HEATING,
COOLING,
LIGHTING
FOREWORD TO THE FOURTH EDITION  xi
Edward Mazria

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James Marston Fitch

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The compelling words written by James Marston Fitch in 1991 in the Foreword to the first edition (which follows) are still valid, but the stakes are now much higher. Because the fate of the planet is at stake, it is no longer just a question of following a particular architectural or design philosophy. Buildings consume about half the energy produced in the United States and around the world. Today, more than 50 percent of the world’s population lives in cities, a figure that is likely to rise to 60 percent over the next two decades. It is clear that timing is critical: with 900 billion ft² (80 billion m²) of urban environment projected to be built and rebuilt in the next twenty years (an area equal to three times the total building stock of the United States), we are presented with an extraordinary window of opportunity to meet present and looming threats. Our best chance of doing so is to ensure that the architecture, planning, and development community, the primary agents shaping the built environment through design and construction, have access to the knowledge and tools necessary for the transition to a decarbonized, sustainable, and adaptive world.

Professor Lechner’s book describes how to achieve this transition in the built environment. The book illustrates the many sustainable strategies available to designers and provides the information needed during the early phases of the design process, when a building’s energy consumption patterns are defined. By using the strategies presented in this book, much of the energy consumed to heat, light, and cool buildings can be dramatically reduced.

Professor Lechner’s book is also an important resource for those architects who are concerned about the aesthetic aspects of sustainability. He convincingly explains and demonstrates how lessons learned from vernacular architecture can be combined with the best of modern ideas to create low-impact yet beautifully designed humane architecture. Since carbon neutral buildings can be fully powered by renewable resources, a future of low-impact buildings is not only necessary but also elegantly achievable.

EDWARD MAZRIA, AIA
Professor Lechner’s book differs from most of its predecessors in several important respects: (1) he deals with the heating, cooling, and lighting of buildings, not as discrete and isolated problems, but in the holistic sense of being integral parts of the larger task of environmental manipulation; (2) he deals with the subjects not merely from the engineer’s limited commitment to mechanical and economic efficiency but from the much broader viewpoint of human comfort and physical and psychic well being; (3) he deals with these problems in relation to the central paradox of architecture—how to provide a stable, predetermined internal environment in an external environment that is in constant flux across time and space; and finally, (4) he approaches all aspects of this complex subject from a truly cultural—as opposed to a narrowly technological—perspective.

This attitude toward contemporary technology is by no means hostile. On the contrary, Professor Lechner handles it competently and comprehensively. But he never loses sight of the fact that the task of providing a truly satisfactory enclosure for human activity is that one must view the building as a whole. He points out, quite correctly, that until the last century or so, the manipulation of environmental factors was, of necessity, an architectural problem.

It was the building itself—and only incidentally any meager mechanical equipment that the period happened to afford—that provided habitable space. To illustrate this point, he makes continuous and illuminating analysis to both high-style and vernacular traditions, to show how sagaciously the problems of climate control were tackled by earlier, prescientific, premechanized societies.

This is no easy-to-read copybook for those designers seeking shortcuts to glitzy postmodern architecture. On the contrary, it is a closely reasoned, carefully constructed guide for architects (young and old) who are seeking an escape route from the energy-wasteful, socially destructive cul-de-sac into which the practices of the past several decades have led us. Nor is it a Luddite critique of modern technology; to the contrary, it is a wise and civilized explanation of how we must employ technical and scientific knowledge if we in the architectural field are to do our bit toward avoiding environmental disaster.

JAMES MARSTON FITCH
Hon. AIA, Hon. FRIBA
In this new edition the goal of previous editions remains: to provide the appropriate knowledge at the level of complexity needed at the schematic design stage. In the years since the first edition was published, we have moved from a shortage of information to a flood because of the Internet. This book will aid the designer because it presents the information in a concise, logical, and accessible arrangement and at a useful level.

Since heating, cooling, and lighting are accomplished by adding energy to or removing it from a building, and since the consumption of energy is causing global warming, it is vital for architects to design low energy, sustainable buildings. Although sustainability deals with many issues, the energy issues are the most critical. Thus, an additional goal of this book is to provide architects with the skills and knowledge needed to create low energy and low carbon-emission buildings.

In addition to improving and updating every chapter, three new chapters have been added. Chapter 17 on tropical architecture was added because a large portion of the world’s population lives in the tropical zone and because many architects trained in designing buildings in temperate climates end up designing buildings in the tropics. Case studies, formerly in Chapter 17, are now in Chapter 18. Because of the extensive information available on the Web, only a brief description is given of a personal selection of buildings.

Chapter 19, the third new chapter, presents a checklist to help in the design of low energy, sustainable buildings. The checklist guides the designer through the decision-making process so that important options are considered at the appropriate time.

This book focuses on the schematic design stage, where the key decisions are made. The graph below points out how the earliest decisions have the greatest impact on a project. A building’s cost and environmental impact are established mainly at the schematic design stage. The most basic decisions of size, orientation, and form often have the greatest impact on the resources required during both construction and operation. Thus, designs for sustainable buildings are achieved primarily by the earliest decisions in the design process rather than by add-ons and engineering decisions made after the architectural design of the building has been essentially completed.

The information in this book is presented to support the three-tier approach to sustainable design of the heating, cooling, and lighting of buildings. The first tier is load avoidance. Here the need for heating, cooling, and lighting is minimized by the design of the building itself. The second tier consists of using natural energies through methods such as passive solar, passive cooling, natural ventilation, and daylighting. This tier is also accomplished mainly by the design of the building itself. The third and last tier uses mechanical and electrical equipment to satisfy the needs not provided for by the first two tiers.

With the knowledge and information presented in this book, the first two tiers can provide most of the thermal and lighting requirements of a building. As a consequence, the mechanical and electrical equipment of the third tier will be substantially smaller and will use much less energy than is typical now, thereby resulting in more sustainable buildings. Since tiers one and two are the domain of the architect, the role of the engineer at the third tier is to provide only the heating, cooling, and lighting that the architect could not.
For the fourth edition, I would like to thank especially John Marusich for his excellent work on the new and revised drawings. Since this book is built on the previous three editions, I also want to thank again all of the people who helped me write those earlier editions. The typing and proofreading for the fourth edition were done by my son, Walden Lechner.

And again, I want to thank my wife, Prof. Judith Lechner, whose help, support, and love are invaluable to me.

NORBERT LECHNER
Prof. Emeritus and Architect
Auburn University
Two essential qualities of architecture [commodity and delight], handed down from Vitruvius, can be attained more fully when they are seen as continuous, rather than separated, virtues.

... In general, however, this creative melding of qualities [commodity and delight] is most likely to occur when the architect is not preoccupied either with form-making or with problem-solving, but can view the experience of the building as an integrated whole. ... 

John Morris Dixon,
Editor of Progressive Architecture, 1990

All design projects should engage the environment in a way that dramatically reduces or eliminates the need for fossil fuel.

The 2010 Imperative,
Edward Mazria, AIA,
Founder of Architecture 2030
1.1 INTRODUCTION

Architecture has been called journalism in stone, since it reflects the culture, climate, and resources of the time and place. During the Renaissance, for example, the main influence was the rediscovery of the classical world. What is the agent of change today?

The story that is now shaping the future of architecture is sustainability. There are few people left today who are not in favor of creating a sustainable world or who would claim that we are living in a sustainable world. Since building impacts the environment more than any other human activity, architects have both the responsibility and the opportunity to lead humankind to a sustainable future.

Sustainable architecture can be achieved by using "the best of the old and the best of the new." A new architecture is being created by using modern science, technology, and ideas of aesthetics combined with traditional ideas that responded to human needs, nationalism, and climate. Such architecture will be more varied than contemporary architecture, which gives no clue to where a building is located. Much contemporary architecture looks the same in New York, Paris, New Delhi, or Tokyo. Furthermore, this de facto "international" architecture is equally inappropriate wherever it is built since it is not sustainable for any climate.

Sustainability covers many issues, but none is as important as energy consumption. More than any other factor, the energy consumption of buildings is destroying the planet as we know it. Buildings use about 48 percent of all the energy consumed, with 40 percent for their operation and 8 percent for their construction (Fig. 1.1a). This energy is mostly derived from fossil sources that produce the carbon dioxide that is the main cause of global warming. We must replace these polluting sources with clean, renewable energy sources such as wind, solar energy, and biomass, or we must increase the efficiency of our building stock so that it uses less energy. Of course, we need to do both, but decreasing the energy consumption of buildings is both quicker and less expensive. Furthermore, the design of energy-responsive buildings will yield a new aesthetic that can replace both the blandness of most modern buildings and the inappropriate copying of previous styles.

Is it really possible for architecture to seriously address the problem of global warming? The answer is an unambiguous yes, both because present buildings are so wasteful of energy and because we know how to design buildings so energy efficient that we can now build zero-energy buildings. The small amount of energy that they still need can be supplied by renewable sources such as photovoltaics (Fig. 1.1b). We have the know-how (see Sidebox 1.1); all we need is the will.

**Figure 1.1a** Buildings are the main cause of global warming because they use about 48 percent of all energy. Of that 48 percent, about 40 percent is for operating the buildings (heating, cooling, lighting, computers, etc.) and about 8 percent is for their construction (creating materials, transportation, and erection). (Courtesy of Architecture 2030.)

**Figure 1.1b** The good news is that buildings do not have to use climate-changing fossil fuels. Over the years, we have learned how to design buildings so energy efficient that we can now build zero-energy buildings. The small amount of energy that they still need can be supplied by renewable sources such as photovoltaics. (Fig. 1.1b).

---

**SIDEBOX 1.1**

**Characteristics of a Zero-Energy House**

- Correct orientation
- Form as compact as appropriate for the climate and function
- Extensive use of white or very light colored surfaces
- Superinsulated walls, roof, and floor
- Airtight construction with a heat recovery unit for ventilation
- High-performance, properly oriented windows
- Windows fully shaded in summer
- Passive solar space heating
- Active solar domestic hot water
- High-efficiency appliances
- High-efficiency electric lighting
- High-efficiency heating and cooling equipment (e.g., earth-coupled heat pump)
- Photovoltaics on roof that produce the small amount of electricity still needed
There is a widespread belief that engineers design the heating, cooling, and lighting of buildings. The truth is that they only design the systems and equipment still needed after the architect designs the building to heat, cool, and light itself. Thus, the size of the mechanical and electrical equipment is an indicator of how successful the architect was. It is most important to realize that in designing a building to do most of the heating, cooling, and lighting, the architect is also designing the form and other aesthetics of a building.

This book was written to help the reader design sustainable buildings that use very little energy. It presents rules of thumb, guidelines, and examples that are drawn from the best of the old and the best of the new. Because traditional buildings used little energy, the methods they used to respond to their climate, locality, and culture can be a source of ideas and inspiration for modern architects.

1.2 INDIGENOUS AND VERNACULAR ARCHITECTURE

One of the main reasons for regional differences in architecture is the response to climate. This becomes apparent when looking at indigenous buildings, because they usually reflect the climate in which they were built.

In hot and dry climates, one usually finds massive walls and roofs used for their time-lag effect. Since the sun is very intense, small windows will adequately light the interiors. The windows are also small because during the daytime the hot outdoor air makes ventilation largely undesirable. The exterior surface colors are usually very light to minimize the absorption of solar radiation. Interior surfaces are also light to help diffuse the sunlight entering through the small windows (Fig. 1.2a).

Since there is usually little rain, roofs can be flat and are often used as additional living and sleeping areas during summer nights. Outdoor areas cool quickly after the sun sets because of the rapid radiation to the clear night sky. Thus, roofs are more comfortable than the interiors, which are still quite warm from the daytime heat stored in the massive construction.

Even community planning responds to climate. In hot and dry climates, buildings are often closely clustered for the shade they offer one another and the public spaces between them.

In hot and humid climates, we find a very different kind of building. Because water vapor blocks some solar radiation, air temperatures are lower than in hot and dry climates, but the high humidity still creates great discomfort. The main relief comes from shading and moving air across the skin to increase the rate of evaporative cooling. The typical antebellum house (see Fig. 1.2b) responds to the humid climate by its use of many large windows, large overhangs, shutters, light-colored walls, and high ceilings. The large windows maximize ventilation, while the overhangs and shutters protect from both solar radiation and rain. The light-colored walls minimize heat gain.

Since in humid climates nighttime temperatures are not much lower than daytime temperatures, massive construction is a disadvantage. Buildings are, therefore, usually made of lightweight wood construction. High ceilings permit larger windows and allow the air to stratify with people inhabiting the lower and cooler layers. Vertical ventilation through roof monitors or high windows not only increases ventilation but also exhausts the hottest air layers first. For this reason, high gabled roofs without ceilings (i.e., cathedral ceilings) are popular in many parts of the world that have hot and humid climates (Fig. 1.2c). Buildings are sited as far apart as possible for maximum access to the cooling breezes. In some humid regions of the Middle East, wind scoops are used to further increase the natural ventilation through the building (Fig. 1.2d).
In hot and humid climates, natural ventilation from shaded windows is the key to thermal comfort. This Charleston, South Carolina, house uses covered porches and balconies to shade both windows and walls, as well as to create cool outdoor living spaces. The white color and roof monitor are also important in minimizing summer overheating.

In hot and humid climates such as in Sumatra, Indonesia, native buildings are often raised on stilts and have high roofs with open gables to maximize natural ventilation.

When additional ventilation is desired, wind scoops can be used, as on this reconstructed historical dwelling in Dubai. Also note the open weave of the walls to further increase natural ventilation. Although this is a desert area, lightweight construction is appropriate because the region along the Persian Gulf is humid. (Photograph by Richard Millman.)
In mild but very overcast climates, like the Pacific Northwest, buildings open up to capture all the daylight possible. In this kind of climate, the use of bay windows is quite common (Fig. 1.2e).

In a predominantly cold climate, we again see a very different kind of architecture. In such a climate, the emphasis is on heat retention. Buildings, like the local animals, tend to be very compact to minimize the surface-area-to-volume ratio. Windows are few because they are weak points in the thermal envelope. Since the thermal resistance of the walls is very important, wood rather than stone is usually used (Fig. 1.2f). Because hot air rises, ceilings are kept very low—often below 7 ft (2.2 m). Trees and landforms are used to protect against the cold winter winds. In spite of the desire for views and daylight, windows are often sacrificed for the overpowering need to conserve heat.

Despite the name, temperate climates are not mild. Instead, they are usually cold in the winter and hot in the summer. Consequently, temperate climates are difficult to design for.

1.3 FORMAL ARCHITECTURE

Throughout history, most master builders and architects have included environmental controls in their designs, just as their unschooled neighbors creating indigenous buildings did. After all, the Greek portico is simply a feature to protect against the rain and sun (Fig. 1.3a). The perennial popularity of classical architecture is based on not only aesthetic but also practical grounds. There is hardly a better way to shade windows, walls, and porches than with large...
overhangs supported by columns (Fig. 1.3b).

The Roman basilicas consisted of large high-ceilinged spaces that were very comfortable in hot climates during the summer. Clerestory windows were used to bring daylight into these central spaces. Both the trussed roof and groin-vaulted basilicas became prototypes for Christian churches (Fig. 1.3c).

One of the Gothic builders’ main goals was to maximize the window area for a large, fire-resistant hall. By means of the inspired structural system of groin vaulting, they were able to
send an abundance of daylight through stained glass windows (Fig. 1.3d).

The need for heating, cooling, and lighting had also affected the work of the twentieth-century masters such as Frank Lloyd Wright. The Marin County Civic Center emphasizes the importance of shading and daylighting. To give most offices access to daylight, the building consists of linear elements separated by a glass-covered atrium (Fig. 1.3e). The outside windows are shaded from the direct sun by an arcade-like overhang (Fig. 1.3f). Since the arches are not structural, Wright shows them hanging from the building.

Modern architecture prided itself on its foundation of logic. “Form follows function” was seen as much more sensible than “form follows some arbitrary historical style.” However, “function” was usually interpreted as referring to structure or building circulation. Rarely did it refer to low energy usage, which was seen as a minor issue at best and usually was not considered at all. Although that belief was never logical, it is clearly wrong today since energy consumption is the number-one issue facing the earth.

Like Frank Lloyd Wright, Le Corbusier also felt strongly that the building itself should be effective in heating, cooling, and lighting. He included thermal comfort and energy as functions in his interpretation of “form follows function.” His development of the brise-soleil (sunshades) will be discussed in some detail later. A feature found in a number of his buildings is the parasol roof, an umbrella-like structure covering the whole building. A good example of this concept is the Maison de l’Homme, which Le Corbusier designed in glass and painted steel (Fig. 1.3g).

Today, with no predominant style guiding architects, they occasionally use a mild form of revivalism. The buildings in Figure 1.3h use the classical portico for shading. Such historical adaptations can be more climate responsive than the “international style,” which typically ignores the local climate. Buildings in cold climates can continue to benefit from

Figure 1.3d Daylight gained a mystical quality as it passed through the large stained glass windows of the Gothic cathedral made possible by groin vaulting. (Photograph by Clark Lundell.)

Figure 1.3e In the linear central atrium of the Marin County Civic Center, Frank Lloyd Wright used white surfaces to reflect light down to the lower levels. The offices facing the atrium have all-glass walls.

Figure 1.3f The exterior windows of the Marin County Civic Center are protected from direct sun by an arcade-like exterior corridor.
compactness, and buildings in hot and dry climates still benefit from massive walls and light exterior surfaces. Looking to the past in one’s locality helps lead to the development of new and sustainable regional styles.

1.4 THE ARCHITECTURAL APPROACH TO SUSTAINABLE DESIGN

The sustainable design of heating, cooling, and lighting buildings can be more easily accomplished by understanding the logic of the three-tier approach to sustainable design (Fig. 1.4a). The first tier consists of all of the decisions that are made in designing any building. When the designer consistently thinks of minimizing energy consumption as these decisions are made, the building itself can accomplish about 60 percent of the heating, cooling, and lighting.

The second tier involves the use of natural energies through such methods as passive heating, passive cooling, and daylighting systems. The proper decisions at this point can reduce the energy consumption another 20 percent or so. Thus, the strategies in tiers one and two, both purely architectural, can reduce the energy consumption of buildings up to 80 percent. Tier three consists of designing the mechanical and electrical equipment to be as efficient as possible. That effort can reduce energy consumption another 5 percent or so. Thus, only 15 percent as much energy is needed as in a conventional building. That small amount of energy can be derived from renewable sources both on- and off-site. Table 1.4A shows some of the design topics that are typical at each of the three tiers.

Figure 1.3g The Maison de l’Homme in Zurich, Switzerland, demonstrates the concept of the parasol roof. The building is now called Centre Le Corbusier. (Photograph by William Gwin.)

Figure 1.3h These postmodern buildings promote the concept of regionalism in that they reflect a previous and appropriate style of the hot and humid Southeast.
The heating, cooling, and lighting design of buildings always involves all three tiers, whether consciously considered or not. Unfortunately, in the recent past minimal demands were placed on the building itself to affect the indoor environment. It was assumed that it was primarily the engineers at the third tier who were responsible for the environmental control of the building. Thus, architects sometimes designed buildings that were at odds with their environment. For example, buildings with large glazed areas were designed for very hot or very cold climates. The engineers were then forced to design giant, energy-guzzling heating and cooling plants to maintain thermal comfort. Ironically, these mostly glass buildings had their electric lights on...
during the day, when daylight was abundant, because they were not designed to gather quality daylighting. As this shows, a building's energy consumption for heating, cooling, and lighting is mainly determined by the architect at the conceptual design stage.

In some climates, it is possible to reduce the mechanical equipment to zero. For example, Amory Lovins designed his home/office for the Rocky Mountain Institute in Snowmass, Colorado, where it is very cold in the winter and quite hot in the summer, to have no heating or cooling system at all. He used the strategies of tiers one and two to accomplish most of the heating and cooling, and he used photovoltaics, active solar, and very occasionally a wood-burning stove for any energy still needed.

### Table 1.4B Building Form Implications

<table>
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<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>• compactness to minimize surface area, thereby reducing heat gain/loss</td>
<td>• cannot be oriented to give most windows the ideal orientation of north and south</td>
</tr>
<tr>
<td>• minimum footprint on land</td>
<td>• minimum potential for daylighting, passive solar, and passive cooling</td>
</tr>
<tr>
<td>• good for cold climates</td>
<td></td>
</tr>
<tr>
<td>• better for daylighting and natural ventilation than form I</td>
<td>• cannot be oriented to give most windows the ideal orientation of north and south</td>
</tr>
<tr>
<td>• more people have access to views, although some only to the atrium</td>
<td>• less compact than form I unless atrium is covered</td>
</tr>
<tr>
<td>• daylighting for whole space if one story and daylighting for most if two stories</td>
<td>• larger footprint on land than form I</td>
</tr>
<tr>
<td>• very high quality daylighting since it is mostly top lighting</td>
<td></td>
</tr>
<tr>
<td>• very high potential for passive solar heating through south-facing clerestories</td>
<td></td>
</tr>
<tr>
<td>• high potential for passive cooling through:</td>
<td>• very large footprint on land</td>
</tr>
<tr>
<td>• roof vents for natural and forced ventilation</td>
<td>• very large surface-area-to-volume ratio</td>
</tr>
<tr>
<td>• solar chimneys</td>
<td>• all windows cannot face the ideal orientation of north and south, but clerestories can</td>
</tr>
<tr>
<td>• direct evaporative cooling from roof</td>
<td></td>
</tr>
<tr>
<td>• no vertical circulation needed if one story and little vertical circulation if two stories</td>
<td></td>
</tr>
<tr>
<td>• if site permits, all or most windows can face the ideal orientation of north and south</td>
<td>• larger surface to volume ratio than either form I or II</td>
</tr>
<tr>
<td>• very high potential for daylighting</td>
<td>• if the site requires the long facades to face east and west, the building will perform poorly; cooling loads will be very high due to all or most windows facing east or west; quality daylighting will also be poor</td>
</tr>
<tr>
<td>• high potential for cross ventilation</td>
<td></td>
</tr>
<tr>
<td>• very high potential for passive solar heating</td>
<td></td>
</tr>
<tr>
<td>• can fit on sites that may not work for form IV</td>
<td>• only some windows can face the ideal orientation of north and south</td>
</tr>
<tr>
<td>• good potential for daylighting especially for the windows facing north and south</td>
<td>• many windows will be facing the problematic orientations of east and west</td>
</tr>
<tr>
<td>• very good potential for cross ventilation</td>
<td></td>
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When it is consciously recognized that each of these tiers is an integral part of the heating, cooling, and lighting design process, buildings are improved in several ways: they can be less expensive because of reduced mechanical equipment and energy needs; they are usually also more comfortable because the mechanical equipment does not have to fight such giant thermal loads; and they are often more interesting because some of the money that is normally spent on the mechanical equipment is spent instead on the architectural elements. Unlike hidden mechanical equipment, features such as shading devices are a very visible part of the exterior aesthetic—thus, the name of this chapter is “Heating, Cooling, and Lighting as Form-Givers in Architecture.”

Table 1.4B outlines the advantages and disadvantages of the main massing schemes. Figure 1.4b illustrates how massing relates to climate in traditional building. The appearance of a building is also impacted by surface treatments such as shading devices, balconies, and green walls, which further impact the heating, cooling, and lighting of a building.

1.5 DYNAMIC VERSUS STATIC BUILDINGS

Is it logical that a static system can respond to a dynamic problem? A building experiences a very dynamic environment: cold in the winter, hot in the summer, sunny one day, cloudy the next, sunshine from the east in the morning and west in the afternoon, and the angle of sunrays changing minute by minute and day by day. Nevertheless, most buildings are static except for the mechanical and electrical equipment. Would it not make more sense for the building itself to change in response to the environment? The change can occur continuously over a day as, for example, a movable shading device that extends when it is sunny and retracts when it is cloudy. Alternatively, the change could be on an annual basis, whereby a shading device is extended for the summer and retracted for the winter, much like a deciduous tree. The dynamic aspect can be modest, as in movable shading devices, or it can be dramatic, as when the whole building rotates to track the sun (Figs. 9.15b to 9.15d). Since dynamic buildings are more energy efficient than static ones, it is likely that all future buildings will have dynamic facades. A major objection has been the difficulty of maintaining movable systems exposed to the weather. However, the present reliability of cars shows that movable systems can be made that need few if any repairs over long periods of time. With good design and materials, exposed building systems have become extremely reliable even with exposure to salt water and ice in the winter. Perhaps the modern airplane is an even better example of a reliable movable system than the automobile. Since no one shape of wing is ideal for all stages of flight, modern passenger jets change the shape of their wings as conditions change (Fig. 1.5). If planes can do this flying at hundreds of miles per hour in all weather conditions, certainly a building on the ground moving zero miles per hour can also have extremely reliable dynamic facades.

Not only will dynamic buildings perform much better than static buildings, but they will also provide an exciting aesthetic, the aesthetic of change. Numerous examples of dynamic buildings are included throughout the book, but most will be found in the chapters on shading, passive cooling, and daylighting.
1.6 RESILIENT DESIGN

We should design buildings not only to sustain the planet but also to sustain its occupants during an emergency. For example, houses on stilts had a better chance to survive the storm surges of Hurricanes Katrina and Sandy than the typical houses built close to the ground.

We rely on our buildings' mechanical systems and imported energy supplies to keep us warm in the winter, cool in the summer, and out of the dark all year. Yet, in January 1998, an ice storm in eastern Canada left four million people without power for weeks during the height of the winter. Heat waves in the United States and Europe are becoming more severe and frequent. Is it wise to rely on mechanical equipment and uninterrupted energy supplies? There is a growing conviction that buildings should be designed for passive survivability, today more commonly called resilience. Others prefer the word "adaptive" because we must now design buildings that can adapt to a changing climate.

For a building to be resilient it must be able to operate at least for a while without energy or water inputs from the outside, and it must be able to survive storms and floods. Because we heat, cool, and light buildings with energy, this book focuses only on resilience related to energy. Fortunately, sustainable buildings are more resilient because they require much less energy to operate through efficiency, passive design, and possibly on-site energy production. When power or other energy supplies are not available, resilient (i.e., sustainable) buildings will get only moderately cold in the winter and moderately hot in the summer, and they will be illuminated with daylight most of the day. Thus, from an energy standpoint resilience is just another argument for sustainable design.

1.7 BIOPHILIC DESIGN

The biophilia hypothesis states that human beings have a need for connection with living things such as pets, wild animals, plants, and views of nature. Recent research in neuroscience and endocrinology support what social research and traditional knowledge have long indicated: experiencing nature has significant benefits. Consequently, bringing nature into, onto, and around buildings is not a luxury but is instead important for health, productivity, energy conservation, and, crucially, as this book will show, aesthetics (Colorplates 27, 30, and 34).

1.8 COLOR AND ORNAMENTATION

White is the greenest color outdoors as well as indoors. White roofs have half the heat gain of black roofs. White walls also reduce heat gain, and in urban canyons they deliver more daylight to lower floors and the streets. White cities will experience cooler heat islands than typical cities. Indoors, white ceilings and walls reflect precious daylight and electric lighting. White is unquestionably the most sustainable color.

Polished metal and glass are also used as exterior wall finishes, but both materials perform more poorly than flat white. All-glass facades are popular, but without shading devices or light shelves they have disadvantages besides the most serious of poor energy performance. Whatever sunlight is not transmitted indoors or absorbed by the glass is reflected like a mirror to adjacent buildings and the ground below. This reflected sunlight causes serious glare and overheating where it was not expected, such as on the north facade of neighboring buildings. Flat white walls,
on the other hand, reflect some solar radiation back into space and the rest becomes a source of quality daylight for other buildings and the ground, which is especially important in urban areas. Glass buildings are also responsible for killing millions of birds each year. Because all-glass building facades are not energy efficient, they are not sustainable. The aesthetic of a facade should come from limited glazing, shading devices, light shelves, and ornamentation.

At its peak influence, modern architecture had no tolerance for ornamentation. Instead the emphasis was on form. Basing the aesthetic only on complex forms has strong energy implications, since more compact buildings are generally more sustainable. They require less material to build and less energy to operate for their lives. Thus, compact designs with ornamentation, small patches of color, or murals usually produce the most sustainable design (Fig. 1.8 and Colorplate 25). Fortunately, some types of ornamentation are again acceptable. The role of ornamentation in architecture is discussed by Brent C. Brolin in his book *Architectural Ornament: Banishment & Return*.

### 1.9 ENERGY AND ARCHITECTURE

The heating, cooling, and lighting of buildings are accomplished by either adding or removing energy. Consequently, this book is about the manipulation and use of energy. In the 1960s, the consumption of energy was considered a trivial concern. For example, buildings were sometimes designed without light switches because it was believed that it was more economical to leave the lights on continuously. Additionally, the most popular air-conditioning equipment for larger buildings was the terminal reheat system, in which the air was first cooled to the lowest level needed by any space and then reheated as necessary to satisfy the other spaces. The double use of energy was not considered an important issue.

The building in which the author taught architecture for thirty years was built in 1974. At that time, the “rational economic decision” was to put no insulation in the walls since it would not pay for itself quickly enough. Today we think that decision was idiotic. Will our “rational economic decisions” today seem just as short-sighted thirty years from now?

Buildings now use about 40 percent of all the energy consumed in the United States for their operation. To construct them takes another 8 percent of all the energy. Clearly, then, the building industry has a major responsibility in the energy picture of this planet. Architects have both the responsibility and the opportunity to design in an energy-conserving manner.

The responsibility is all the greater because of the effective life of the product. Automobiles last only about ten years, and so any mistakes will not burden society too long. Most buildings, however, should have a
useful life of at least fifty years. The consequences of design decisions now will be with us for a long time.

When people realize that the fossil energy that buildings consume causes global warming, the immediate reaction is to support the production of renewable energy that causes no pollution and no global warming. The quickest, most effective, and least expensive ways to fight global warming, however, come from using less energy.

Unfortunately, the phrase “energy conservation” has negative connotations. It makes one think of shortages and discomfort. Yet architecture that conserves energy can be comfortable, sustainable, humane, and aesthetically pleasing. It can also be less expensive than conventional architecture. Operating costs are reduced because of lower energy bills, and first costs are often reduced because of the smaller amount of heating and cooling equipment that is required. To avoid negative connotations, the more positive and flexible phrases “energy-efficient design” or “energy-conscious design” have been adopted to describe a concern for energy conservation in architecture. Energy-conscious design yields buildings that minimize the need for expensive, polluting, and nonrenewable energy. Because of the benefit to planet Earth, such design is now called sustainable, green, or low carbon.

Because of global warming, it is now widely recognized that reducing the energy appetite of buildings is the number one green issue. As Figure 1.9 illustrates, the energy issues are a very large subset of all the sustainability issues. Figure 1.9 also demonstrates that the solar issues are a surprisingly large subset of the energy issues. One reason for this is that “solar” refers to many strategies: photovoltaics (solar cells), active solar (hot water), passive solar (space heating), daylighting, and shading. Although shading is the reverse of collecting solar energy, it is one of the most important solar design strategies, because it can save large amounts of air-conditioning energy at low cost.

I.10 CLIMATE AND ARCHITECTURE

In extreme climates, as are found in Russia and Indonesia, it is clear whether heating or cooling are the architect’s main concern, but in temperate climates, buildings must be designed for both heating and cooling (Fig. 1.10a). However, the energy used and the money spent on heating or cooling are rarely equal in temperate climates. Figure 1.10b shows the heating and cooling degree-days, which predict the energy required for heating and cooling, for four
American cities. For an explanation of degree-days, see Section 5.6(k).

Some aspects of building design are equally valid for both the heating and cooling loads. Insulation levels and an east-west building orientation reduce energy requirements in both summer and winter. However, other aspects of building design favor one season over another. For example, high ceilings are appropriate for a cooling-dominated climate while low ceilings are better for a heating-dominated climate.

Because a building designed for its climate will be more energy efficient, it is important for the architect to know if heating or cooling loads dominate. For this reason, Chapter 5 gives detailed climate information for seventeen climate regions in the United States and Canada.

The problem of designing for a climate is further complicated because the heating and cooling loads vary with building type in the same climate. For example, an office building will have smaller heating and larger cooling loads than a house in the same climate. For simplicity, this book places building types into one of two categories: "internally dominated" buildings such as large office buildings and "envelope-dominated" buildings such as houses.

Because most people in the world live in hot climates, and because they are becoming wealthier, the use of air-conditioning is growing exponentially (Fig. 1.10c). Even in the United States,
the energy for cooling is increasing as more people can afford it and as more people move to the South. To reduce the growth of energy consumption for air-conditioning, architects must focus on heat avoidance strategies such as shading and light colors.

I.11 SUSTAINABILITY CODES AND VOLUNTARY PROGRAMS

All over the world, codes and programs have been put in place to impel buildings to be low energy and low carbon. In the United States, the main codes are ASHRAE 90.1 and 189.1, the International Energy Conservation Code (IECC), and the International Green Construction Code (IGCC). However, it is mostly up to states and municipalities to pass laws that make codes mandatory.

To supplement the impact of codes, a number of programs have been created to spur the movement to low energy buildings. The most famous by far is Leadership in Environmental and Energy Design (LEED), created and run by the United States Green Building Council (USGBC). With each new version, the LEED program increases its focus on creating low energy buildings. The Green Building Initiative's Green Globes program is an alternative to LEED in the United States. Passive House is a rigorous program most appropriate to cold climates, and maybe the most demanding program of all is the Living Building Challenge.

The Environmental Protection Agency (EPA) of the United States government administers the voluntary Energy Star program, which produces ratings for products and appliances. The program also promotes efficient building methods.

Another method for encouraging sustainable design is to give awards. Every year the American Institute of Architecture Committee on the Environment (AIA/COTE) announces the “Top Ten” from all the submissions of sustainable design it receives. Energy responsiveness is an important criterion.

Perhaps the most important organization for making buildings adapt to climate change is Architecture 2030. In 2006 it issued the 2030 Challenge, which would reduce greenhouse gas emissions of buildings to zero by 2030 in steps—70 percent reduction by 2015, 80 percent reduction by 2020, 90 percent reduction by 2025, and 100 percent reduction by 2030. The 2030 Challenge has been adopted by the AIA; the U.S. Council of Mayors; the National Association of Governors; the U.S. Green Building Council; the U.S. government, which requires all new and renovated federal buildings to meet the challenge (2007 Energy Independence and Security Act); and numerous other governmental, for-profit, and nonprofit organizations.

The reader is encouraged to visit Architecture 2030’s website: www.architecture2030.org.

Figure 1.11 The energy performance of buildings constructed under the influence of energy codes and voluntary programs varies greatly, as this diagram indicates. The ranking is based on the Home Energy Rating System (HERS) index. (After the Rocky Mountain Institute.)
The combination of codes and voluntary programs is having a profound effect on how America builds. See Figure 1.11 on how the various codes and programs compare in achieving great energy performance.

**1.12 INTEGRATED DESIGN**

Buildings have become too complex for any one individual to design, and the need for sustainability has further increased the complexity of buildings. The traditional linear design process, where the various building professions make their contributions sequentially, is not suited to creating high-performing buildings (Fig. 1.12a). In such a design process, the various building systems are not able to work together most efficiently. Instead, they are often competing with one another. For example, an all-glass facade will result in a huge energy guzzling mechanical system. In the sequential design process, it is usually too late to redesign the glass facade when the mechanical equipment is being designed and found to be excessively large. In the integrated whole-building design process, on the other hand, the needs of the various systems are considered at the very beginning of the architectural design so that they can all work together most efficiently.

**TRADITIONAL DESIGN PROCESS BY PROFESSIONS**

*Figure 1.12a* In the traditional linear design process, the various building design professionals work on a project sequentially. Unfortunately, this method does not promote the design of high-performing sustainable buildings.

**INTEGRATED DESIGN PROCESS BY FUNCTION**

*Figure 1.12b* In the whole-building integrated design process, the needs of the various building systems are considered from the very beginning of the design process. The resultant designs are then harmonious with the needs of the various systems to create high-performance buildings. It also makes possible synergies that further improve the performance and sustainability of a project.
together to create a high-performance building (Fig. 1.12b). For example, the heating and cooling loads on the mechanical equipment influence not only the facade design but also the orientation and form of the building. For the various building systems to work together, the appropriate professionals must form a team that together creates the design (Fig. 1.12c). The team must start meeting before the first line is drawn because that first line has so many significant consequences.

1.13 DECISION MAKING

The design process is essentially a decision-making process based on asking the right questions in the right order. For example, the first line in the first drawing should be made only after the many consequences of the building’s location, orientation, and length have been considered. That first line will have great impact on the heating, cooling, and lighting energy that that building will consume. The wrong orientation of a building, for instance, will have great negative consequences later on when design decisions are made about shading, passive solar, and daylighting.

The set of decisions necessary to create a sustainable building can be divided into three subsets: decisions for which a clear-cut best answer exists; decisions which are not clear-cut but modeling can give the best answer; and decisions which are essentially subjective (Fig. 1.13). The architect and other building professionals should be aware of the issues that are clear-cut, and they should start the design process using these proven ideas. To use an extreme example, in designing a car the decision that the wheels should be round must come at the beginning. It is not necessary to model square wheels to find out if they are the best choice. Indeed, it is not appropriate to use square wheels even if they are visually more consistent with a square body. The shape of the wheels is not open to a subjective decision. Similarly, to create high-performance sustainable buildings most subjective decisions should made only after the important objective decisions have been considered.
1.14 CONCLUSION

The following design considerations have an impact on both the appearance and the heating, cooling, and lighting of a building: form, orientation, compactness (surface-area-to-volume ratio), size and location of windows, and the nature of the building materials. Thus, when architects draw the first line at the schematic design stage to design a building, they simultaneously start the design of the heating, cooling, and lighting. Because of this inseparable relationship between architectural features and the heating, cooling, and lighting of buildings, we can say that the environmental controls are form-givers in architecture.

It is not just tiers one and two that have aesthetic impact. The mechanical equipment required for heating and cooling is often quite bulky, and because it requires access to outside air, it is frequently visible on the exterior. The lighting equipment, although less bulky, is even more visible. Thus, even tier three is interconnected with the architectural aesthetics, and, as such, must be considered at the earliest stages of the design process.

KEY IDEAS OF CHAPTER 1

1. Both vernacular and formal architecture were traditionally designed to respond to the heating, cooling, and lighting needs of buildings.
2. Borrowing appropriate regional design solutions from the past (e.g., the classical portico for shade) can help in creating sustainable buildings.
3. In the twentieth century, engineers dealing with mechanical and electrical equipment had the primary responsibility for the environmental needs of buildings. Architects had provided for these needs in the past, and they can again be important players in the future.
4. The heating, cooling, and lighting needs of buildings can be designed by the three-tier approach:

**TIER ONE**: the basic design of the building form and fabric (by the architect)

**TIER TWO**: the design of passive systems (mostly by the architect)

**TIER THREE**: the design of the mechanical and electrical equipment (by the engineer).

5. Buildings use about 40 percent of all the energy consumed in the United States. Their construction takes another 8 percent.

6. Currently, the dynamic mechanical equipment responds to the continually changing heating, cooling, and lighting needs of a building. There are both functional and aesthetic benefits when the building itself is more responsive to the environment (e.g., movable shading devices). Buildings should be dynamic rather than static.

7. Sustainable buildings also provide resilience (“passive survivability”) in case of power outages or high fuel costs.

8. Sustainable buildings should also be adaptive by anticipating a more severe climate due to global warming.

9. Sustainable buildings should consider biophilia for both functional and psychological reasons.

10. White is the greenest color. Roofs and walls should be white in order to create cooler buildings and cooler cities.

11. Because a compact “shoebox” building is often the most sustainable form, color and ornamentation should be used to create interest.

12. Energy codes are necessary to make most buildings more energy efficient. Voluntary programs like LEED are helping to change the worldview of the building industry.

13. The integrated whole-building approach to design creates much higher performing, more sustainable buildings.

14. The design process is a decision-making process. The early decisions in the process are the most important because they affect the available options later on.

15. Because of global warming, it is imperative that buildings use less energy and achieve zero greenhouse gas emissions by 2030.

16. There is great aesthetic potential in energy-conscious architecture.

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**Resources**

**FURTHER READING**

See the Bibliography in the back of the book for full citations.

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**PAPERS**


------. "Rhythm and Ritual." www.rcf.usc.edu/~rknowles.


**ORGANIZATIONS**


GreenSource, www.greensource.construction.com

Environmental Building News (EBN), www.buildinggreen.com/news

Rocky Mountain Institute, www.rmi.org
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.*

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).
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,
THE SUSTAINABLE APPROACH TO
WASTE MANAGEMENT

Reduce (best option)

Reuse

Recycle

Regenerate

Dispose (worst option)

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.

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.

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.” 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.

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.

\[ \text{EUI} = \frac{\text{kBtu}}{\text{ft}^2 \cdot \text{year}} \]

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

1From 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.
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 restorative 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

\[ I = \text{environmental impact} \]
\[ P = \text{population} \]
\[ A = \text{affluence per person} \]
\[ T = \text{technology} \]

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

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
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.

![Table](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)

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

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

<table>
<thead>
<tr>
<th>Time</th>
<th>Percent of the bottle filled</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>100</td>
</tr>
<tr>
<td>10:01</td>
<td>200</td>
</tr>
<tr>
<td>10:02</td>
<td>400</td>
</tr>
</tbody>
</table>

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.
8. Save Water: Design buildings and landscapes that are water-efficient.
9. Make the Buildings Healthy: Provide a safe and comfortable indoor environment.
11. “Green Up” Your Business: Minimize the environmental impact of your own business practices, and spread the word.

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 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.

*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.
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
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 2.11b 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.

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.
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.

Table 2.11 Contribution to Atmospheric Carbon Dioxide, by Country

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

Source: World Resource Institute

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.

Regrettfully, 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.

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...
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
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,
2.17 Nonrenewable Energy Sources

2.17 Nonrenewable Energy Sources

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.

### 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.

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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.

**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,
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. 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.

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.”

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, ft³ 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 ft³ per minute (6 m and 48 l/s), or 40 ft of head and a flow of 50 ft³ 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...
when fish cannot reach their spawning grounds. For this reason, many existing dams in the United States are being demolished.

Figure 2.18i 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
power, (3) ocean-current power, and
(4) ocean thermal-energy conversion.

Tidal power has been used for cen-
turies 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 har-
ness. 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 dif-
ference 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 orig-
nating 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 gey-
sers 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 num-
ber, 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 capi-
tol. The United States has enough ge-
othermal resources (Colorplate 23) to
meet 6 percent of its 2025 energy needs.

Geo-Exchange

The low-grade thermal energy con-
tained 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 sum-
mer. 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 effi-
cient than resistance electric heating.

The use of geo-exchange heat
pumps can significantly reduce our
consumption of energy and the cor-
responding emission of pollution and
greenhouse gases. Reductions of 40
percent over air-source heat pumps
and reductions of 70 percent com-
pared to electric-resistance heating
and standard air-conditioning equip-
ment 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 impor-
tant role in a sustainable economy.
Hydrogen is the ideal nonpolluting
fuel because when it is burned, only
water is produced. It does not con-
tribute to global warming.

Hydrogen is abundant, but all of
it is locked up in compounds, such
as water (H₂O). 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.

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
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. Efficiency is the best, quickest, and most cost-effective way to reduce our dependence on fossil and nuclear energy.

11. We must switch to renewable, nonpolluting energy sources such as solar, wind, biomass, hydro-power, and geothermal energy.

12. Geo-exchange heat pumps have great potential for energy conservation.

13. Although not a source of energy, hydrogen has the potential to be the clean fuel of the future.

14. As architect Bob Berkabire said, “If a building makes animals or people or the planet sick, it’s not beautiful and it’s not good design.”

References

Resources
FURTHER READING
(See the Bibliography in the back of the book for full citations.)
Solar architecture is not about fashion, it is about survival.

_Sir Norman Foster_

If we are anything, we must be a democracy of the intellect. We must not perish by the distance between people and government, between people and power. . . .

And that distance can only be conflated, can only be closed, if knowledge sits in the homes and heads of people with no ambition to control others, and not up in the isolated seats of power.

_J. Bronowski_

_The Ascent of Man, 1973_
3.1 INTRODUCTION

The heating, cooling, and lighting of buildings are accomplished by adding or removing energy. A good basic understanding of the physics of energy and its related principles is a prerequisite for much of the material in the following chapters. Consequently, this chapter is devoted to both a review of some rather well-known concepts and an introduction to some less familiar ideas such as mean radiant temperature, time lag, the insulating effect of mass, and embodied energy.

3.2 HEAT

Energy comes in many forms, and most of these are used in buildings. Much of this book, however, is concerned with energy in the form of heat, which exists in three different forms:

1. Sensible heat—can be measured with a thermometer
2. Latent heat—the change of state or phase change of a material
3. Radiant heat—a form of electromagnetic radiation

3.3 SENSIBLE HEAT

The random motion of molecules is a form of energy called sensible heat. An object whose molecules have a larger random motion is said to be hotter and to contain more heat (see Fig. 3.3a). Because this type of heat can be measured by a thermometer and felt by our skin, it is called sensible heat. If the two objects in Fig. 3.3a are brought into contact, some of the more intense random motion of the object on the left will be transferred to the object on the right by the heat-flow mechanism called conduction. Since the molecules must be close to each other in order to collide, and since in air the molecules are far apart, air is not a good conductor of heat. A vacuum allows no conduction at all.

Temperature is a measure of the intensity of the random motion of molecules. We cannot determine the heat content of an object just by knowing its temperature. For example, in Figure 3.3b (top), we see two blocks of a certain material that are both at the same temperature. Yet the block on the right will contain twice the heat because it has twice the mass.

The mass alone cannot determine the heat content either. In Figure 3.3b (bottom), we see two blocks of the same size, yet one block has more heat content because it has a higher temperature. Thus, sensible heat content is a function of both mass and temperature. Heat content is also a function of heat capacity, which is discussed in Section 3.15.

In the United States, we still use the Fahrenheit (°F) scale for temperature and the British thermal unit (Btu) as our unit of heat. The rest of the world, including Great Britain, uses the international system of units (SI), where temperature is measured in Celsius (°C) and heat in the joule or calorie. (See Table 3.3.)

<table>
<thead>
<tr>
<th>Table 3.3 Units of Heat and Temperature</th>
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<tbody>
<tr>
<td><strong>I-P System</strong></td>
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<tr>
<td>Heat</td>
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<tr>
<td>Heat flow</td>
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<tr>
<td>Temperature Fahrenheit (°F)</td>
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*1°F = inch-pound.
**A degree Celsius and a degree Kelvin have the same magnitude and are, therefore, interchangeable in many cases. They differ only in what they call zero (i.e., 0 degrees K = −273°C).
3.4 LATENT HEAT

By adding 1 Btu of heat to 1 pound of water, its temperature is raised 1°F (4.2 joules added to a gram of water will raise its temperature 1°C). It takes, however, 144 Btu to change a pound of ice into a pound of water and about 1000 Btu to change a pound of water into a pound of steam (Fig. 3.4). It takes very large amounts of energy to break the bonds between the molecules when a change of state occurs. "Heat of fusion" is required to melt a solid and "heat of vaporization" is required to change a liquid into a gas. Notice also that the water is no hotter than the ice and the steam is no hotter than the water, even though a large amount of heat is added. This heat energy, which is very real but cannot be measured by a thermometer, is called latent heat. In melting ice or boiling water, sensible heat is changed into latent heat, and when steam condenses and water freezes, the latent heat is turned back into sensible heat.

Latent heat is a compact and convenient form for storing and transferring heat. However, since the melting and boiling points of water are not always suitable, other materials called refrigerants are used because they have the melting and boiling temperatures necessary for refrigeration machines.

A change of state is also known as a phase change. Materials that melt at a useful temperature can be used to store heat or be used as a heat sink to cool a building. Such materials are called phase change materials (PCM).

3.5 EVAPORATIVE COOLING

When sweat evaporates from the skin, a large amount of heat is required. This heat of vaporization is drawn from the skin, which is cooled in the process. The sensible heat in the skin is turned into the latent heat of the water vapor.

As water evaporates, the air next to the skin becomes humid and eventually even saturated. The moisture in the air will then inhibit further evaporation. Thus, either air motion to remove this moist air or very dry air is required to make evaporative cooling efficient (Fig. 3.5).

Buildings can also be cooled by evaporation. Water sprayed on the roof can dramatically reduce its temperature. In dry climates, air entering buildings can be cooled with

![Figure 3.4](image-url) Figure 3.4 Latent heat is the large amount of energy required to change the state of a material (phase change), and it cannot be measured by a thermometer. The values given here are for 1 lb or 1 g of water, ice, or steam.

![Figure 3.5](image-url) Figure 3.5 The rate of evaporative cooling is a function of both humidity and air movement. Evaporation is rapid when the humidity is low and air movement is high. Evaporation is slow when the humidity is high and air movement is low.
water sprays. Such techniques will be described in Chapter 10.

3.6 CONVECTION

As a gas or liquid acquires heat by conduction, the fluid expands and becomes less dense. It will then rise by floating on top of denser and cooler fluid, as seen in Figure 3.6a. The resulting currents transfer heat by the mechanism called natural convection. This heat-transfer mechanism is very much dependent on gravity and, therefore, heat never convects down. Since we are surrounded by air, natural convection in air is a very important heat-transfer mechanism in our goal of being comfortable.

When there is no air motion due to the wind or a fan, natural convection currents tend to create layers that are at different temperatures. In rooms, hot air collects near the ceiling and cold air near the floor (Fig. 3.6b). This stratification can be an asset in the summer and a liability in the winter. Strategies to deal with this phenomenon will be discussed throughout this book. A similar situation occurs in still lakes where surface water is much warmer than deep water (Fig. 3.6b).

A different type of convection occurs when the air is moved by a fan or by the wind, or when water is moved by a pump (Fig. 3.6c). When a fluid (gas or liquid) is circulated between hotter and cooler areas, heat will be transferred by the mechanism known as forced convection.

3.7 TRANSPORT

In the eighteenth and nineteenth centuries, it was common to use warming pans to preheat beds. The typical warming pan, as shown in Figure 3.7, was about 12 in. (30 cm) in diameter and about 4 in. (10 cm) deep, and it had a long wooden handle. It was filled with hot embers from the fireplace, carried to the bedrooms, and passed between the sheets to remove the chill. In the early twentieth century,
it was common to use hot-water bottles for the same purpose. This transfer of heat by moving material is called transport. Because of its convenience, forced convection is much more popular today for moving heat around a building than is transport.

3.8 ENERGY-TRANSFER MEDIUMS

In both the heating and cooling of buildings, a major design decision is the choice of the energy-transfer medium. The most common alternatives are air and water. It is, therefore, very valuable to understand the relative heat-transfer capacity of these two materials. Because air has both much lower density and much less specific heat than water, much more of it is required to store or transfer heat. To store or transfer equal amounts of heat, a volume of air about 3000 times greater than that of water is needed (Fig. 3.8).

3.9 RADIATION

The third form of heat is radiant heat. All parts of the electromagnetic spectrum transfer radiant energy. All bodies facing an air space or a vacuum emit and absorb radiant energy continuously. Hot bodies lose heat by radiation because they emit more energy than they absorb (Fig. 3.9a). Objects at room temperature radiate in the long-wave infrared region of the electromagnetic spectrum, while objects hot enough to glow radiate in the visible part of the spectrum. Thus, the wavelength or frequency of the radiation emitted is a function of the temperature of the object.

Since radiation is not affected by gravity, a body will radiate down as much as up. Radiation is, however, affected by the nature of the material with which it interacts and especially the surface of the material. The four possible interactions, as illustrated in Figure 3.9b, are as follows:

1. Transmittance—the situation in which radiation passes through the material.
2. Absorptance—the situation in which radiation is converted into sensible heat within the material.
3. Reflectance—the situation in which radiation is reflected off the surface.
4. Emittance—the situation in which radiation is given off by the surface, thereby reducing the sensible heat content of the object. Polished metal surfaces have low emittance, while most other materials have high emittance.

For opaque materials the absorptance and reflectance both tell the same story. A high reflectance surface will be a low absorptance surface and vice versa (Fig. 3.9c).