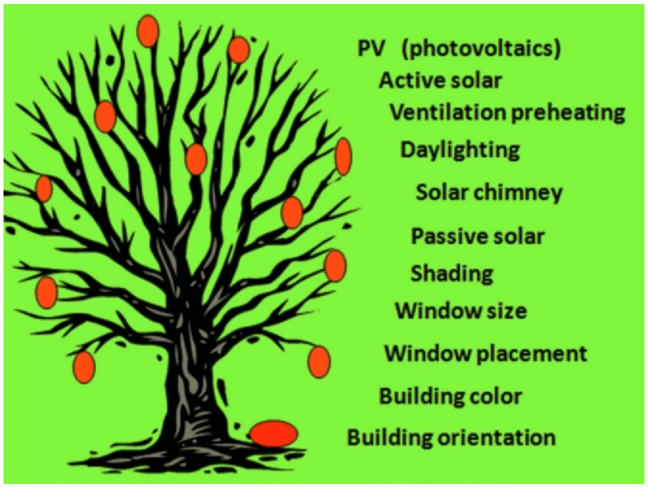

Figure 2.18a The solar-responsive design tree not only shows all of the existing solar strategies but also the order in which they should be picked (i.e. the lowest-hanging fruit first).

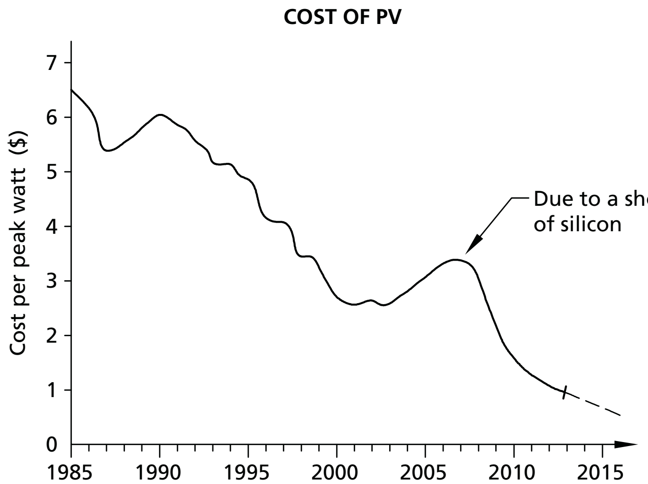

Figure 2.18b The cost of PV electricity has declined dramatically and will almost certainly continue to decline. Nevertheless, PV is more expensive than other solar strategies, especially the free ones.

Photovoltaic Energy

If one were to imagine the ideal energy source, it might well be photovoltaic (PV) cells. They are often made of the most common material on earth: silicon. They produce the most flexible and valuable form of energy: electricity. They are very reliable—no moving parts. They do not pollute in any way—no noise, no smoke, no radiation. And they draw on an inexhaustible source of energy: the sun.

Over the last thirty years, the cost of PV electricity has been declining steadily, and it is in the process of becoming competitive with conventional electricity (Fig. 2.18b). PV electricity is already competitive for installations that are far from the existing power grid, and during peak demand times when electricity is very expensive.

The greatest potential may lie with building-integrated photovoltaics (BIPV) both for our energy future and for architecture. For more information about PV see Chapter 8.

Wind Energy

The ancient Persians used wind power to pump water. Windmills first came to Europe in the twelfth century for grinding wheat and pumping water. More than six million windmills and wind turbines have been used in the United States over the last 150 years partly to grind wheat but mostly to pump water on farms and ranches (Fig. 2.18c and d). Wind turbines also produced electricity for some remote areas before rural electrification in the 1930s.

Today, wind turbines are having a major revival because they can produce clean, renewable energy at the same cost as conventional energy. Where wind is plentiful and electricity is expensive, wind power is often the least expensive source of electricity. All over the world, giant wind turbines and wind farms are generating electricity for the power grid, and wind

Figure 2.18c This windmill in Colonial Williamsburg, Virginia, was used to grind wheat.

Figure 2.18d Windmills still pump water on some ranches and farms, and small modern wind turbines produce electricity for individual homes.

Figure 2.18e Utility-size wind farms like this one in Oklahoma are being built all over the world.

electricity could supply all U.S. energy needs (Fig. 2.18e).

Small wind turbines can be a source of electricity for individual buildings where the wind resource is sufficient, which is a function of both velocity and duration. Color plate 20 shows where favorable wind conditions can be found in the United States. Of course, local conditions are critical, and a local survey should be made. Mountaintops, mountain passes, and shorelines are often good locations in all parts of the country. For economic reasons, minimum annual average wind speeds of 9 mph (14 kph), or 4 meters per second (m/s), are needed. See the end of the chapter for information on wind-resource availability.

Both theory and practice have shown that wind turbines are not appropriate for urban areas because turbines require smooth airflow, and buildings create much turbulence. Furthermore, vibration and noise make wind turbines inappropriate even for isolated, very tall buildings.

Since the power output of a wind turbine is proportional to the cube of the wind speed (see Sidebox 2.18), a windy site is critical, and there is a great incentive to raise the turbine as high into the air as possible to reach higher wind speeds. Most often, wind machines are supported on towers,

SIDEBOX 2.18

The power produced by a wind machine is proportional to the cube of the wind speed and the square of the rotor radius,

$$P \approx v^3 \times d^2$$

Where

P = power output
v = air speed
d = rotor diameter

For example, the power output will be 8 (2^3) times as large if the wind speed doubles. Stated another way, a 12.6 mph (20 kph) wind will yield twice the power of a 10 mph (16 kph) wind.

Also, if the rotor diameter is doubled (2^2), the power output will be four times as large.

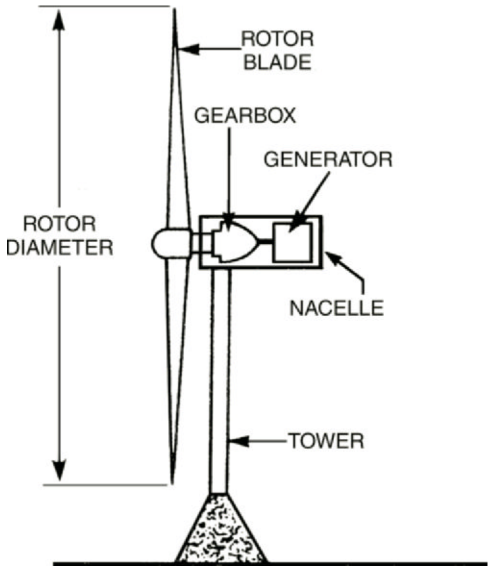

Figure 2.18f The essential components of a wind turbine are shown. (Drawing from DOE/CE-0359P.)

some as high as 400 ft (125 m). Wind turbines come in all sizes, but even the small ones should be mounted at least 40 ft (12 m) above the ground in order to catch enough wind.

The power output of a wind turbine is also proportional to the square of the length of the rotor blades (Fig. 2.18f). A 6.6 ft (2 m) diameter rotor is enough to power a television, while a 66 ft (20 m) diameter rotor can generate enough electricity for five hundred Americans or one thousand Europeans. Because larger is much better in the case of wind turbines, the largest today are 500 ft (150 m) in diameter and still larger ones are on the drawing boards.

The intermittent nature of wind power is not a serious problem, since other energy sources can supply the electricity to the grid when there is not enough wind. Although wind's intermittent nature must be accounted for, it is nevertheless one of the best renewable energy sources.

In stand-alone systems, a large battery is needed to supply electricity when the wind is not blowing. It has been found, however, that hybrid systems combining wind power with PV cells are very efficient because they complement each other. In winter, there is less sun but more wind, while in summer, the PV cells generate more electricity than the wind turbine. Similarly, on stormy days, there is less sun but more wind. Thus, wind turbines and PV cells are frequently used together, as shown in Figure 8.5c. Also see Sections 8.5 and 8.6 for a discussion of typical electrical systems.

Especially in certain locations, wind machines have killed some birds. Although this is a concern, it is a minor problem when compared with the approximately 57 million birds that are killed each year in collisions with cars and 97 million birds killed in collisions with plate-glass windows.

Although some wind farms are spread over large areas of land, the land can still be used for crops and grazing. This is not the case for hydropower, where the land behind the dam is flooded and lost. Also, wind farms require only about one-fifth the amount of land that hydropower needs.

There is also some concern about the aesthetic impact of wind farms because, by their very nature, wind machines must be high in the air. There have been few complaints about actual installations, and the author believes there is inherent beauty in a device that produces renewable, nonpolluting energy.

Biomass Energy

Photosynthesis stores solar energy for later use. This is how plants solve the problems of diffuseness and intermittent availability, which are associated with solar energy. This stored energy can be turned into heat or electricity, or converted into such fuels as methane gas, alcohol, and hydrogen. Because biomass is renewable and carbon neutral, and because with modern technology its use is relatively pollution-free, it is an attractive energy source. Two major sources of biomass exist: (1) plants grown specifically for their energy content and (2) organic waste from agriculture, industry, and consumers (garbage).

Some types of biomass can be converted into biofuels, while the rest is burned to create electricity. There are three major types of biofuels: (1) ethanol alcohol, (2) biodiesel, and (3) methane.

Because ethanol alcohol is presently made from sugars or carbohydrates, large-scale use will compete with food production, and on a worldwide basis there is no food to spare. Consequently, alcohol made from cellulose is a better source. Plants like switchgrass, which can grow on land too poor for food production, would be ideal sources of cellulose. Unfortunately, at this point, creating alcohol from cellulose is a process still being perfected.

Biodiesel can use oil wastes from restaurants, but when made from other plants it again competes with food or causes ecological damage. Thus, biodiesel is good but limited in its use.

Methane, the main component of natural gas, is an excellent biofuel when made from the decay of waste materials on farms, ranches, or landfills (Fig. 2.18g). Not only is it a valuable fuel, but its collection and combustion prevent its addition to the atmosphere, where it acts as a greenhouse gas twenty-one times more powerful than carbon dioxide.

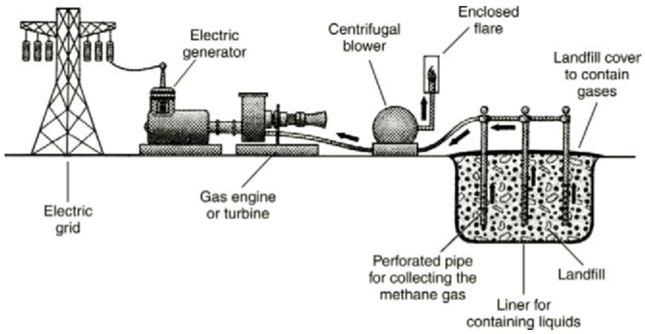

Figure 2.18g Landfill gas can be collected to generate electricity. (Fact Sheet No. 16, Texas State Energy Conservation Office.)

We must be careful about turning biomass into energy, because decomposed biomass is food for new plants (Fig. 2.18h). As William McDonough, architect, author, and former dean of the School of Architecture at the University of Virginia, said, "Waste is food."

Figure 2.18h Saving biomass to replenish the soil makes sense at both the macro and micro level. This sign was found in a residential development outside of Houston, Texas.

Burning biomass instead of fossil fuels can reduce the problem of global warming because biomass is carbon neutral. When growing, plants remove the same amount of carbon dioxide from the atmosphere that is returned when the biomass is burned. Thus, over time, there is no net change in the carbon-dioxide content of the atmosphere.

Wood used to heat houses is an example of biomass energy. Large-scale burning of wood in fireplaces or stoves, however, is not desirable because of the low efficiency and large amount of air pollution produced. Fireplaces are very inefficient (see Section 16.2), and wood stoves are better but still polluting.

Biomass is a desirable source of energy, but limited, for several reasons: it is needed to produce food and products such as lumber; it is advantageous to agriculture that it be returned to the ground to fertilize the next crop; and it provides a means to sequester carbon from the atmosphere, through creation of permanent topsoil (see Colorplate 22).

Hydroelectric Energy

The use of water power, also called hydropower or hydroelectricity, has an ancient history: watermills were already popular in the Roman Empire. The overshot wheel (Fig. 2.18i) was found to be the most efficient, but it required at least a 10 ft (3 m) fall (head) of the water. When there was little vertical fall in the water but sufficient flow, an undershot wheel (Fig. 2.18j) was found to be best. Today, compact turbines are driven by water delivered in pipes.

The power available from a stream is a function of both head and flow. Head is the pressure developed by the vertical fall of the water, often expressed in pounds per square inch (kilopascals). Flow is the amount of water that passes a given point in a given time as, for example, ft^3 per minute (liters per second). The flow is the result of both the cross section and velocity of a stream or river.

Since power output is directly proportional to both head and flow, different combinations of head and flow will work equally well. For example, a very small hydropower plant can be designed to work equally with 20 ft of head and a flow of 100 ft^3 per minute (6 m and 48 l/s), or 40 ft of head and a flow of 50 ft^3 per minute (12 m and 24 l/s).

Today, water power is used almost exclusively to generate electricity. The main expense is often the dam that is required to generate the head and store water to maintain an even flow (Fig. 2.18k). One advantage of hydropower over some other renewable sources is the relative ease of storing energy. The main disadvantage of hydroelectricity is that large areas of land must be flooded to create the storage lakes. This land is most frequently prime agricultural land and is often highly populated. Another disadvantage is the disturbance of the local ecology as

Figure 2.18i An overshot waterwheel is best used where river water can be diverted high enough to be dropped onto the waterwheel. The waterwheel shown is in Korea.

Figure 2.18j Undershot waterwheels use the flow of the river for power. These Chinese waterwheels were used to lift river water for irrigation.

Figure 2.18k Hydroelectric dams produce pressure (head). Some also store water, and therefore energy, for later use.

when fish cannot reach their spawning grounds. For this reason, many existing dams in the United States are being demolished.

Figure 2.18l illustrates a simple, small-scale hydroelectric system. The dam generates the required head, stores water, and diverts water into the pipe leading to the turbine located at a lower elevation. Modern turbines have high rotational speeds (rpm) so that they can efficiently drive electric generators.

All but the smallest systems require dams, which are both expensive and environmentally questionable. Very small systems are known as "micro-hydropower" and can use the run of the river without a dam. The site must still have an elevation change of at least 3 ft (1 m) in order to generate the minimum head required. Of course, the more head (elevation change), the better.

About 5 percent of the energy in the United States is supplied by falling water. At present, we are using about one-third of the total hydroelectric resource available. Full use of this resource is not possible because some of the best sites remaining are too valuable to lose. For example, it would be hard to find anyone who would want to flood the Grand Canyon or Yosemite Valley behind hydroelectric dams. Most Americans now see our scenic rivers and valleys as great resources to be protected.

Hydroelectric energy will continue to be a reliable but limited source for our national energy needs.

Marine Energy

The four types of marine power sources are (1) tidal power, (2) wave

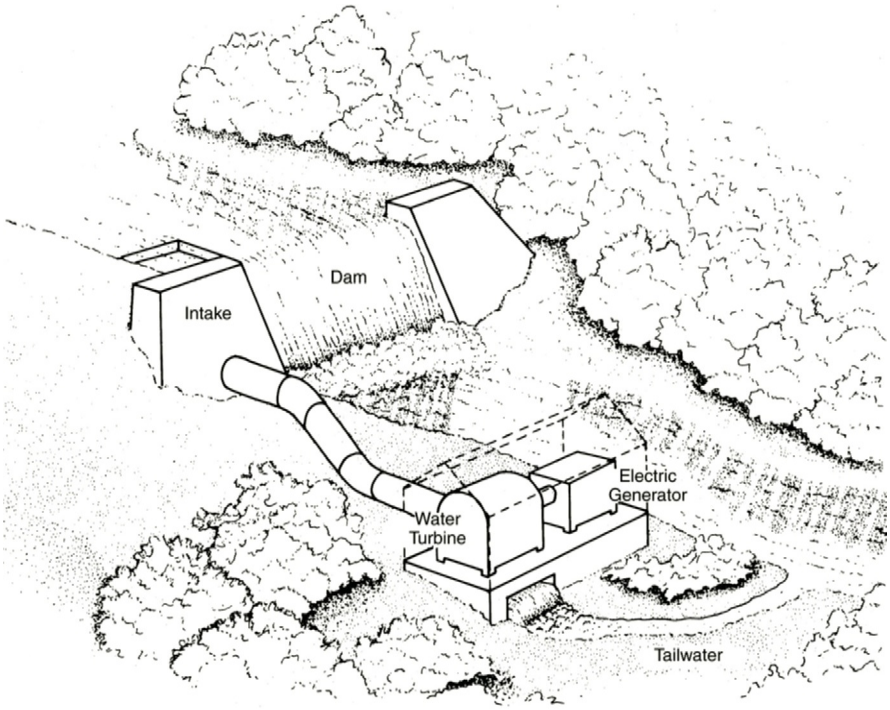

Figure 2.18l A simple, small-scale hydroelectric system. The dam can be eliminated with a run-of-river system in a fast-flowing stream or river by placing propeller-driven generators in the flow of water. (From *Building Control Systems* by Vaughn Bradshaw. 2nd edition. © John Wiley & Sons, Inc. 1993.)

power, (3) ocean-current power, and (4) ocean thermal-energy conversion.

Tidal power has been used for centuries with great success. Because it is most efficient where bays have small openings to the sea, its application is limited. Wave power is more widely distributed but more difficult to harness. Ocean-current power is very much like wind power except that water turbines are used. Like wind, it is available only in certain locations. Ocean thermal-energy conversion (OTEC) uses the large temperature difference between the deep ocean and its surface to generate power. All of the marine energy sources except tidal power are still in their experimental and development stages.

Geothermal Energy

The term "geothermal" has been used to describe two quite different energy systems: (1) the extraction of heat originating deep in the earth, and (2) the use of the ground just below the surface as a source of heat in the winter and a heat sink in the summer. To eliminate confusion, the second system is often called by the much more descriptive name "geo-exchange."

Geothermal energy is available where sufficient heat is brought near the surface by conduction, bulges of magma, or circulation of groundwater to great depths. In a few places, like Yellowstone National Park, hot water and steam bring the heat right to the surface. Other such sites, like the geysers in northern California and the Hatchobaru power station in Japan, use this heat to generate electricity. In some places like Iceland, geothermal energy is also used to heat buildings. Although surface sites are few in number, there is a tremendous resource of hot rock energy at depths of 5 to 10 mi (8 to 16 km). By drilling two holes, water can be pumped down one hole to the hot rock layers where it is heated, and then the hot water and/or steam can be returned through the second hole to drive a turbine or heat buildings. In the city of Boise, Idaho, a geothermal system heats over 360 buildings, including the state capitol. The United States has enough geothermal resources (Colorplate 23) to meet 6 percent of its 2025 energy needs.

Geo-Exchange

The low-grade thermal energy contained by the ground near the surface can be extracted by a heat pump to heat buildings or domestic hot water (heat pumps are explained in Section 16.10). This same heat pump can use the ground as a heat sink in the summer. Since the ground is warmer than the air in winter and cooler than the air in summer, a ground-source heat pump is much more efficient than normal air-source heat pumps. Also, since electricity is used to pump heat and not create it, a geo-exchange heat pump is three to four times more efficient than resistance electric heating.

The use of geo-exchange heat pumps can significantly reduce our consumption of energy and the corresponding emission of pollution and greenhouse gases. Reductions of 40 percent over air-source heat pumps and reductions of 70 percent compared to electric-resistance heating and standard air-conditioning equipment are feasible. See Section 16.11 for a more detailed discussion of this excellent system.

2.19 HYDROGEN

Although hydrogen is not a source of energy, it might play an important role in a sustainable economy. Hydrogen is the ideal nonpolluting fuel because when it is burned, only water is produced. It does not contribute to global warming.

Hydrogen is abundant, but all of it is locked up in compounds, such as water (H_2O). The closest place to mine free hydrogen is the planet Jupiter. Until we can go there, we will have to manufacture it here on earth. To produce free hydrogen, energy is needed to break the chemical bonds.

Although several methods exist for producing hydrogen, the process must use renewable energy sources if it is to produce a truly clean, sustainable fuel. Hydrogen can be separated from natural gas, coal, or other hydrocarbons by a process called reformation, but this source of hydrogen is not sustainable, since it still uses fossil fuels as the source of energy. Hydrogen can also be created by living organisms in ponds, but the most practical source is electrolysis using electricity generated by wind and PV. Hydrogen is a good match for the intermittent sources of solar and wind whose main weakness is energy storage. Whenever excess electricity is produced, it can be used to produce hydrogen from water by electrolysis (Fig. 2.19). The hydrogen can then be used to generate pollution-free electricity in fuel cells, which are explained in Section 3.22. It can also be used as a fuel to power automobile engines.

The efficient and economical storage of hydrogen remains a technical problem, however. The high-pressure tanks are heavy and expensive. To store hydrogen as a liquid is even more difficult because it then must be cooled to −423°F (−253°C). A more efficient solution might be to store the hydrogen in chemical compounds called **hydrides**. However, much more research is needed to make hydrogen the fuel of choice.

Hydrogen has the potential to become a clean, renewable fuel to power our cars and buildings, but since it is not a source of energy, we must still develop the renewable energy sources described above.

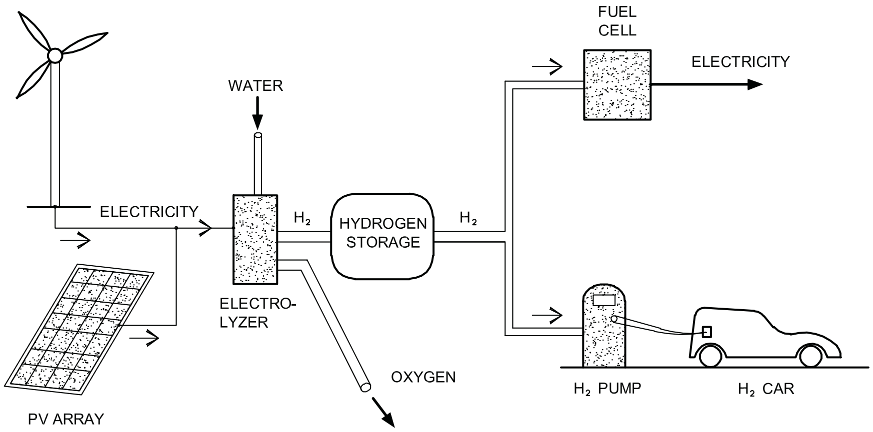

Figure 2.19 Hydrogen will be sustainable only if it is produced by renewable energy such as PV and wind. It can be used as both a fuel for our vehicles and for fuel cells that power and heat our buildings.

2.20 CONCLUSION

> If we are looking for insurance against want and oppression, we will find it only in our neighbors' prosperity and goodwill and, beyond that, in the good health of our worldly places, our homelands. If we were sincerely looking for a place of safety, for real security and success, then we would begin to turn to our communities—and not the communities simply of our human neighbors, but also of the water, earth, and air, the plants and animals, all the creatures with whom our local life is shared.
>
> —*Wendell Berry, Author*

We are not achieving safety by the way we use energy. We are damaging the environment, changing the climate, and using up our nonrenewable energy sources at a phenomenal rate. Our present course is not sustainable.

Since buildings use almost one-half of all the energy consumed and almost three-quarters of all the electricity, the building-design community has both the responsibility and the opportunity to make major changes in the way we use energy. The amount of energy a building consumes is mainly a function of its design.

Since the energy crisis of 1973, many fine buildings have shown us that buildings can be both energy efficient and aesthetically successful. As Bob Berkebile, one of our most environmentally responsive architects, has said, "If a building makes animals or people or the planet sick, it's not beautiful and it's not good design" (Wylie, 1994).

We in the United States have a special obligation because we use 25 percent of the world's energy and produce 22 percent of the carbon dioxide, but have only 5 percent of the world's population (Fig. 2.20a). As mentioned before, each American produces more

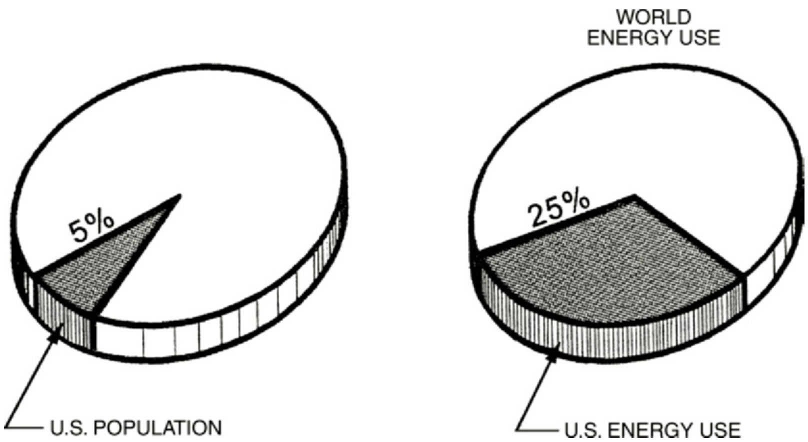

Figure 2.20a The United States has about 5 percent of the world's population, but it consumes about 25 percent of the world's energy.

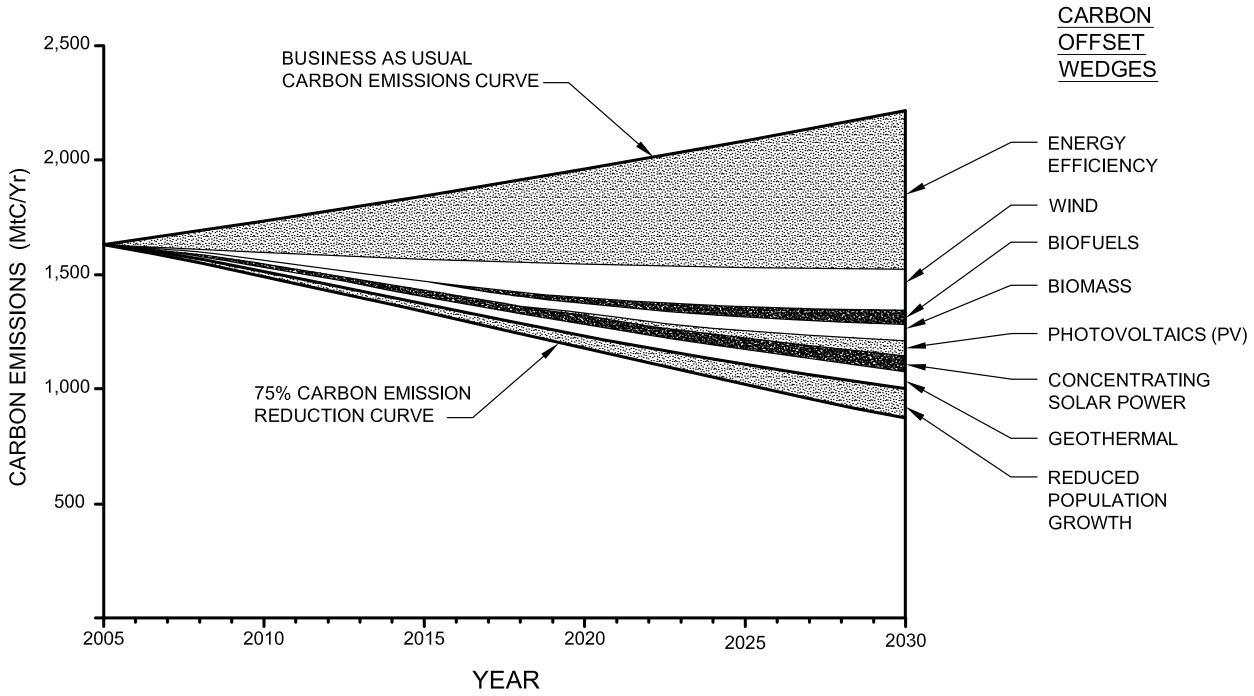

Figure 2.20b To prevent a global warming catastrophe, we must reduce our carbon dioxide emissions from the top curve to the bottom curve by reducing our dependence on fossil energy. By using all of the renewable energy wedges, and especially the efficiency wedge, we can accomplish this most important planetary goal. This graph is based on the work of "stabilization wedges" by Pacala and Socolow (Pacala, 2004).

carbon dioxide than the citizen of any other country (see Table 2.11). The only exceptions are citizens of a few oil-rich countries like Qatar. We also have been producing carbon dioxide for a long time, so as a country we are responsible for just a little less than 30 percent of all the man-made carbon dioxide in the atmosphere (see Table 2.11). We also have the wealth and resources to lead the way. As a leader in research and technology, we can create and share the technical tools needed for creating a sustainable world.

Some people incorrectly assume that nothing can be done about global warming. However, the renewable energies mentioned above, together with efficiency, can radically reduce greenhouse gases and lead us to a sustainable world (Fig. 2.20b).

The following chapters present the information and design tools needed to create aesthetic, energy-conscious buildings. The goal is to reduce the amount of energy that buildings need using the three-tier approach: design of the building itself, use of passive systems, and finally, efficient mechanical systems.

Since heating, cooling, and lighting are consequences of energy manipulation, it is important to understand certain principles of energy. The next chapter reviews some of the basic concepts and introduces other important relationships between energy and objects.

KEY IDEAS OF CHAPTER 2

1. We are squandering the earth's riches, destroying the environment, and changing the climate without regard to the needs of future generations.
2. Sustainability can be achieved by implementing the four Rs: reduce, reuse, recycle, and regenerate.
3. Sustainable design is also known as green, ecological, or environmentally responsible design.
4. The greater the population, the more difficult it is to achieve sustainability.
5. The greater the affluence, the more difficult it is to achieve sustainability.
6. Limitless growth is the enemy of sustainability.
7. Because many important phenomena, such as energy consumption, are exhibiting exponential growth, and because people do not have a good understanding of the implications of exponential growth, improper decisions are being made about the future.
8. Sustainability can be achieved only if we design and build energy-efficient buildings.
9. The massive use of fossil fuels is causing global warming and climate change.

10. At present, most of our energy comes from nonrenewable and polluting energy sources, such as coal, oil, gas, and nuclear energy.
11. Efficiency is the best, quickest, and most cost-effective way to reduce our dependence on fossil and nuclear energy.
12. We must switch to renewable, nonpolluting energy sources such as solar, wind, biomass, hydropower, and geothermal energy.
13. Geo-exchange heat pumps have great potential for energy conservation.
14. Although not a source of energy, hydrogen has the potential to be the clean fuel of the future.
15. As architect Bob Berkabile said, "If a building makes animals or people or the planet sick, it's not beautiful and it's not good design."

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Videos

(See Appendix K for full citations and ordering information.)

Affluenza. KCTS Television Arithmetic, Population, and Energy. Dr. Albert A. Bartlett. 65 minutes.

An Inconvenient Truth. Al Gore.

*Keeping the Earth: Religious and Scientific Perspectives on the Environmen*t. 27 minutes.

World Population. ZPG.

Organizations

(See Appendix K for full citations and ordering information.)

American Hydrogen Association
(E-mail): aha@getnet.com
www.clean-air.org

American Solar Energy Society
www.ases.org

National Renewable Energy Laboratory
www.nrel.gov
Good source for detailed information on renewables.

Oak Ridge National Laboratory
www.ornl.gov
An excellent source of information on renewable energy and energy efficient building.

Rocky Mountain Institute
www.rmi.org
An excellent source of objective energy information.

Union of Concerned Scientists
www.ucsusa.org

U. S. Department of Energy
www.energy.gov
Portal for all kinds of information from the U. S. government about making buildings energy efficient.

CHAPTER 17

TROPICAL ARCHITECTURE

Do unto those downstream as you would have those upstream do unto you.
Wendell Berry

17.1 INTRODUCTION

The part of the world that lies between the Tropic of Cancer (23.5°N latitude) and the Tropic of Capricorn (23.5°S latitude) is called the tropics, and it contains much of the earth's landmass. In the Americas, the tropics extend from the middle of Mexico to the southern part of Brazil. Most of Africa, half of India, all of Southeast Asia, and all of Indonesia fall in the tropics (Fig. 17.1).

The tropics will see much of the world's future construction because it contains many quickly developing countries. Furthermore, its already large population will continue to grow rapidly, from the present 40 percent to about 60 percent of the world's population by 2060. These trends will result in much work for architects and builders but will also present a great challenge for the sustainability of the planet.

This chapter will explain how to design buildings in the tropics that are cooled and lit as sustainably as possible. Since the design of buildings in the tropics is similar to those designed in very hot regions of the temperate zones, this chapter only discusses how they differ. For those aspects where the design is the same, the reader is referred to the appropriate chapters elsewhere in the book. Consequently, anyone designing buildings in the tropics should study all of the chapters in this book except for Chapter 7, which covers passive solar heating. Especially relevant are Chapters 6, 9, and 10.

17.2 TRADITIONAL TROPICAL ARCHITECTURE

To be low energy, modern buildings must borrow as many strategies as possible from traditional buildings that were properly designed for their climate. Because of cultural, climate, and sun angle differences, traditional tropical buildings come in a great variety. The degree of comfort that they can provide also varies greatly, with greater indoor comfort possible in hot and dry than in hot and humid climates. Because the resulting designs are so different, hot and dry climates will be discussed separately from hot and humid.

Hot and Dry Climates

Although daytime temperatures are much higher in dry than humid climates, the high diurnal temperature range of dry climates can create comfort by the use of massive walls and roof structures. The time lag of the resulting large thermal mass, combined with night-flush cooling, can create indoor comfortable temperatures most of the year and most of each day (see especially Section 10.9).

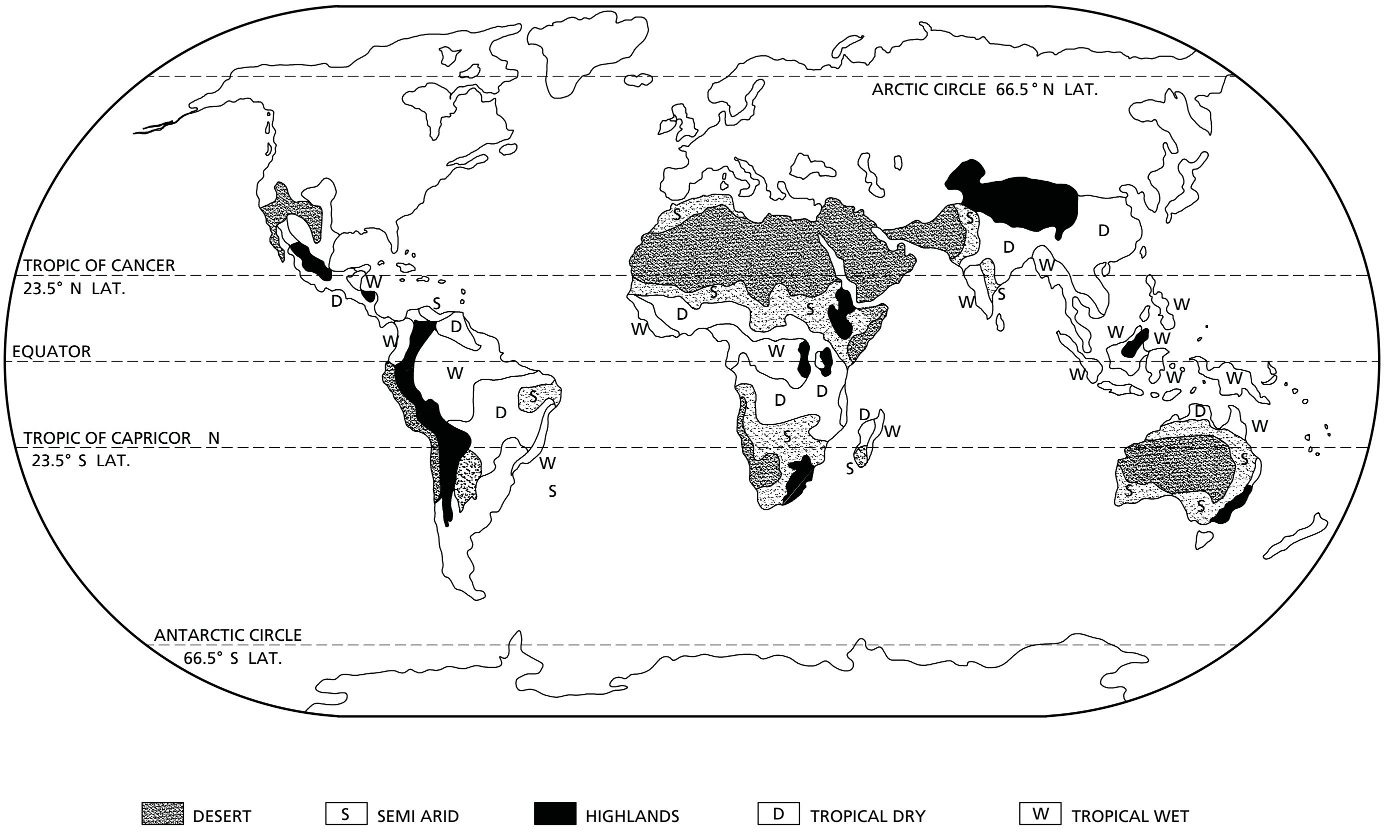

Figure 17.1 The land area of the tropics is about equally divided between dry and wet climates. Most people, however, inhabit the wet regions because more food can be grown there.

However, the benefits of thermal mass in hot and dry climates can be negated if too much sun is allowed to enter during the day. Thus, because keeping the sun out is critical, a common shading strategy was to have small windows facing a narrow street or alley (Fig. 17.2a). When windows were not shaded by neighboring buildings or when large windows were desired, various shading devices were used. The most common of these were louvered shutters that kept most of the sun out while allowing a small amount of daytime ventilation (see far left in Fig. 17.2b). The shutters would then be opened for night-flush cooling. Also quite common were overhangs which would work well on south facades (north in the Southern Hemisphere), but on east and west facades additional vertical shading devices such as shutters or outdoor curtains were required to keep out the low morning and afternoon sun. Outdoor curtains were popular on east and west windows because they, like shutters, could be left open half of the daytime hours and all of the night to again maximize night-flush cooling (Fig. 17.2b). Evaporative cooling by means of hanging wet blankets in the path of incoming air was also used in some regions.

Multistory buildings with small but deep courtyards were very popular and appropriate in hot and dry climates (see Fig. 10.2g). Most if not all windows faced the courtyard, which is self-shaded much of the day. Because cool air sinks and because the bottom floor is most shaded, the family spent much of the summer there. In the winter, the top floor was most comfortable, because it gets the most sun and warm air rises. When possible, ceilings were high to benefit from stratification. The outdoor walls were usually of a light color to reflect the sun.

Shading was not limited only to buildings. Market streets often had either overhead shading if they were narrow or colonnades or arcades if they were wide. If these covered sidewalks were on north–south streets, their exposure to the east or west was frequently protected by movable vertical shading (Fig. 17.2c).

Figure 17.2a This narrow alley in the old section of Fez, Morocco, provides much shade for the windows, walls, and the alley itself. The white walls further reduce solar heat gain.

Figure 17.2b In hot climates, shade is the top priority for achieving thermal comfort. This street scene in modern Fez, Morocco, shows many of the strategies used: louvered shutters (far left), a small overhang (window in center), covered balconies, and outdoor curtains.

Figure 17.2c Arcades and colonnades are popular in hot climates to shade both storefronts and pedestrians. Although this colonnade in Casablanca, Morocco, is quite wide, it nevertheless uses outdoor roller shades to protect from the low morning or late afternoon sun because it is on a north–south street.

Hot and Humid Climates

Although the daytime temperatures are much lower in humid climates than in dry climates, when combined with the high humidity, they create great discomfort. The high humidity makes it very hard for the body to cool itself through sweating. The low diurnal range results in nighttime temperatures that are still too high for thermal mass to be helpful. The only strategies available in hot and humid climates are heat avoidance and maximizing natural ventilation both during the day and at night.

Traditionally, heat avoidance was primarily achieved by shading, as can be seen in Figure 17.2d. Thus shading is a critical strategy in all hot climates. Shading is achieved mostly by large roof overhangs, porches, and shutters (Fig. 17.2e). On east and west facades, vertical shading was required in addition to overhangs, and it was usually accomplished by shutters or bamboo roll-up shades (Fig. 17.2f). Heat was also avoided by using low light levels and by cooking outdoors.

Even when the indoor temperature was minimized by heat avoidance, it was still too warm for comfort because of the high humidity. However, thermal comfort could be achieved or at least approached by moving air across human bodies by means of natural ventilation. A building with no walls would be ideal, but privacy and security usually require a barrier, such as the very open screens seen in Figures 17.2g and 17.2h. Raising the building on stilts increases natural ventilation because wind speeds increase with height. Buildings on stilts also provide security against people and animals, since the walls are often nothing more than an open weave punctured with windows. In urban areas with a high cost of land, buildings tend to be higher and can therefore experience more natural ventilation. Traditionally, one common strategy was to place monitors on the roof to exhaust hot air by means of both a negative pressure caused by the wind and the stack effect (Fig. 17.2i).

Figure 17.2d Shade is the number-one priority in hot climates, as these motorcyclists in a very hot and humid part of China demonstrate.

Figure 17.2e This traditional Indonesian house demonstrates many of the strategies appropriate in hot and humid climates. The house is raised on stilts both to get above the humidity and surface water on the ground and to raise the building to catch more wind. The high roof allows for stratification and good gable ventilation. The large covered porch provides shading for windows, walls, and an outdoor living space. To maximize natural ventilation, the windows are floor to ceiling and protected by louvered shutters.

Ceilings would be high or nonexistent for the benefit of stratification. In one-story buildings or the top floor of multistory buildings, there would be no ceiling. Since roofs are typically steep gables, these spaces would be very high and well ventilated all the way to the ridge, thereby exhausting the hottest air, which collects there.

Figure 17.2f The low east and west sun make shading those orientations very difficult but especially necessary. A common solution was to have deep covered porches with roll-down bamboo curtains.

Figure 17.2h This traditional upper-class home in Malaysia maximizes natural ventilation while providing significant security through carved screens and windows with shutters. Note how the roof seems to float on the walls to further maximize natural ventilation.

Figure 17.2g To maximize natural ventilation, this Southeast Asian rustic home has walls that are as porous as possible while still providing some security and privacy. Also note the gable vents that also allow light to enter.

Windows needed to be large to maximize natural ventilation. Louvered shutters were popular because they allowed much nighttime ventilation and some daytime ventilation while keeping the sun out. Since daytime ventilation will heat the indoors while cooling people by evaporation, thermal mass is not desired. It would only store heat during the day to make it even hotter at night. Furthermore, it is not cool enough at night to cool the mass sufficiently for it to be a heat sink the next day. Instead, traditional buildings in hot and humid climates were made of lightweight materials such as wood. Even palaces were made of wood (Fig. 17.2j), which was perforated with carved screens in both the outdoor walls and indoor partitions.

Before air-conditioning became available, the above strategies were used from the lowliest structure to the most expensive buildings of the rich and noble. Although not ideal in hot and humid climates, masonry walls were sometimes used either to protect against fire, especially in urban areas, or for protection against storms and human enemies. This was especially true of buildings constructed by the colonial powers. These buildings were usually a blend of the type used in the home country of the imperial power and the local strategies more suited to the climate (Figs. 17.2k and 17.2l).

Traditional site planning and landscaping also contributes to thermal comfort. When possible, buildings in the hot and humid tropics were sited to maximize access to the wind. When courtyards were used, they were open to the wind either by having the building on stilts or by maintaining breezeways between the four buildings that formed the courtyard. The landscape would consist of mostly tall trees because they provide shade without blocking the wind near ground level.

Figure 17.2i In the traditional urban Chinese building in hot and humid areas, the first floor was commercial and the second floor was residential. To maximize natural ventilation, the commercial activity was completely open to the street during the day, with awnings providing additional shade. Upstairs, large windows with louvered shutters allowed much natural ventilation at night and some during the day. The ventilation is greatly improved by the roof monitors, which operate through a combination of the stack effect, the Bernoulli effect, and the venturi effect (see Section 10.5 for an explanation of these).

Figure 17.2k The design of this European-style building in Bangkok, Thailand, adjusted as much as possible to a climate alien to its origins by means of the extensive use of large windows protected by louvered shutters. Transplanting building styles that are appropriate for one climate to an alien and inappropriate climate is a phenomenon that runs throughout the history of architecture. Unfortunately, only in some cases are the styles modified either immediately or over time to fit the new climate. For example, Auburn University in the hot South is built in the English Georgian style more suitable for a mild cloudy climate.

Figure 17.2j Lack of money was not the reason this royal palace in Bangkok, Thailand, was made of wood. Rather, it was the recognition that massive materials like stone and brick were inappropriate for promoting thermal comfort in a hot and humid climate. An abundance of beautiful carved wood screens under each window maximize ventilation.

Figure 17.2l The Raffles Hotel in Singapore is an example of a European colonial building very well adapted to the local hot and humid climate. Not only are all of the rooms protected by exterior corridors, but also the low sun is blocked by louvered screens.

The typical dress in each type of climate suggests some basic logic for designing appropriate buildings. In hot and dry climates, people are typically completely covered by clothing to protect against the sun. Of course, white garments are best. Nevertheless, in some very hot and dry climates, men wear white while women wear black. My suggestion for such places is for a switch so that the men wear black and women white. It would be interesting to see if the men would then conclude that both sexes should wear white. Quite differently, in hot and humid climates, people tend to wear very little clothing so that evaporative cooling is maximized. Although shading the skin is still beneficial, humid climates usually have lots of shade trees, which is not the case in dry climates, where shading the skin is more important than maximizing evaporative cooling. However, in any hot climate the clothing is very loose to help with evaporative cooling.

Since all of the above strategies can also be found in hot temperate climates, it is important to understand what is different about the tropical climates.

17.3 THE TROPICAL CLIMATE

As mentioned in Chapter 5, the word "climate" comes from the ancient Greek word for "incline." The Greeks understood that the climate of a region is very much influenced by the angle of sunrays throughout the year. In general, the higher the incline of sunrays, the warmer the climate.

A major difference between temperate and tropical climates is that it almost never gets cold enough to require heating systems in the tropics. The main exceptions are high elevations on the equator, like the Andes in Ecuador. Africa's Mount Kilimanjaro, with its year-round snowcap, is another famous example, especially since it is only 3° south of the equator. It is important to realize that it is not hotter in the tropics than it is in some temperate climates during the summer. The tropics are hotter in duration rather than in degree. In some tropical climates the temperature is almost constantly hot or very warm throughout the year, while in others it varies from hot to warm but almost never from hot to cold.

The tropical climate is often assumed to be mostly hot and humid, but the tropics also contain deserts. One of the main differences in the various tropical climates is the amount and timing of rainfall. In places such as northern Africa, rainfall is so scarce that deserts have formed (Figure 17.1). In other places, it is dry most of the year, but there is a short rainy season. For example, in some parts of India, more than 90 percent of the rain falls during the monsoon season, which occurs from June to September. And, of course, there are the lush regions of the tropics where rainfall is plentiful all year. Just as there are large variations in tropical climates, there will be large variations in the design of tropical buildings.

In dry climates, the sky is mostly clear with occasional clouds. Consequently, most solar heating comes from direct solar radiation. However, there is also a significant reflected component from the mostly bare surrounding land and structures. The sky is clear unless there is haze caused by dust raised by strong winds. The relative humidity is usually below 20 percent during the day when it has the main impact on thermal comfort. Although the relative humidity rises when air is cooled, thermal comfort does not decline, because it is a function of the simultaneous effect of temperature and relative humidity. Temperatures during a typical day tend to vary from 75° to 115°F (24° to 46°C), which gives a large diurnal range of about 40°F (22°C).

In humid climates, the sky is mostly hazy from the humidity, and clouds can be plentiful. Consequently, direct solar radiation is weaker, but the solar heating load is still very large because of the greatly increased diffuse component from the bright hazy sky. Consequently, some light from the sky must be shaded along with the direct solar radiation. Because the ground surface tends to be covered by plants, the reflected solar load is small. The relative humidity, when combined with the simultaneous air temperature, creates conditions outside the comfort zone. Temperatures during a typical day tend to vary between 80° and 95°F (26° and 35°C), which results in a small diurnal range of about 15°F (9°C).

The actual local microclimate, however, can vary greatly from the above depending on latitude, time of year, proximity to water, elevation, and local weather patterns. Latitude was mentioned first because sun angles have a great impact on the design of a building.

17.4 THE SOLAR GEOMETRY OF THE TROPICS

At the equator, the sun is directly overhead at 12 noon on both March 21 and September 21 (Fig. 17.4a). Moving north on the planet from the equator,

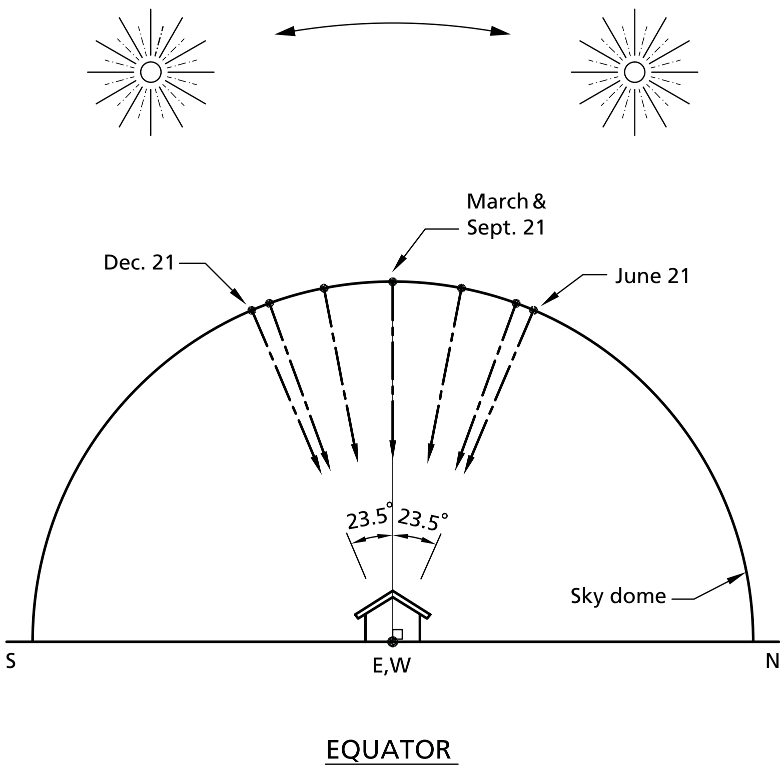

Figure 17.4a This north–south section of the skydome shows that at the equator, the sun is lowest in the sky on December 21 and June 21 and highest and directly overhead at 12 noon on the equinoxes (March 21 and September 21).

the sun continues passing overhead twice each year until one reaches the Tropic of Cancer (23.5°N latitude), where the sun is overhead only once each year on June 21 (Fig. 17.4b). Moving farther north, the sun is never overhead and gets progressively lower in the sky. The same pattern exists in the Southern Hemisphere, except that the last place the sun is ever directly overhead is the Tropic of Capricorn (23.5°S latitude) on December 21 (Fig. 17.4c). Thus, only in the tropics is the sun ever directly overhead.

At the equator, the sun shines for half the year from the south and for the other half of the year from the north. Consequently, south and north facades experience the same sun angles but at different times of the year. Since summer results from high sun angles and winter from low sun angles, the equator experiences two "summers" (sun directly overhead) and two "winters" (i.e., slightly less hot periods) when the sun is 23.5° lower in the sky (Fig. 17.4a). The existence of two summers creates not only high temperatures but also a more uniform temperature throughout the year, since it takes time to heat up and cool down (i.e., time lag) the great mass of the earth's surface. Temperatures are also quite constant at the equator because every single day of the year has twelve hours of daytime and twelve hours of nighttime. Of course, temperatures become less uniform as one moves away from the equator toward the tropics of Cancer and Capricorn, where tropical and temperate climates meet. Daily and annual temperature ranges are also affected by the presence of large bodies of water, which further dampen temperature changes.

Because heating is mostly not required, solar design in the tropics focuses only on shading and daylighting. Since the sun rises in the eastern sky and sets in the western sky everywhere on the planet, east

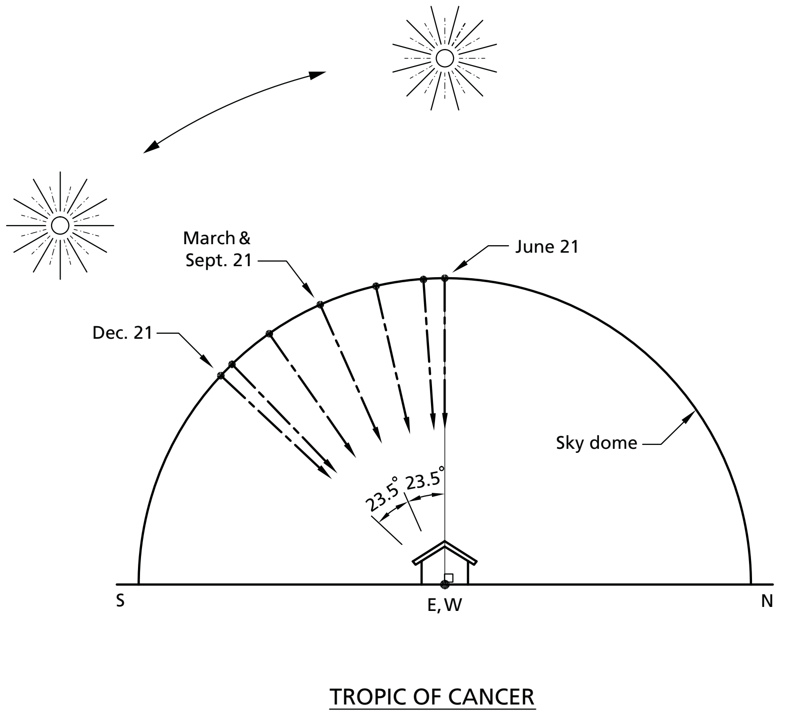

Figure 17.4b At the Tropic of Cancer, the sun is highest in the sky and directly overhead only on June 21 at 12 noon. The Tropic of Cancer is the latitude line where the tropics end and the temperate zone starts in the Northern Hemisphere.

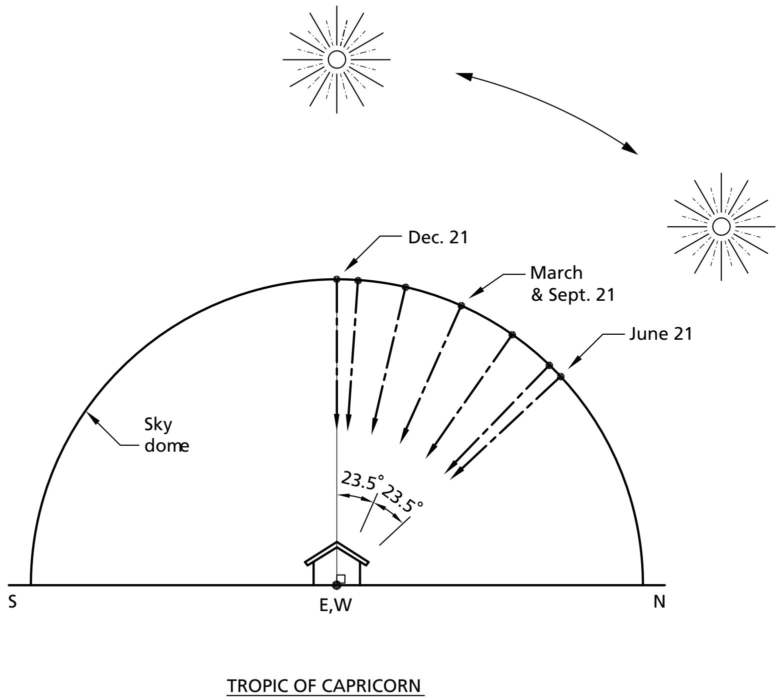

Figure 17.4c At the Tropic of Capricorn, the sun is highest in the sky and directly overhead only on December 21 at 12 noon (summer in the Southern Hemisphere). The Tropic of Capricorn is the latitude line where the tropics end and the temperate zone starts in the Southern Hemisphere.

and west windows are a problem everywhere on the planet. In the tropics, east and west windows are not just a seasonal problem; they are a problem every day of the year. Thus, the discussion in Chapter 9 in regard to minimizing east and west windows in temperate climates applies even more in the tropics. However, the north and south facades in the tropics experience significantly different sun angles than they do in temperate climates. For example, in the Northern Hemisphere, as one moves south toward the equator the sun shines increasingly into north windows until, at the equator, the north facade gets just as much sun at the same sun angles as the south facade. The two facades can therefore be symmetrical in design. Then, moving south of the equator, the north facade sees increasingly more sunlight than the south facade.

Figure 17.4d This building in Singapore seems to have gotten everything right: long axis running east–west, narrow rectangle to maximize daylighting, and exterior shading on the long facade. But what about the other long facade?

The importance of understanding solar geometry in the tropics is illustrated by the building shown in Figures 17.4d and 17.4e. This building in Singapore at 1°N latitude looks like it was designed for a temperate climate. The long axis running east–west is correct, as is the exterior shading on one long side. However, at the equator the north and south facades should look the same.

Besides the geometry of sunbeams, it is also important to understand the amount of solar radiation falling on each face of a building. Figure 17.4f shows the intensity of solar radiation at 16°N latitude on the four walls of a building aligned with the cardinal directions of the compass for both June 21 and December 21.

Figure 17.4e The other long facade of the building shown in Figure 174.d looks as if it were the northern facade of a building in the northern temperate zone. However, Singapore is practically on the equator, so north and south facades should be the same.

At 16°N latitude, the south wall receives direct solar radiation on December 21 but not on June 21, while the north wall receives direct radiation on June 21 but not December 21. The direct solar radiation on the north wall is about one-third of that on the south wall. Heading south from that parallel, the solar radiation will increase on

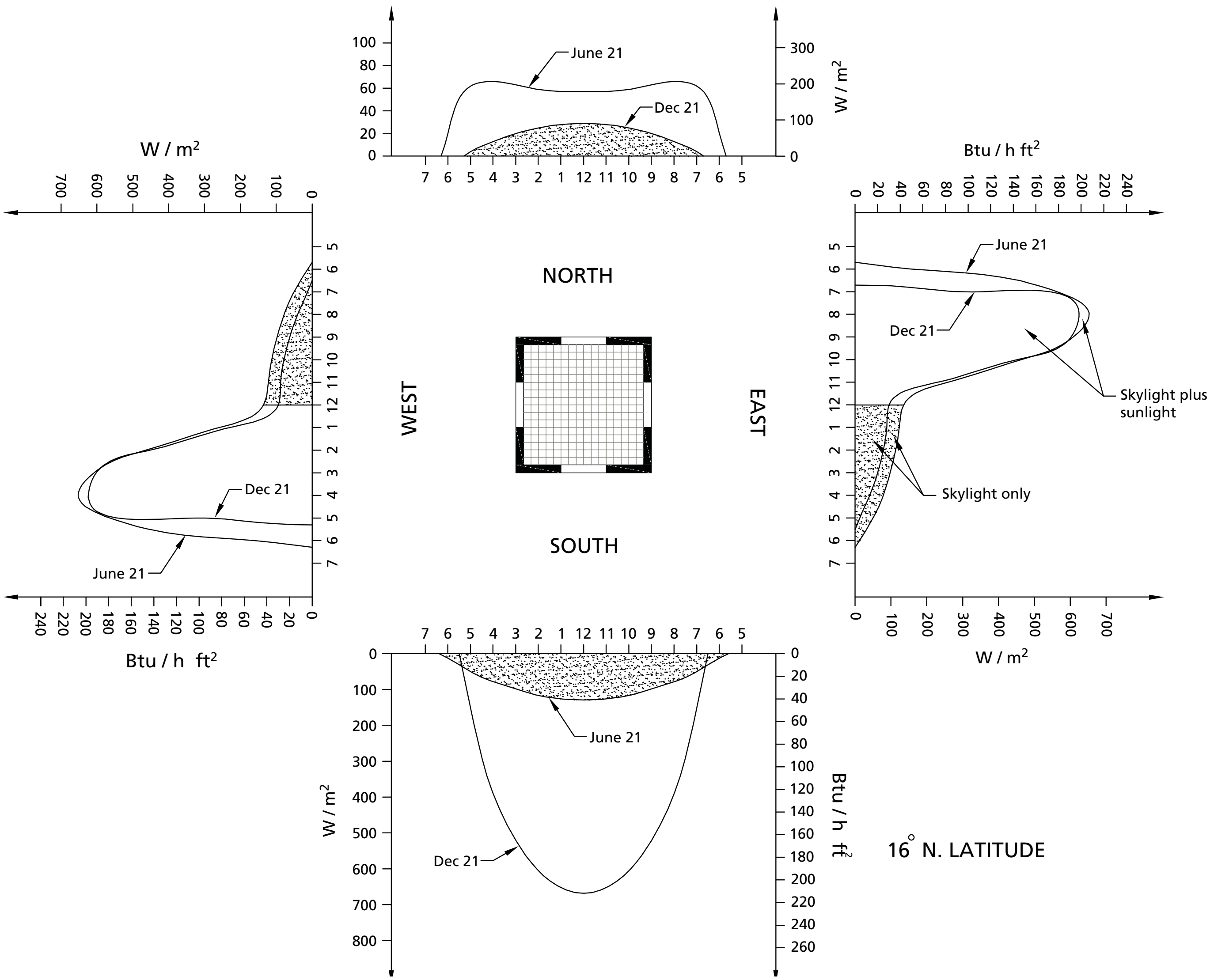

Figure 17.4f The four graphs show the solar intensity on the four facades of a building oriented along the cardinal directions of the compass at 16°N latitude. Each graph has a curve for December 21 and a curve for June 21. Note that on June 21 the south facade needs less shading than the north facade. Also note that there is almost no difference on the east and west facades all year long.

the north wall and decrease on the south wall until they are equal at the equator.

East and west walls receive the same amount of solar radiation unless local conditions such as a large building immediately to the east or afternoon rains modify the symmetry. Unlike in the northern temperate zones, the solar radiation is almost the same on June 21 and December 21. In effect, the solar load is about the same on east and west windows every day of the year.

A skylight receives almost as much solar radiation on December 21 as on June 21 (Fig. 17.4g), and at the equator the solar radiation is the same on December 21 and June 21. Thus, in the tropics skylights deliver almost constant daylighting for all days of the year, but of course it is not constant during daylight hours. Because high light levels are available about three hours before and after noon, a skylight should be designed to block much of the light around the noon hours and collect more light in the early morning and late afternoon.

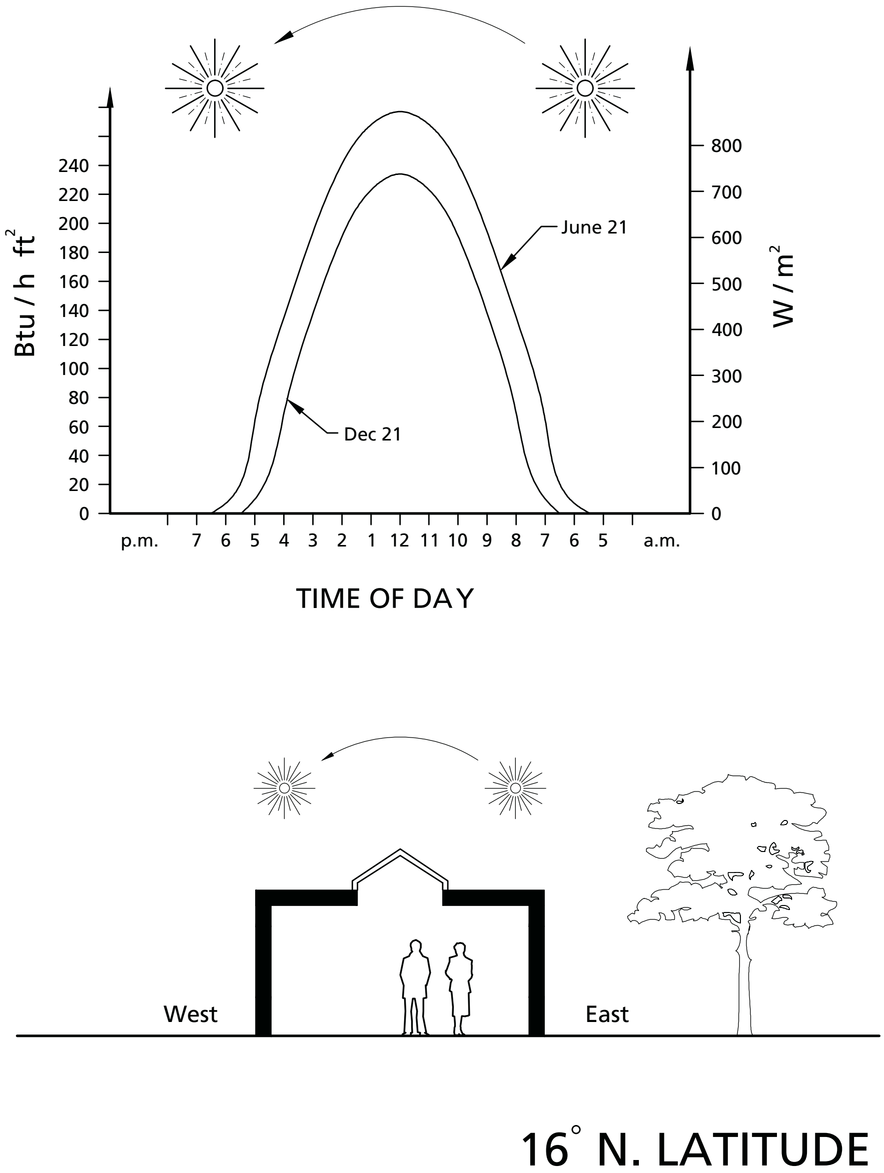

Figure 17.4g The graph shows the solar intensity on a skylight at 16°N latitude on both December 21 and June 21. Unlike the temperate zones, skylights n the tropics receive about the same amount of light every day of the year.

17.5 SHADING IN TROPICAL CLIMATES

Since there is no winter in the tropics and since it is too warm most if not all of the year, the whole year is usually the overheated period. Consequently, windows should be shaded all year long and not only from direct solar radiation but also from diffuse or reflected radiation. In humid climates, there is significant diffuse radiation from the sky, and in very dry climates there is usually significant radiation reflected from the bare ground or adjacent buildings. In all cases, the direct sun radiation should be blocked by external shading devices. In humid climates, the shading devices and especially the overhang should be extra long to block some of the hazy sky. However, in very dry regions, extending the overhangs does not block reflected radiation from the ground and adjacent buildings because the light is not coming from above. Instead, the most common traditional solutions are shutters and dense shade screens as mentioned in Section 17.2. Because both of these strategies severely block the view, they are much less acceptable today. As a result, in arid climates windows should be small, and a combination of overhang and low solar heat gain glazing could be used.

Since the shading strategies for north and south windows reverse at the equator, there is the potential for much confusion. For that reason, the following discussion of shading north and south windows will be in the format of a table with two columns: the left column for the Northern Hemisphere and the right column is for the Southern Hemisphere. *To avoid confusion, read only the relevant column.*

Unlike north and south windows, east and west windows cannot be fully shaded while maintaining a view. The only exception is a site where the windows are well shaded by neighboring high buildings or trees. For fixed east and west shading devices, the better the shade, the worse the view. For example, even an eggcrate shading device, which severely restricts the view, still allows some sun to enter at certain times of day and year. To maximize the view, which is almost mandatory in the modern world, movable shading devices should be used. For example, a very large overhang on a west window will provide both full shade and full view until the midafternoon, when the descending sun will start to outflank the overhang. At that point, an additional movable shading system must take over to block the low sun. See Figure 17.2b and Section 9.11 for various techniques to shade the low sun. Figure 17.5 shows a very effective strategy when balconies are

Table 17.5 North and South Window Shading in the Tropics

For Northern Hemisphere	For Southern Hemisphere
South Windows: South windows get easier to shade as one moves toward the equator from the Tropic of Cancer because the sun is progressively higher in the sky. Thus, south windows in the tropics need larger shading devices at the Tropic of Cancer than at the equator. The best shading device for south windows continues to be the overhang, and it is sized in the same manner as are south windows in Section 9.9 which is based on the Northern Hemisphere temperate zone. In most cases, the overhang can be fixed rather than movable.	North Windows: North windows get easier to shade as one moves toward the equator from the Tropic of Capricorn because the sun is progressively higher in the sky. Thus, north windows in the tropics need larger shading devices at the Tropic of Capricorn than at the equator. The best shading device for north windows continues to be the overhang, and it is sized in the same manner as are south windows in Section 9.9, even though it is based on the Northern Hemisphere temperate zone. In most cases, the overhang can be fixed rather than movable.
North Windows: North windows experience the opposite of south windows. North windows are easier to shade at the Tropic of Cancer than at the equator, where north and south windows experience the same solar exposure. At the Tropic of Cancer, small fins and a small overhang are sufficient. At the equator, the overhang is much larger while the fins are just a little bit smaller for full shading. Size the fins for north windows in the same manner as described in Section 9.13.	South Windows: South windows experience the opposite of north windows. South windows are easier to shade at the Tropic of Capricorn than at the equator, where south and north windows experience the same solar exposure. At the Tropic of Capricorn, small fins and a small overhang are sufficient. At the equator, the overhang is much larger while the fins are just a little bit smaller for full shading. Size the fins for south windows in the manner described for north windows in Section 9.13, even though it is based on the Northern Hemisphere temperate zone.

Figure 17.5 The smart condo owners in this Chongqing, China, apartment building added reflective curtains at the outer edge of their balconies to shade not only the windows but also the balcony.

present. An improvement on that strategy would be to extend the balconies to protect all the windows. Overhangs are especially appropriate in humid climates because they shade both direct and diffuse solar radiation, protect from heavy rain, and funnel more air into the building.

The design of east and west overhangs in the tropics is the same as in the temperate zones. However, fixed slanted fins are inappropriate in the tropics. Slanting the fins toward the southeast or southwest works well in the northern temperate zone because the summer sun rises in the northeast and sets in the northwest. At the equator, however, the sun must be shaded not only when it rises in the northeast but also when it rises in the southeast. And, of course, the same problem exists with the setting sun. Consequently, fixed fins are even less useful in the tropics than in the temperate zones. Although movable fins are better than fixed fins, they block the view much more than an overhang with backup movable shading for the low sun.

Since there is no ideal shading system for east and west windows, buildings should be designed with their long axis running east–west because that minimizes the size of the east and west facades. If windows cannot be avoided on those facades, the windows should be as few and small as possible. Also use windows in the "landscape" rather than "portrait" format, since short windows are easier to shade than tall windows.

East and west glazing should be minimized!

If shading is defined as blocking the sun, then the color of roofs and walls should be discussed along with shading. The best color by far is white because it has both a very high solar reflectance and a high infrared emissivity, which produces a very high solar reflective index (SRI) (see Section 9.21). The worst color is black, which transmits twice as much solar heat into the building as does white. Fortunately, most flat roofs now use white membranes.

For sloped roofs, smooth white metal provides the best protection against solar heating. Because clay tiles are popular in hot and wet regions, it is important to realize that white tiles are available and should be used. There is even a composite white tile that has an excellent SRI of 90. Common functional objections to sloped white roofs are that they get dirty and that they cause glare. Dirt accumulation on sloped roofs can be minimized by using a very smooth roofing material such as metal. Another option is to use a self-cleaning coating of titanium oxide, which acts as a cleaning catalyst when exposed to ultraviolet radiation. Although sloped roofs can on occasion cause glare, the problem is rarely severe; otherwise, all the roofs would not be white in Bermuda and Santorini. Furthermore, the author did not experience a glare problem when looking at buildings with white roofs in the United States. Dirt accumulation is not just an aesthetic problem, because roofs lose much of their reflectiveness when the get dirty. Fortunately, flat roofs are easy to clean.

White is the greenest color!

The color of walls is less critical because of the following reasons: black walls transmit only one and a half times as much heat as white walls; they are less exposed to the sun than the roof; they can be shaded by roof overhangs; and they are often shaded by adjacent trees and buildings. Nevertheless, white is still the best color for walls as well as roofs. White walls, which could be a greater glare problem than roofs, are quite popular all over the world, with one city proudly promoting them with its name—Casablanca (house-white). The author did not experience glare when he visited Casablanca. As a matter of fact, the worst glare is usually the result of large expanses of glass causing specular reflections of the sun. If the walls are well shaded, it is less important for them to be white. Instead, pale colors could be used.

Roofs should be white and walls as light-colored as possible!

17.6 DAYLIGHTING IN THE TROPICS

Daylighting can be more successful in the tropics than in the temperate zones because there is no winter when daylight hours are too few. Also, the north facade in the tropics receives much more daylight than it does in the temperate zones, and at the equator the north facade can harvest as much daylight as the south facade. The daylighting strategies in the tropics are just the same as in the temperate zone, except for the north facade, where windows should also have a light shelf of minimal size at the Tropic of Cancer, of the same size as the south windows at the equator, and of increasingly large size as one continues moving south toward the Tropic of Capricorn (the reverse is true in the Southern Hemisphere, of course).

As in the temperate zones, east and west windows are best minimized for both daylighting and shading benefits. Since heating is not required, all glazing should be of the "high light to solar gain" type. Near the Tropic of Cancer, clerestories should face north because they are easier to shade than clerestories facing any other direction, but at the equator north and south clerestories need equal shading. Since clerestories are vertical windows on or above the roof, they need to follow the same rules as windows.

Skylights, however, are quite different from windows and make more sense in the tropics than in the temperate zones. In the tropics, they supply a more even amount of daylight throughout the year, while in temperate climates they supply the most light in the summer and the least in the winter, which is exactly the opposite of what is desired. Skylights should be just large enough that electric lights can be turned off.

Because light shelves and skylights collect sunlight instead of skylight, windows can be quite small, thereby reducing the heat gain. However, sunlighting designs are more challenging than skylighting designs. For example, great care must be taken to spread the intense sunlight over a large area without creating glare (Colorplate 32). See Chapter 13 for a full discussion of daylight and sunlight.

17.7 PASSIVE COOLING

A passive cooling design will only save energy when it is too hot for comfort and air-conditioning is avoided or its use is minimized. Thus, if air-conditioning will be used all or most of the year, a passive cooling design is not appropriate and is even harmful, because a predominantly air-conditioned building must be designed differently from a passively cooled building. For example, in a hot and humid climate, an air-conditioned building must be very airtight, whereas a fully passively cooled building should leak like a sieve. The design of air-conditioned buildings in the tropics will be discussed in the next section.

As mentioned before, the first step in achieving thermal comfort in hot climates is, always has been, and always will be heat avoidance. In the case of a modern passively cooled building, heat avoidance is achieved by extensive use of shading, white roofs, light-colored walls, daylighting, efficient electric lighting, efficient appliances, a well-insulated roof, and the isolation of heat-producing elements (e.g., kitchens). An air-conditioned building would use all of these strategies, plus an efficient thermal envelope and a tight air-barrier. Since passive cooling design is very different for hot and dry climates and hot and humid climates, the design strategies for each will be discussed separately.

Heat avoidance is always the most important cooling strategy!

Passive Cooling in Very Hot and Dry Climates

Because of the large diurnal temperature range in very hot and dry climates (above 30°F or 17°C), the cool night air can be used not only for nighttime comfort but also to lower indoor temperatures during the day. The appropriate passive strategy is called night-flush cooling, because it utilizes large amounts of thermal mass exposed to the indoors from which heat is extracted by the cool night air that is brought into the building. The next day, the cooled thermal mass soaks up indoor heat to keep the indoor temperature from rising too high. To keep the sun and outdoor air from heating this mass, the windows are closed and shaded. Furthermore, the thermal mass should be protected from the outdoor air and sun by means of thermal insulation on its outdoor side. Performance can be further improved by using fans to bring in more outdoor air at night, and blowing it over the exposed thermal mass. Indoor fans (e.g., ceiling fans) are used during the day to extend the comfort zone to higher temperatures. For more information on night-flush cooling, see Section 10.9.

Passive Cooling in Very Hot and Humid Climates

Because of the small diurnal temperature range in very hot and humid climates (below 20°F or 11°C), the nighttime temperatures are not cool enough to significantly cool any thermal mass. Instead, outdoor air is brought into the building both during the night and during the day. The ventilation is not intended to cool the building but rather to cool people by increasing evaporative cooling on their skin. Consequently, this passive cooling strategy is known as comfort ventilation. For fully passively cooled buildings in hot and humid climates, thermal mass is a liability and should not be used. Natural ventilation is maximized by large windows and ventilating devices such as monitors on the roof. Windows must be placed at a location and height on a wall so that natural ventilation will pass over people and not the building structure. In sleeping areas or other locations where people are close to the floor, the windows must be equally low on the wall. Fans can be used to both increase the ventilation rate through the building and to blow more air over the occupants. For more information on comfort ventilation, see Section 10.8. See also Figure 10.9a, which shows the relationship between the diurnal temperature range and the choice of passive cooling systems.

There are plenty of regions where the climate is somewhere between very hot and dry and very hot and humid. Furthermore, in many places the climate is not constant throughout the year. There are also regions in the tropics that are still very hot but with medium humidity levels, and there are regions where part of the year it is very humid and another part very dry.

In climates with moderate humidity all year where the diurnal temperature range is medium (20°–30°F or 11°–17°C), thermal mass is still useful but less effective than in very dry climates. In such medium humidity climates, the windows should be wide open at night to provide both night-flush cooling and comfort ventilation, and closed during the day. Since the mass will not be cooled sufficiently, indoor temperatures will likely rise to uncomfortable levels in the afternoon. Indoor fans will then be a necessity. A modest amount of air-conditioning will also be desirable. Thus, for complete comfort in such a climate, a hybrid passive/active system will be best.

In regions where the climate varies from humid to dry during the year, the diurnal temperature range will also vary. Since it is not possible to have thermal mass at one time of year and not have it at another time, the decision to have mass depends on the length of the dry period. If it is dry for more than half the year, thermal mass could be used. The rules for when to open windows will change as the climate changes during the year. Windows will be open at night during the whole year but closed during the day when night-flush cooling is used during the dry part of the year.

Since in hot and humid climates passive cooling depends on natural ventilation, catching the maximum of wind is imperative. To maximize the wind, living areas should be as far off the ground as possible. If a building is not multistory, it can be raised on posts. Low vegetation should also be minimized, keeping only high canopy trees for shade. Since daytime ventilation is important in hot and humid climates, solar chimneys can be used to augment the wind (Section 10.16). To avoid adding to the humidity, avoid water elements in the landscape and provide good runoff for rainwater.

Except in special cases where the winds have a predominant direction, are fairly strong, and are fairly constant, a building should be oriented in an east–west direction to best respond to solar geometry. Thus, in most circumstances the long axis should run east–west.

For emphasis, it must be repeated that passive cooling will not work or will work only poorly if heat avoidance strategies like shading are not fully used. Heat avoidance is a necessary strategy in almost every sustainable design.

17.8 AIR-CONDITIONED BUILDINGS IN THE TROPICS

In very hot and dry climates, passive techniques are able to achieve a high level of thermal comfort without air-conditioning, but in humid climates the passive techniques are limited in the comfort they can achieve. It is important to realize that not all desert regions have a dry climate. Some coastal areas (e.g., along the Persian Gulf) receive almost no rain yet get humid air from offshore winds. Unfortunately for passive design, most people live in humid climates because it rains there sufficiently to produce food or they live along humid coasts because of fishing and trade. Consequently, air-conditioning is popular in much of the tropics, and its use will increase as more people can afford it (Fig. 17.8a; see also Fig. 1.10c).

In very humid regions, the goal for either a modern or a developing society should be to minimize both the size of the air-conditioning equipment and the length of time that the equipment is using energy. In any hot climate, heat avoidance strategies should be fully used, and the passive cooling strategies should be used as much as possible. In addition, fully or partly air-conditioned buildings should be well insulated and airtight to keep hot and/or humid air from entering. Thermal mass is helpful with air-conditioning because it allows smaller equipment to maintain comfort. For example, the system can run at night to precool the mass for the next day. Thermal mass can also reduce expensive peak demand charges, because the air-conditioning equipment can be turned off for a while during the peak demand time because of the buffering effect of the mass.

The cooling load of a building is a function of its climate, its type, and its design. In dry climates, the very high temperatures require a very well insulated thermal envelope to keep the sensible heat out. In humid climates, where the maximum temperatures are lower, less insulation can be used, but there must be a greater emphasis on keeping the humid air out because of its high latent heat content (i.e., moisture). In either case, the insulation should be on the outdoor side of the thermal mass so that the mass absorbs indoor heat. Also, in all climates, indoor fans (especially ceiling fans) should be used to reduce the size and energy consumption of the air-conditioning system. Since indoor fans do not cool the building but only the occupants, the moving air should be aimed at the people. Fans should be controlled by occupancy sensors along with the lights.

Taylor's University Lakeside Campus in Malaysia is a case study of the challenges of building an air-conditioned complex in a hot and humid climate. The campus was built in 2010 and illustrates both good and bad design decisions in regard to the cooling load.

The design includes many good features. All of the buildings are white, and the administrative and classroom buildings have their long axes in the ideal east–west direction (Fig. 17.8b). The small but still problematic east and west facades are partly shaded by outdoor screens and large trellises made of vertical cables supporting vines (Fig. 17.8c). Large overhangs, canopies, and covered walkways allow students and faculty to move between buildings in shade (Fig. 17.8d). The student housing consists of two parallel seven-story buildings with the space between covered to protect from both rain and sun (Fig. 17.8e). The ends of this "courtyard" are open to maximize natural ventilation. The prominent and attractive stairs make walking between floors very convenient and pleasant.

The main weaknesses of the campus design include the wrong orientation for the student housing and inadequate outdoor shading of most windows (Fig. 17.8f). About half of

Figure 17.8a In hot and humid climates all over the world, people buy air conditioners as soon as they can afford them. Multiply this image by many millions (soon billions) to understand the scale of this expansion in the use of air conditioners. Unfortunately, too many people assume that shading is no longer necessary, as can be seen in the deterioration of many awnings or the lack of awnings once there is air-conditioning. Consequently, more planet-harming electricity is consumed than would be necessary if windows were properly shaded.

Figure 17.8b The classroom buildings at Taylor's University in Malaysia are properly designed by having their long axis running east–west and practically no windows on the short east and west facades. The outdoor projecting stairway is protected by a shade screen.

Figure 17.8c The east and west facades of the administrative building are protected by very large overhangs and vine trellises. This photo was taken shortly after the completion of construction. The vines should be doing great shading by now.

Figure 17.8d The student housing, unfortunately, was not oriented correctly and the east and west windows are not even shaded. But another good feature is that all of the buildings on this campus are connected by shaded passages.

Figure 17.8e A shaded and protected atrium type of space is created between the two blocks of student housing. The windows facing this interior space are well shaded.

Figure 17.8f A major weakness in the design is the inadequate shading of many windows. Although the air-conditioned penthouses are enclosed by very low solar gain glazing, they are unbearably hot inside because of both solar and conduction gains. Instead, the penthouses should have had much less glass and extensive outdoor shading.

all student housing windows are fully exposed to the east and west sun (Fig. 17.8d). Although the academic and administrative buildings are oriented correctly, their windows are without outdoor shading devices. While low solar gain glazing was used, the excessive use of glazing and lack of outdoor shading devices still create a huge unnecessary cooling load.

Because of tradition, many stores and restaurants in Malaysia do not use storefronts to keep out the hot and humid air. Many restaurants on campus, for example, have their seating both indoors and outdoors with no barrier between them. Thus, the hot and humid outdoor air moves freely indoors, and the air-conditioned air freely spills to the outdoors. Before air-conditioning this arrangement was logical, but now it is a serious waste of energy and is not sustainable.

A questionable design feature of the campus is that all corridors are shaded but open to the outdoors. Thus, all classrooms open to the un-air-conditioned corridors. The benefit is that the building volume to be cooled has been reduced, but the problem of infiltration of hot and humid air has been greatly increased. The author believes that air-conditioned corridors would have been more energy efficient because both the infiltration and exposed surface area of the buildings would have been reduced. The author found using the elevators especially uncomfortable because the elevator shafts and landings were exposed to outdoor air, and consequently the elevator doors always opened to outdoor air. The elevator cab fan and possible air-conditioning could not keep up with the heat gain.

Overall, the Lakeside campus is a success. However, the campus could have been much more energy efficient if there had been more emphasis on orientation, shading, and the problem of the excessive infiltration of hot and humid air.

17.9 CONCLUSION

The design of a tropical building is very similar to the design of a building in the hot parts of the temperate zones where winter heating is not required. The main differences from such a temperate design are based on sun angles, with the differences being most extreme at the equator and least extreme at the Tropic of Cancer and the Tropic of Capricorn.

Table 17.9 presents a summary of the design strategies appropriate for the hot and dry and hot and humid tropics in the quest of minimizing the energy consumption of buildings and in maximizing their sustainability.

Table 17.9 Summary of Design Strategies for the Tropics

Topic	Hot and Dry	Hot and Humid
Climate		
annual temperature range	45°–130°F (8°–55°C)	65°–100°F (18°–37°C)
diurnal temperature range	>30°F (>17°C)	<20°F (11°C)
rainfall	little	much (except some coastal areas)
wind	varies greatly with microclimate	varies greatly with microclimate
clouds	few	many
sky	clear	hazy
source of most sunlight	direct and reflected	direct and diffuse
Form and Plan		
best plan	elongated rectangle with width mainly determined by access to daylight	slender elongated rectangle to allow cross ventilation and daylighting less slender rectangle if air-conditioned
courtyard	very desirable	not desirable because it blocks cross ventilation
spacing between buildings	minimize so that buildings can shade each other and streets	maximize to allow for natural ventilation
Ventilation		
at night	yes	yes
during the day	no	yes
purpose	to cool building and people at night	both day and night but only to cool people
shutters	for use during the day to block both sun and air	use louvered shutters during the day to block sun but not air
Windows		
purpose	for view, daylighting, and natural ventilation mainly to cool thermal mass at night	for view, daylighting, and natural ventilation to pass over people both day and night
number	few	many
size	small	large
height on wall		
a. for daylighting	high	high
b. for natural ventilation	high, to cool ceiling mass	at height of people in spaces
Shading of Windows		
purpose	shade both direct and reflected radiation	shade both direct and diffuse sky radiation
which orientation?	all	all
outdoor shading	all	all
indoor shading	as backup and glare control	as backup and glare control
movable shading	on east and west windows for low sun	on east and west windows for low sun
plants	if sufficient water is available	as much as possible
Shading of Roof		
desirable	yes	yes
how	roof canopy or PV panels	roof canopy, vegetated roof, or PV panels
by color	very highly reflective white roof should be used	white roof is highly desirable

(*Continued*)

Topic	Hot and Dry	Hot and Humid
Shading of Walls		
desirable?	very much	yes
how	mostly by having buildings shade each other by being very close to each other	mostly by large roof overhangs, porches, high trees, or trellises
color	white is highly recommended	white, especially if other shading is inadequate
Daylighting		
source of light	mostly from direct and reflected	mostly from direct and bright hazy sky
intensity of source	a little from the blue sky	a little from reflected
	very intense direct	intense direct
	intense from reflected	intense diffuse
	not intense from sky	not intense from reflected*
Thermal Mass		
appropriate?	yes	no for full passive cooling
purpose	to be cooled at night	yes for air-conditioned building
	to soak up indoor heat during the day	act as buffer to reduce peak air-conditioning load
		allow nighttime precooling
area	maximize exposed area	maximize exposed area in air-conditioned building
thickness	at least one 1 ft (0.3 m)	at least 6 in. (15 cm)

*except in cases where there is water, or man-made objects such as reflective buildings or light-colored streets.

KEY IDEAS OF CHAPTER 17

1. The tropics lie between the Tropic of Cancer (23.5°N latitude) and the Tropic of Capricorn (23.5°S latitude).
2. Traditional architecture in hot and dry climates consists of massive wall and roof structures, small windows, narrow alleys, and shading devices.
3. Courtyard houses are appropriate for hot and dry climates.
4. Traditional architecture in hot and humid climates consists of lightweight structures, maximum natural ventilation, and shading devices.
5. Courtyard buildings are not appropriate for hot and humid climates.
6. Tropical climates vary from temperate climates in that there are no winters. Summers in tropical climates are much as are summers in temperate climates. Summers are year-round at the equator and get slightly shorter toward the Tropics of Cancer and Capricorn.
7. Avoid east and west windows because they cannot be shaded well.
8. The shading requirement is identical for north and south orientations at the equator but varies somewhat toward the Tropics of Cancer and Capricorn.
9. The shading requirements for north and south facades reverse south of the equator.
10. Instead of skylights use shaded north and south clerestories.
11. The greenest color is white, especially for the roof.
12. Daylighting strategies for east and west windows are similar to those for the temperate climates. However, the daylighting design for north and south windows is different at the equator, where strategies should be the same for both.
13. Heat avoidance is the number-one cooling strategy.
14. Passive cooling strategies are the same as those in temperate climates (see Chapter 10).
15. When air-conditioning cannot be avoided, it should be minimized in both size and necessary duration of use, mostly by heat avoidance strategies.
16. The tradition of open storefronts in many parts of the tropics is not sustainable when air-conditioning is used.
17. Heat avoidance and shading are the two most important strategies for creating low energy sustainable buildings in hot climates!

Resources

Further Reading

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Salmon, C. *Architectural Design for Tropical Regions*. John Wiley & Sons,. 1999.

Tan, H. B. *Tropical Architecture and Interiors: Tradition-Based Design of Indonesia, Malaysia, Singapore, Thailand*. Page One Publishing, PTE Ltd., 1994.

CHAPTER 19

CHECKLIST FOR DESIGNING INTEGRATED SUSTAINABLE BUILDINGS

We are evaporating our coal mines into the air.
Svante Arrhenius, Swedish chemist, 1896

19.1 INTRODUCTION

A building design is the result of innumerable decisions, and the success of the final design depends on which alternatives are chosen at every step of the design process. However, because the most important decisions are made at the front end of the schematic design stage, this book is written to provide that information and those concepts needed at that early stage with an emphasis on designing low energy sustainable buildings. Even if all of the relevant knowledge has been acquired, it is still a major challenge to know what applies to a specific project and at what point in the design process a particular decision should be made.

The checklist below is a guide for the designer about what important options are available for the heating, cooling, and lighting of buildings. To achieve a sustainable integrated design, it is important that the best alternative is chosen at the correct point in the design process. The single best example of how a particular decision has a major impact on many future decisions and the success of the final design is the choice of orientation. Only the correct choice will allow for high-performance passive solar, shading, and daylighting, and for their successful integration.

The checklist is arranged as much as possible in the order that the decisions are made in the schematic design process of a building.

19.2 SITE SELECTION

1. Consider a site that allows the building to be oriented along an east–west axis.
2. Consider a site with winter solar access, if the building will need a heating system.
3. Consider a site that is shaded in the summer by neighboring buildings or trees to the east and west.
4. Determine if there are legal or physical restrictions to the site that could prevent the use of solar collectors, white roofs, etc.

19.3 FORM

1. Consider an elongated rectangle with its long axis running east–west.
2. Consider a compact design to minimize surface area and building materials. Aesthetics achieved through complex forms is less sustainable than aesthetics achieved through ornamentation.
3. Consider limiting the width (depth) of the building to allow full use of daylighting and/or cross ventilation.
4. Consider using an atrium to get light and views to the center of a large compact building.
5. Consider a covered atrium to reduce the exposed surface area of the building (i.e., achieve greater compactness).
6. Avoid using an articulated facade that would block access to the winter sun. For example, avoid wings toward the south which would shade the main building in the winter.
7. Consider building projections on the east and west to allow north and south windows instead of east and west on those facades.
8. Consider the fact that a solar-responsive building will have facades that vary with orientation. The east and west facades should have the fewest windows and north and south the most.
9. When daylighting is very important, consider a form that will maximize the area of the top floor (i.e., maximize the building footprint) because the best daylighting is through the roof.

19.4 PLAN

1. Consider placing rooms that benefit from winter sun on the south side of building (e.g., living rooms, classrooms, and offices).
2. Consider placing rooms that benefit from being cold on the north side of the building (e.g., kitchens, bedrooms, computer rooms, and offices that generate a lot of heat).
3. Consider using buffer spaces on the east and west sides of a building (e.g., garage, storage, and fire stairs).
4. Consider discouraging healthy people from using elevators and escalators when traveling only one or two floors in order to both save energy and increase healthy exercise. Use beautiful prominent stairs while making elevators and escalators less prominent and less attractive.
5. Use an open floor plan to maximize daylight and natural ventilation.

19.5 WINDOWS

1. Consider placing all or most windows on the north and south facades. Place most windows on south facade for buildings that will need much winter heating. Place most windows on north facade for buildings that need little or no winter heating.
2. If windows are needed on the east and west facades, consider using as few as possible and making them as small as possible.
3. Consider making east and west windows as short as possible because they are easier to shade with overhangs (i.e., landscape rather than portrait). Consider using ribbon windows.
4. Consider placing windows as high on wall as possible for greater daylight penetration.
5. Consider using operable windows in all buildings. However, there should be a system that shuts down the air-conditioning and heating equipment if any windows are open. For example, use security-type switches on windows that are in series with the thermostat in that zone.
6. Do not use windows with an R-value of less than 3 (double glazing with low-e) unless indoor night insulation is provided. Consider using windows with higher R-values in cold climates.

19.6 DAYLIGHTING

1. Remember that quality is more important than quantity.
2. Consider using light shelves on south windows, and on any east and west windows that were necessary.
3. Consider high ceilings that allow for high windows.
4. Consider using clerestories for top lighting. Use south-facing clerestories in buildings that need winter heat or use north-facing clerestories for buildings that do not need winter heat.
5. Avoid using skylights because they collect more sun in the summer than in the winter.
6. Consider using an atrium to bring light to the center of a building. A covered atrium should use north- or south-facing clerestories depending on whether heating is required or not.
7. Use baffles or louvers with south-facing clerestories to control glare and puddles of sunlight.
8. Consider using light tubes through the roof to illuminate small core areas.
9. Consider using high R-value light-transmitting translucent panels for the roof or a section of the roof.
10. On windows, consider using indoor blinds and shades mainly to control glare and light levels.
11. Consider using prismatic daylighting glass in upper windows instead of light shelves.
12. To avoid glare, avoid translucent walls or windows except near the ceiling of high spaces like a gymnasium.
13. Consider using as much borrowed light as possible by using glass partitions and glass doors, as was common in the first half of the twentieth century.
14. Consider using very light-colored (white) paved areas just outside first-floor windows to reflect more light further into the building.
15. Remember that daylighting will not reduce energy consumption unless the electric lights are turned off. Thus, automatic controls are a requirement.

19.7 SHADING

1. Consider using overhangs for south, east, and west windows. Use fixed overhangs for buildings that have no heating system, and movable overhangs (e.g., awnings) for buildings that do have a heating system.
2. Consider using outdoor venetian blinds or roller shades in addition to or instead of overhangs to block the low east and west sun.
3. Avoid vertical fins on the east and west windows, since they work less well than horizontal louvers. Use fins on north windows or to keep sun from outflanking overhangs.
4. Consider using trees and other plants to shade east and west windows. Do not use trees or other plants to shade the south windows if passive solar will be used. Also do not shade the roof since solar hot water and solar electric (PV) panels would be shaded.
5. Test your shading design to make sure the sun cannot outflank it. Consider using a heliodon.
6. Consider also shading the roof, walls, and land around the building.
7. Consider using plants for shading walls. In tall buildings, a vegetated wall (especially east and west) may be more important than a vegetated roof. Vines may be the best option for green walls.
8. Understand that outdoor shading is four times better than indoor shading.
9. Only use low solar-heat gain glazing if the building has no heating system. For buildings with heating systems, use high solar-gain glazing, especially for south windows, to make passive solar possible.
10. Windows should be fully shaded during the whole overheated period of the year.
11. The south windows of buildings with heating systems should be fully exposed to the sun during the whole underheated period of the year by means of movable shading devices. Consequently, do not use large roof overhangs or other fixed shading devices on south windows.

19.8 COLOR

1. Consider using white for sloped as well as flat roofs, since it reduces the heat gain by 50 percent compared to black roofs. If the roof is flat, use a white membrane, and if it is sloped, use white metal. White roofs are best even in cold climates because the winter and summer conditions are not symmetrical. The low winter sun sees much less of the roof than the high summer sun, and there are about sixteen solar heating hours per day in the summer and only about eight hours in the winter.
2. Consider using high-tech "cool roof" shingles or tiles if white metal roofing is not an option. Use the highest solar reflectivity index (SRI) possible.
3. Consider using white or very light-colored walls. Different orientations could have different colors, with north being the darkest and east and west the lightest.
4. Consider using light-colored paving instead of asphalt around the building to reflect more sunlight back into space and up into windows.
5. Consider minimizing paving and maximizing vegetated areas around building.
6. Ceilings should almost always be high reflectance white.
7. Consider using light-colored (white) walls, furniture, and floor finishes to help create the best and most efficient lighting. The light-colored surfaces also create the perception of a well-lit space using the least amount of light.

19.9 THERMAL ENVELOPE

1. Consider using more insulation than is now recommended or considered economical, because having more insulation will be economical in the future, and insulation is very hard to add at a later date.
2. Avoid as many heat bridges as possible and especially large ones.
3. Avoid structural penetration of the thermal envelope like beams or slabs that support balconies. Instead, hang balconies. The structure should be on the indoor side of the insulation.
4. All ducts and pipes should be on the indoor side of the thermal envelope.
5. Consider placing all insulation on the exterior side of steel studs or joists and not in the space between them. Steel studs derate cavity insulation by 50 percent.
6. Consider using SIP panels whenever possible.
7. Consider using very high R-value windows unless windows are used to collect passive solar because solar transmission declines with increasing R-value.
8. In cold climates, consider using double glazing without the low-e coating on south windows, because low-e coatings lower the solar heat gain coefficient. Instead supplement the windows with indoor night insulation.
9. Thermal mass should be on the indoor side of the insulation but not insulated from the indoor air.
10. Thermal mass is not a substitute for insulation in modern buildings.
11. Consider earth sheltering, especially if the site is on a south-facing slope where much sunshine can be harvested with only a few small windows. Earth sheltering also protects against storms and noise. Avoid earth berms with penetrations because each opening in the berm is a major heat bridge.

19.10 THERMAL MASS

1. Consider using indoor thermal mass to support passive solar, passive cooling, and air-conditioning.
2. The exposed indoor area of mass is much more important than the thickness of mass.
3. For passive solar, the best mass is usually the floor exposed to direct sunlight.
4. For passive cooling and air-conditioning, have mass exposed to airflow. Consider using exposed concrete joists or T beams to increase the exposed surface area.
5. Consider using phase change material (PCM) or water as compact substitutes for concrete. Water in translucent or transparent tubes can also provide aesthetic benefits.
6. Do not cover thermal mass with any insulating material such as carpets or acoustical materials. Instead of carpets, have occupants wear cushioned slippers, as is common in some Asian countries. Slippers are quiet, comfortable, and promote indoor air quality. Instead of acoustical insulation on the ceiling, hang the acoustic panels in vertical planes and use acoustical partitions.
7. Consider burying plastic tubes filled with water in concrete floor slabs to reduce the amount of concrete required as well as to increase the heat storage capability.

19.11 GLAZING

1. Consider "tuning the glazing" by using a different glazing type on each facade of a building and even in different parts of a window.
2. When daylighting but not heat is desired, use high light-to-solar-gain ratio glazing in the daylight windows (e.g., glazing above light shelf and in south-facing clerestories) and consider using low solar transmission (including light) for the view windows if winter passive solar is not desired.
3. When passive solar is desired, use very high solar-gain glazing for south windows and possibly east and west windows. Also use outdoor shading in the summer and indoor night insulation in the winter. Use high R-value windows on the north facade.
4. Consider using insulated translucent panels instead of glazing for clerestories and small skylights. Because they can cause glare, do not use translucent panels on walls unless they are used near the top of very high walls (e.g., in a gymnasium).
5. Do not use reflective glazing in any situation where the reflected light can cause a problem such as glare and overheating for neighbors or the area around a building. Never use reflective glazing on any concave facade because the sunlight will be concentrated.
6. Single glazing should not be used in any heated or cooled building. Remember that single glazing has an R-value of 1 while a good wall will have an R-value of about 15. Except for south windows used for passive solar, the lowest R-value should be R-3.
7. Remember that conventional glazing does not respond to changes in the environment. For example, conventional glazing cannot have high solar transmission in the winter and low transmission in the summer. Instead, use dynamic systems. The following are some examples:
   a. Movable shading devices such as awnings for full summer shade and full solar access in the winter.
   b. Operable louvers or venetian blinds to control solar access to respond to changing sun angles and cloud-cover changes.
   c. Night insulation that allows high solar gain during the winter day and provides low heat

loss at night. Night insulation can also reduce daytime heat gain in the summer if views and daylight are not a high priority as in a residence when nobody is at home.

8. Be aware that although tinted single glazing reduces the transmission of solar radiation, it is not very effective in reducing solar-caused heat gain, because tinted glazing absorbs the sun, gets hot, and transmits much of that heat indoors.
9. Be aware that the use of outdoor shading devices are best at blocking direct solar radiation, while low solar heat-gain glazing is best to block diffuse radiation from the lower sky and reflected radiation from the surroundings.
10. Consider the aesthetic benefits of external shading devices since they enrich the 3-D texture of the facade.
11. Consider the high cost and limitations of dynamic glazing at this time.

19.12 AIR BARRIER

1. Use an air barrier to minimize infiltration and water penetration.
2. Consider using windows and doors with excellent weatherstripping.
3. Consider using a vestibule or revolving door at the entrance.
4. Consider using a heat exchanger ventilation system instead of infiltration to maintain indoor air quality.

19.13 PASSIVE SYSTEMS

1. Consider transpired solar collectors for preheating ventilation air.
2. Consider using Trombe walls for solar heating without light.
3. Consider using a mixture of direct gain (i.e., south windows) and Trombe walls to maximize solar heating while controlling the amount of solar radiation (e.g., light) entering the building.
4. Consider using solar and stack-effect chimneys to augment the wind for natural ventilation.
5. Consider using cowl-type roof ventilators, which can rotate like a wind vane to maximize the natural ventilation.
6. Consider using exterior wing walls to divert the wind in order to increase natural ventilation.

19.14 ELECTRIC LIGHTING

1. Remember that quality is more important than quantity.
2. Keep all surface colors as light as possible. Ceilings should almost always be a high reflectance white.
3. Consider using task ambient lighting for the highest quality and the least energy consumption. LEDs make great task lights.
4. Consider the fact that LED lights are not always the best choice at this time. That may or may not change in the future. LEDs are best for spotlighting, while fluorescent lamps are often the best for area lighting.
5. Remember that lighting efficiency is not just a function of the lamp efficacy but also of the performance of the lighting fixture and room finishes.
6. Remember that veiling reflections are a major lighting problem. Do not place fixtures so that the angle of incidence equals the angle of reflection relative to the eye. Geometry is the key.
7. Because the brightness of the walls is the key factor in the perception of room brightness, very light colors should be used. Remember that a room with mostly dark surfaces cannot be made to look well-lit no matter how much light is supplied.
8. Consider avoiding light pollution outdoors, since it is both objectionable and inefficient. All outdoor light should end up where it is needed or useful (e.g., walkways, parking areas, building illumination) and not in the sky or on a neighbor's property. Building illumination should be from the top down rather than from the bottom up, because spilled light will then illuminate the ground rather than the sky. Use a building "crown" to hold light fixtures away from the building so that they can be aimed down toward the building.
9. Consider using occupancy sensors to turn off lights, personal fans, and personal heaters when not needed.
10. Consider automatically reducing the illumination level in corridors and stairwells at night or when no one is present.
11. Do not use indirect lighting fixtures unless the wall or ceiling is white or a very light color. For example, do not use sconces on colored walls.
12. Do not use indirect up lights unless they will be cleaned often. This is especially true outdoors.

19.15 MECHANICAL EQUIPMENT

1. All ductwork must be on the indoor side of the thermal envelope.
2. Consider a radiant floor heating system in cases where mechanical cooling is not required.
3. Consider using a geo-exchange system for both heating and cooling.
4. Consider natural ventilation to supplement mechanical cooling. Except in homes, an interlock system should prevent mechanical heating or cooling if the windows are open.
5. Consider using much larger ducts than normal because they will reduce the required fan power, which is quite substantial.
6. Minimize the number of bends in the ductwork. The initial design of the ductwork and structure should be integrated to allow ductwork to be as straight as possible.

7. Consider placing the MER in a central location to minimize the length of ducts.
8. Consider using highly insulated walls, roofs, and windows so that the mean radiant temperature will allow the use of lower temperatures in the winter and higher temperatures in the summer while maintaining complete comfort. Thus, insulation saves energy in two distinct ways: less direct heat loss/gain because of a higher R-value, and less heat loss/gain resulting from lower (higher) thermostat settings, which create a smaller temperature difference between indoors and outdoors.
9. Consider a heat exchanger to recover both sensible and latent heat otherwise lost by ventilation.
10. Consider using displacement ventilation for greater efficiency and better air quality.
11. Consider heat storage so that the compressors can run at night when they operate more efficiently and electric rates are lower. Heat storage can also help reduce peak demand charges. Consider using ice instead of water since it is a much more compact heat storage medium.
12. Consider allowing individual environmental control for each workstation since people's thermal comfort and lighting needs vary greatly. Supplying a fan at each workstation will allow the thermostat to be set higher in the summer. A heat lamp and/or foot heater at each workstation could allow lower thermostat temperatures in the winter, since these devices only heat the person and not the whole space. These devices should be controlled by an occupancy sensor.
13. Consider using building materials, furniture, and cleaning supplies with low VOCs so that ventilation can be minimized, since it is a major source of heat gain/loss.
14. Consider using CO_2 sensors to reduce the amount of required fresh-air intake.
15. Consider using fireplaces only if they are supplied with outdoor combustion air, doors, and a heat exchanger. Consider wood-burning stoves instead, but use them only in rural areas.