Chapter 1

Introduction and Overview

In the short quarter century after the first significant efforts to apply the *sustainability* paradigm to the built environment in the early 1990s, the resulting *sustainable construction* movement has gained significant strength and momentum. In some countries—for example, the United States—there is growing evidence that this responsible and ethical approach is dominating the market for commercial and institutional buildings, including major renovations. Over 69,000 commercial building projects have been registered for third-party green building certification with the US Green Building Council (USGBC), the major American proponent of built environment sustainability, in effect declaring the project team's intention to achieve the status of an officially recognized or certified green building. The tool the USGBC uses for this process is commonly referred to by its acronym, LEED (Leadership in Energy and Environmental Design). Thus far, 27,000 commercial projects have navigated the LEED certification process successfully. Nowhere has the remarkable shift toward sustainable buildings been more evident than in American higher education. Harvard University boasts 93 buildings certified in accordance with the requirements of the USGBC, including several projects with the highest, or platinum, rating and including more than 1.9 million square feet (198,000 square meters [m^2]) of labs, dormitories, libraries, classrooms, and offices. An additional 27 projects are registered and pursuing official recognition as green building projects. The sustainable construction movement is now international in scope, with almost 70 national green building councils establishing ambitious performance goals for the built environment in their countries. In addition to promoting green building, these councils develop and supervise building assessment systems that provide ratings for buildings based on a holistic evaluation of their performance against a wide array of environmental, economic, and social requirements. The outcome of applying sustainable construction approaches to creating a responsible built environment is most commonly referred to as *high-performance green buildings*, or simply, *green buildings.*

The Shifting Landscape for Green Buildings

There are many signs that the green building movement is permanently embedded as standard practice for owners, designers, and other stakeholders. Among these are four key indicators that illustrate this shift into the mainstream. First, a survey of design and construction activity by McGraw-Hill Construction (2013) found that, for the first time, the majority of firms engaged in design and construction expected that over 60 percent of their work would be in green building by 2015. South Africa, Singapore, Brazil, European countries, and the United States all report this same result: that green building not only dominates the construction marketplace but also continues to increase in market share. This same report suggests that around the world, the pace of green building is accelerating and becoming a long-term business opportunity for both designers and builders. The green building market is growing worldwide and is not isolated to one region or culture. According to McGraw-Hill Construction, architects and engineers around the world are bullish on green building. Between 2012 and 2015, the number of designers and building consultants expecting more than 60 percent of their business to be green more than tripled in South Africa; more than doubled in Germany, Norway, and Brazil; and increased between 33 percent and 68 percent in the United States, Singapore, the United Kingdom, and Australia. The reasons for the rapid growth in high-performance green building activity has changed dramatically over time. In 2008, when a similar survey was conducted, most of the respondents felt that the main reason for their involvement was that they were doing the right thing, that they were simply trying to have a positive impact. Fast-forward just six years to 2014, and the reasons had changed significantly. The most cited triggers for green building around the world are client demand, market demand, lower operating costs, and branding/public relations. Green building has become simply a matter of doing good business, and has entered the mainstream in both the public and the private sectors. Although those interviewed indicated that they were still interested in doing the right thing, this reason moved from the top of the list in 2008 to number five in the six-year period between the two surveys.

A second illustration of the green building movement's staying power occurred at the Arab world's first Forum for Sustainable Communities and Green Building held in late 2014. Mustafa Madbouly, Egypt's minister of housing and urban development, told the audience: "Climate change forces upon us all a serious discussion about green building and the promotion of sustainability" (Zayed 2014). According to the United Nations Human Settlement Program (UNHSP), cities in the Arab world need to introduce stronger standards for green building and promote sustainable communities if they are to have this chance of tackling climate change. The UNHSP estimates that 56 percent of the Arab world's population already lives in cities and urban centers. This number quadrupled between 1990 and 2010 and is expected to increase another 75 percent by 2050. In short, applying sustainability principles to the built environment is essential not only for the well-being of the region's population but also for their very survival. According to the World Bank, the unprecedented heat extremes caused by climate change could affect 70 percent to 80 percent of the land area in the Middle East and North Africa.[1] Green building and climate change are now inextricably linked, and the main strategy for addressing climate change must be to change the design and operation of the built environment and infrastructure to reduce carbon emissions dramatically.

Third, in the United States, activity in sustainable construction continues to increase, some of it marking the continued evolution of thinking about how best to achieve high standards of efficiency in the built environment while at the same time promoting human health and protecting ecological systems. The state of Maryland and its largest city, Baltimore, provide a contemporary example of how strategies are being fine-tuned to embed sustainability in the built environment for the long term. In 2007, both Maryland and Baltimore, the 26th most populous city in the United States, adopted the USGBC's LEED rating system, requiring that most new construction be LEED certified. At the time, this move was considered groundbreaking, and it paralleled efforts by many states and municipalities around the country to foster the creation of a much-improved building stock. Baltimore, along with 176 other American jurisdictions, mandated green buildings and supported their implementation with a variety of incentives, including more rapid approval times, decreased permitting fees, and, in some cases, grants and lower taxes. In 2014, in a move that is likely to become more common, both Maryland and Baltimore repealed the laws and ordinances requiring LEED rating certification and instead adopted the International Green Construction Code (IgCC) as a template for their building codes. A construction or building code such as IgCC, in contrast to a voluntary rating system such as LEED, *mandates* green strategies for buildings. This turn of events marks a significant change in both strategy and philosophy because it indicates a shift from third-party certification systems to mainstreaming green building through the use of standards and building codes enforced by local authorities.

The fourth sign of the shifting landscape for high-performance green building is the fact the major tech giants Apple and Google and a range of other tech companies have announced major projects that indicate their industry is embracing high-performance green building. Apple Campus 2 (see Figure 1.1), scheduled for a late 2016 completion, will house 14,200 employees. In first announcing the new project in 2006, the late Steve Jobs referred to it as “the best office building in the world.” The architects for this cutting-edge facility are Foster + Partners, the renowned British architecture firm whose founder and chairman, Sir Norman Foster, was inspired by a London square surrounded by houses to guide the design concept. As the building evolved, it morphed into a circle surrounded by green space, the inverse of the London square. Located on about 100 acres (40.5 hectares) in Cupertino, California, the 2.8 million–square–foot (260,000 square meters) building is sited in the midst of 7,000 plum, apple, cherry, and apricot trees, a signature feature of the area’s commercial orchards. Only 20 percent of the site was disturbed by construction, resulting in

Figure 1.1 Apple Campus 2 is an NZE building designed to generate all the energy it requires from photovoltaic (PV) panels located on its circular roof. Its many passive design features allow it to take advantage of the favorable local climate such that cooling will be required just 25 percent of the year. (*Source:* City of Cupertino, September 2013)

abundant green space. Apple's Transportation Demand Management program emphasizes the use of bicycles, shuttles, and buses to move its employees to and from two San Francisco Bay regional public transit networks. The transportation program alternatives for Apple Campus 2 include buffered bike lanes and streets near the campus that are segregated from automobile traffic and also wide enough to permit bicycles to pass each other. Hybrid and electric automobile charging stations serve 300 electric vehicles, and the system can be expanded as needed. The energy strategy for Apple's new office building was shaped around the *net zero energy* (NZE) concept, with extensive focus on passive design to maximize daylighting and natural cooling and ventilation. The result is a building that generates more energy from renewable sources than it consumes. Energy efficiency is important for the net zero strategy, and the lighting and all other energy-consuming systems were selected for minimal energy consumption. The central plant contains fuel cells, chillers, generators, and hot and condenser water storage. A low carbon solar central plant with 8 megawatts (MW) of solar panels is installed on the roof, ensuring the campus runs entirely on renewable energy.

Another tech giant with ambitious high-performance green building plans is Google. Early in 2015, as part of a planned massive expansion, Google announced a radical plan for expansion of its Mountain View, California, headquarters into the so-called Googleplex. The radical design included large tentlike structures with canopies of translucent glass floating above modular buildings that would be reconfigured as the company's projects and priorities change. The area beneath the glass canopy included walking and bicycle paths along meadows and streams that connect to nearby San Francisco Bay. The emerging direction of design by the superstar collaboration between the Danish architect Bjarke Ingels and the London design firm, Heatherwick Studio was an eco-friendly project that would feature radical passive design and integration with nature and local transportation networks. However, in mid-2015, the Mountain View City Council voted to allow Google just one-fourth of its planned expansion, with the remaining site being made available to another tech firm, LinkedIn. In spite of this setback, Google, like many other technology-oriented companies, is committed to greening its buildings and infrastructure. One of its commitments is to investing in renewable energy, and the firm committed $145 million to finance a SunEdison plant north of Los Angeles. This was one of many renewable projects in which Google has invested a total of over $1.5 billion as of 2015.

Other tech firms are also leading the way with investments in architecturally significant, high-performance green buildings. Hewlett-Packard hired the renowned architect Frank Gehry to design an expansion of its Menlo Park, California, campus. It is clear that the behavior of these tech firms is part of an emerging pattern among start-up firms, which often begin their lives in college dorm rooms, storage units, garages, and living rooms. They move out of such locations as they mature, renting offices in industrial parks. Then, when they have become supersuccessful and flush with cash, they tend to build iconic monuments. However, in spite of the desire to make a splash by investing in signature headquarters buildings designed by well-known architects, the tech industries have managed to remain eco-conscious and serve as change agents by pushing society toward more sustainable behavior, particularly with respect to the built environment.

These trends, which mark the current state of high-performance green building around the world, indicate a maturing of the movement. The first of these buildings emerged around 1990, and the movement is now being mainstreamed, as evidenced by the incorporation of high performance building rating systems, such as LEED, into standards and codes. Since the inception of its pilot version in 1998, LEED has dealt with building energy performance by specifying improvements beyond the requirements of these standards to earn points toward certification. The main energy standard in the United States is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1, *Energy Standard for*

Buildings Except Low-Rise Residential Buildings. In the years since 1998, the energy consumption standards for new U.S. buildings has been sliced by more than 50 percent, and each issue of ASHRAE 90.1 makes additional cuts. The outcome is that it is becoming more difficult to use green building rating systems to influence additional energy reductions because following ASHRAE 90.1 already results in highly efficient building. Nevertheless, many issues still need attention, such as the restoration of natural systems, urban planning, infrastructure, renewable energy systems, comprehensive indoor environmental quality, and stormwater management. To its credit, the green building movement has succeeded in creating a dramatic shift in thinking in a short time. Its continued presence is now needed to both push the cutting edge of building performance and to ensure that the success of its efforts are maintained for the long term.

The Roots of Sustainable Construction

The contemporary high-performance green building movement was sparked by finding answers to two important questions: What is a high-performance green building? How do we determine if a building meets the requirements of this definition? The first question is clearly important—having a common understanding of what comprises a green building is essential for coalescing effort around this idea. The answer to the second question is to implement a *building assessment* or *building rating* system that provides detailed criteria and a grading system for these advanced buildings. The breakthrough in thinking and approach first occurred in 1989 in the United Kingdom with the advent of a building assessment system known as *BREEAM* (Building Research Establishment Environmental Assessment Method). BREEAM was an immediate success because it proposed both a standard definition for green building and a means of evaluating its performance against the requirements of the building assessment system. BREEAM represented the first successful effort at evaluating buildings on a wide range of factors that included not only energy performance but also water consumption, indoor environmental quality, location, materials use, environmental impacts, and contribution to ecological system health, to name but a few of the general categories that can be included in an assessment. To say that BREEAM is a success is a huge understatement because over 1 million buildings have been registered for certification and about 200,000 have successfully navigated the certification process. Canada and Hong Kong subsequently adopted BREEAM as the platform for their national building assessment systems, thus providing their building industries with an accepted approach to green construction. In the United States, the USGBC developed an American building rating system with the acronym LEED. When launched as a fully tested rating system in 2000, LEED rapidly dominated the market for third-party green building certification. Similar systems were developed in other major countries: for example, *CASBEE* (Comprehensive Assessment System for Building Environmental Efficiency) in Japan (2004) and *Green Star* in Australia (2006). In Germany, which has always had a strong tradition of high-performance buildings, the German Green Building Council and the German government collaborated in 2009 to develop a building assessment system known as *DGNB* (Deutsche Gesellschaft für Nachhaltiges Bauen), which is perhaps the most advanced evolution of building assessment systems. BREEAM, LEED, CASBEE, Green Star, and DGNB represent the cutting edge of today's high-performance green building assessment systems, both defining the concept of high performance and providing a scoring system to indicate the success of the project in meeting its sustainability objectives.

In the United States, the green building movement is often considered to be the most successful of all the American environmental movements. It serves as a template for engaging and mobilizing a wide variety of stakeholders to accomplish an important sustainability goal, in this case dramatically improving the efficiency, health, and performance of the built environment. The green building movement provides a model for other sectors of economic endeavor about how to create a consensus-based, market-driven approach that has rapid uptake, not to mention broad impact. This movement has become a force of its own and, as a result, is compelling professionals engaged in all phases of building design, construction, operation, financing, insurance, and public policy to fundamentally rethink the nature of the built environment.

In the second decade of the twenty-first century, circumstances have changed significantly since the onset of the sustainable construction movement. In 1990, the global population was 5.2 billion, climate change was just entering the public consciousness, the United States had just become the world's sole superpower, and Americans were paying just $1.12 for a gallon of gasoline. Fast-forwarding almost a quarter century, the world's population is approaching 7.4 billion, the effects of climate change are becoming evident at a pace far more rapid than predicted, the global economic system is still floundering from debt crises in Europe, and Japan is still recovering from the impacts of a tsunami and nuclear disaster. Prices for gasoline have fluctuated widely due to a recent abundance of oil produced by fracking but are about two times higher than in 1990. The convergence of financial crises, climate change, and increasing numbers of conflicts has produced an air of uncertainty that grips governments and institutions around the world. What is still not commonly recognized is that all of these problems are linked and that population and consumption remain the twin horns of the dilemma that confronts humanity. Population pressures, increased consumption by wealthier countries, the understandable desire for a good quality of life among the 5 billion impoverished people on the planet, and the depletion of finite, nonrenewable resources are all factors creating the wide range of environmental, social, and financial crises that are characteristic of contemporary life in the early twenty-first century (see Figure 1.2).

These changing conditions are affecting the built environment in significant ways. First, there is an increased demand for buildings that are resource-efficient, that use minimal energy and water, and whose material content will have value for future populations. In 2000, the typical office building in the United States consumed over 300 kilowatt-hours per square meter per year (kWh/m^2/yr) or 100,000 BTU/square foot/year (BTU/ft^2/yr). Today's high-performance buildings are approaching 100 kWh/m^2/yr (33,000 BTU/ft^2/yr).[2] In Germany, the energy profiles of high-performance buildings are even more remarkable, in the range of 50 kWh/m^2/yr

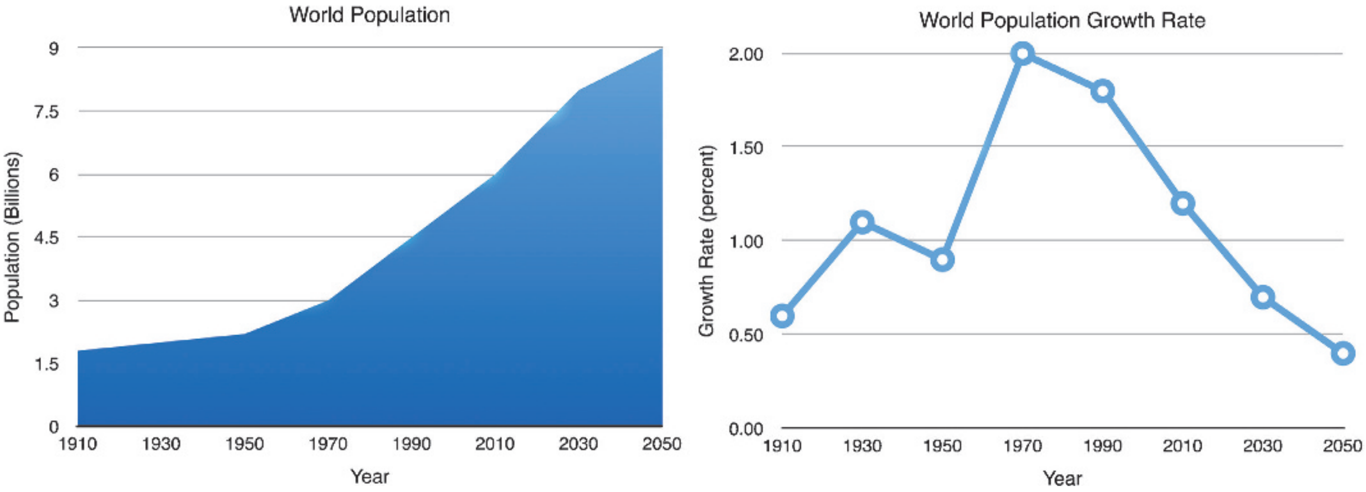

Figure 1.2 World population continues to increase, but the growth rate is declining, from about 1.2 percent in 2012 to a forecasted 0.5 percent in 2050. (*Source:* US Census Bureau, International Database, June 2011)

(17,000 BTU/ft^2/yr). It is important to recognize that reduced energy consumption generally causes a proportional reduction in climate change impacts. Reductions in water consumption in high-performance buildings are also noteworthy. A high-performance building in the United States can reduce potable water consumption by 50 percent simply by opting for the most water-efficient fixtures available, including high-efficiency toilets and high-efficiency urinals. By using alternative sources of water, such as rainwater and graywater, potable water consumption can be reduced by another 50 percent, to one-fourth that of a conventionally designed building water system. This is also referred to as a Factor 4 reduction in potable water use. Similarly impressive impact reductions are emerging in materials consumption and waste generation.

Second, it has become clear over time that building location is a key factor in reducing energy consumption because transportation energy can amount to two times the operational energy of the building (Wilson and Navaro 2007). Not only does this significant level of energy for commuting have environmental impacts, but it also represents a significant cost for the employees who make the daily commute. It is clear that the lower the building's energy consumption, the greater is the proportion of energy used in commuting. For example, a building that consumes 300 kWh/m^2/yr of operational energy and 200 kWh/m^2/yr of commuting energy by its occupants has 40 percent of its total energy devoted to transportation. A high-performance building in the same location with an energy profile of 100 kWh/m^2/yr and the same commuting energy of 200 kWh/m^2/yr would have 67 percent of its total energy consumed by transportation. Clearly, it makes sense to reduce transportation energy along with building energy consumption to have a significant impact on total energy consumption (see Figure 1.3).

Third, the threat of climate change is enormous and must be addressed across the entire life cycle of a building, including the energy invested in producing its materials and products and in constructing the building, commonly referred to as

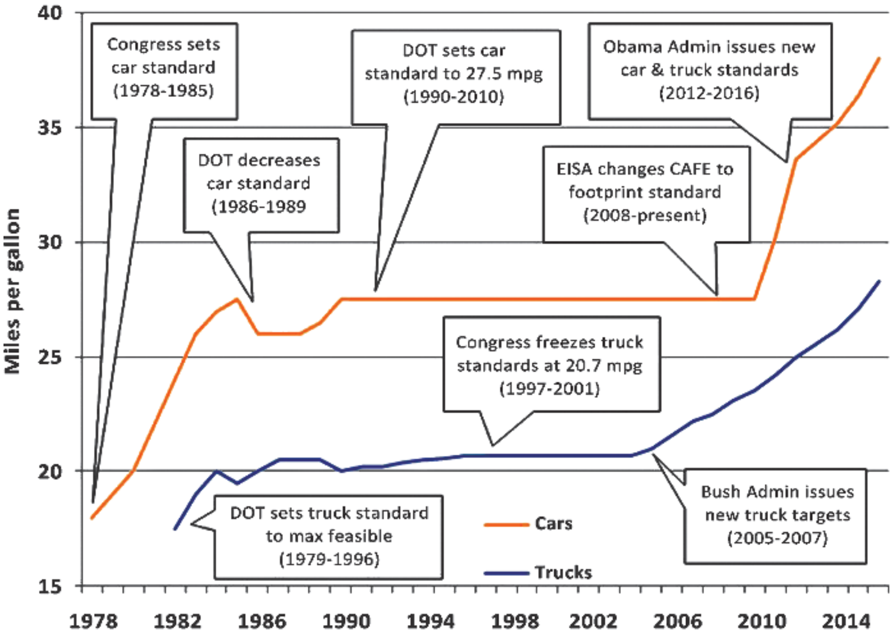

Figure 1.3 The fuel efficiency of US vehicles languished for decades before federal standards, due to the energy crises of the 1970s, demanded significant improvements in fuel performance. More recent requirements have increased dramatically the miles per gallon performance of both automobiles and trucks. (*Source:* Center for Climate and Energy Solutions)

embodied energy. The energy invested in building materials and construction is significant, amounting to as much as 20 percent of the total life cycle energy of the facility. Furthermore, significant additional energy is invested by maintenance and renovation activities during the building's life cycle, sometimes exceeding the embodied energy of the construction materials. Perhaps the most noteworthy effort to address the built environment contribution to climate change is the *Architecture 2030 Challenge* whose goal is to achieve a dramatic reduction in the greenhouse gas (GHG) emissions of the built environment by changing the way buildings and developments are planned, designed, and constructed.[3] The 2030 Challenge asks the global architecture and building community to adopt the following targets:

- All new buildings, developments and major renovations shall be designed to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 70 percent below the regional (or country) average/median for that building type.
- At a minimum, an equal amount of existing building area shall be renovated annually to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 70 percent of the regional (or country) average/median for that building type.
- The fossil fuel reduction standard for all new buildings and major renovations shall be increased to 80 percent in 2020, 90 percent in 2025, and be carbon-neutral in 2030 (using no fossil fuel energy to operate).[4]

The *2030 Challenge for Product* addresses the GHG emissions of building materials and products and sets a goal of reducing the maximum carbon-equivalent footprint to 35 percent below the product category average by 2015 and eventually to 50 percent below the product category average by 2030.

The emerging concept of NZE, which, in its simplest form, suggests that buildings generate as much energy from renewables as they consume on an annual basis, also supports the goals of the 2030 Challenge. Every unit of energy generated by renewables that displaces energy generated from fossil fuels results in less climate change impact. An NZE building would, in effect, have no climate change impacts due to its operational energy. It is clear that influencing energy consumption and climate change requires a comprehensive approach that addresses all forms of energy consumption, including operational energy, embodied energy, and commuting energy.

In summary, high-performance building projects are now addressing three emerging challenges: (1) the demand for high-efficiency or *hyperefficient* buildings, (2) consideration of building location to minimize transportation energy, and (3) the challenges of climate change. These challenges are in addition to issues such as indoor environmental quality, protection of ecosystems and biodiversity, and risks associated with building materials. Building assessment systems such as LEED are being affected by these changes as is the very definition of green buildings. As time advances and more is learned about the future and its challenges, the design, construction, and operation of the built environment will adapt to meet this changing future landscape.

Sustainable Development and Sustainable Construction

The main impetus behind the high-performance green building movement is the sustainable development paradigm, which is changing not only physical structures but also the workings of the companies and organizations that populate the built environment, as well as the hearts and minds of the individuals who inhabit it.[5] Fueled by examples of personal and corporate irresponsibility and negative publicity resulting from events such as the collapse of the international finance system that triggered the Great Recession of 2008–2010, increased public concern about the behavior of private and public institutions has developed. As a result, accountability and transparency are becoming the watchwords of today's corporate world. Heightened corporate consciousness has embraced comprehensive sustainability reporting as the new standard for corporate transparency. The term *corporate transparency* refers to complete openness of companies about all financial transactions and all decisions that affect their employees and the communities in which they operate. Major companies, such as DuPont, the Ford Motor Company, and Hewlett-Packard, now employ triple bottom line reporting,[6] which involves a corporate refocus from mere financial results to a more comprehensive standard that includes environmental and social impacts. By adopting the cornerstone principles of sustainability in their annual reporting, corporations acknowledge their environmental and social impacts and ensure improvement in all arenas.

Still, other major forces, such as climate change and the rapid depletion of the world's oil reserves, threaten national economies and the quality of life in developed countries. Both are connected to our dependence on fossil fuels, especially oil. Climate change, caused at least in part by increasing concentrations of human-generated carbon dioxide (CO_2), methane, and other gases in Earth's atmosphere, is believed by many authoritative scientific institutions and Nobel laureates to profoundly affect our future temperature regimes and weather patterns.[7] Much of today's built environment will still exist during the coming era of rising temperatures and sea levels; however, little consideration has been given to how human activity and building construction should adapt to potentially significant climate alterations. Global temperature increases now must be considered when forming assumptions about passive design, the building envelope, materials selection, and the types of equipment required to cope with higher atmospheric energy levels.

The state of the global economy and consumption continue to significantly affect the state of Earth's environment. The Chinese economy grew at an official rate of 7 percent in 2015 with some estimates that it will continue to grow at or above this pace over the next few years. China produced about 2 million automobiles in 2000, about 6 million in 2005, and 14 million in 2015. China's burgeoning industries are in heavy competition with the United States and other major economies for oil and other key resources, such as steel and cement. The rapid economic growth in China and India and concerns over the contribution of fossil fuel consumption to climate change will inevitably force the price of gasoline and other fossil fuel–derived energy sources to increase rapidly in the coming decades. At present, there are no foreseeable technological substitutes for large-scale replacement of fossil fuels. Alternatives such as hydrogen or fuels derived from coal and tar sands threaten to be prohibitively expensive. The expense of operating buildings that are heated and cooled using fuel oil and natural gas will likely increase, as will industrial, commercial, and personal transportation that is fossil fuel dependent. A shift toward hyperefficient buildings and transportation cannot begin soon enough.

The Vocabulary of Sustainable Development and Sustainable Construction

A unique vocabulary is emerging to describe concepts related to sustainability and global environmental changes. Terms such as *Factor 4* and *Factor 10*, *ecological footprint*, *ecological rucksack*, *biomimicry*, the *Natural Step*, *eco-efficiency*, *ecological economics*, *biophilia*, and the *precautionary principle* describe the overarching philosophical and scientific concepts that apply to a paradigm shift toward sustainability. Complementary terms, such as *green building*, *building assessment*, *ecological design*, *life-cycle assessment (LCA)*, *life-cycle costing (LCC)*, *high-performance building*, and *charrette*, articulate specific techniques in the assessment and application of principles of sustainability to the built environment.

The sustainable development movement has been evolving worldwide for almost 25 years, causing significant changes in building delivery systems in a relatively short period. Sustainable construction, a subset of sustainable development, addresses the role of the built environment in contributing to the overarching vision of sustainability. The key vocabulary of this relatively new movement is discussed in the following sections and in Chapter 2. Additionally, a glossary of key terms and an index of abbreviations is included at the end of this book.

SUSTAINABLE CONSTRUCTION

The terms *high performance*, *green*, and *sustainable construction* often are used interchangeably; however, the term *sustainable construction* most comprehensively addresses the ecological, social, and economic issues of a building in the context of its community. In 1994, Task Group 16 of the Conseil International du Bâtiment (CIB), an international construction research networking organization, defined sustainable construction as “creating and operating a healthy built environment based on resource efficiency and ecological design.”[8] Task Group 16 articulated seven Principles of Sustainable Construction that ideally would inform decision making during each phase of the design and construction process, continuing throughout the building’s entire life cycle (see Table 1.1; see also Kibert 1994). These factors also apply when evaluating the components and other resources needed for construction (see Figure 1.4). The Principles of Sustainable Construction apply across the entire life cycle of construction, from planning to disposal (here referred to as *deconstruction* rather than *demolition*). Furthermore, the principles apply to the resources needed to create and operate the built environment during its entire life cycle: land, materials, water, energy, and ecosystems.

TABLE 1.1

Principles of Sustainable Construction

1. Reduce resource consumption (reduce).
2. Reuse resources (reuse).
3. Use recyclable resources (recycle).
4. Protect nature (nature).
5. Eliminate toxics (toxics).
6. Apply life-cycle costing (economics).
7. Focus on quality (quality).

Source: Kibert (1994)

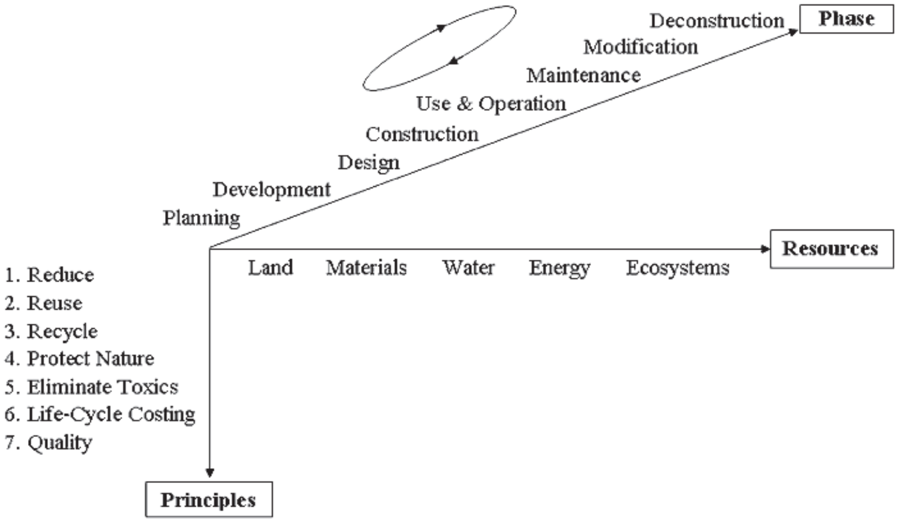

Figure 1.4 Framework for sustainable construction developed in 1994 by the CIB Task Group 16 (Sustainable Construction) for the purpose of articulating the potential contribution of the built environment to the attainment of sustainable development. (Illustration courtesy of Bilge Çelik)

GREEN BUILDING

The term *green building* refers to the quality and characteristics of the actual structure created using the principles and methodologies of sustainable construction. Green buildings can be defined as "healthy facilities designed and built in a resource-efficient manner, using ecologically based principles" (Kibert 1994) Similarly, *ecological design*, *ecologically sustainable design*, and *green design* are terms that describe the application of sustainability principles to building design. Despite the prevalent use of these terms, truly sustainable green commercial buildings with renewable energy systems, closed materials loops, and full integration into the landscape are rare to nonexistent. Most existing green buildings feature incremental improvement over, rather than radical departure from, traditional construction methods. Nonetheless, this process of trial and error, along with the gradual incorporation of sustainability principles, continues to advance the industry's evolution toward the ultimate goal of achieving complete sustainability throughout all phases of the built environment's life cycle.

HIGH-PERFORMANCE BUILDINGS, SYSTEMS THINKING, AND WHOLE-BUILDING DESIGN

The term *high-performance building* recently has become popular as a synonym for green building in the United States. According to the Office of Energy Efficiency and Renewable Energy of the US Department of Energy, a high-performance commercial building "uses whole-building design to achieve energy, economic, and environmental performance that is substantially better than standard practice." This approach requires that the design team fully collaborate from the project's inception in a process often referred to as *integrated design*.

Whole-building design,[9] or integrated design, considers site, energy, materials, indoor air quality, acoustics, and natural resources as well as their interrelation with one another. In this process, a collaborative team of architects, engineers, building occupants, owners, and specialists in indoor air quality, materials, and energy and water efficiency uses systems thinking to consider the building structure and systems holistically, examining how they best work together to save energy and reduce the environmental impact. A common example of systems thinking is advanced daylighting strategy, which reduces the use of lighting fixtures during daylight, thereby decreasing daytime peak cooling loads and justifying a reduction in the size of the mechanical cooling system. This, in turn, results in reduced capital outlay and lower energy costs over the building's life cycle.

According to the Rocky Mountain Institute (RMI), a well-respected nonprofit organization specializing in energy and building issues, whole-systems thinking is a process through which the interconnections between systems are actively considered and solutions are sought that address multiple problems. Whole-systems thinking often is promoted as a cost-saving technique that allows additional capital to be invested in new building technology or systems. RMI cites developer Michael Corbett, who applied just such a concept in his 240-unit Village Homes subdivision in Davis, California, completed in 1981. Village Homes was one of the first modern-era developments to create an environmentally sensitive, human-scale residential community. The result of designing narrower streets was reduced stormwater runoff. Simple infiltration swales and on-site detention basins handled stormwater without the need for conventional stormwater infrastructure. The resulting $200,000 in savings was used to construct public parks, walkways, gardens, and other amenities that improved the quality of the community. Another example of systems thinking is Solaire, a 27-story luxury residential tower in New York City's Battery Park (see Figure 1.5) that, when completed in 2003, was the first green high-rise residential building in the United States. The façade of Solaire contains

Figure 1.5 Solaire, a 27-story residential tower on the Hudson River in New York City built in 2003, was the first high-rise residential building in the United States specifically designed to be environmentally responsible. (Photograph courtesy of the Albanese Development Corporation)

PV cells that convert sunlight directly into electricity, and the building itself uses 35 percent less energy than a comparable residential building. Solaire provides its residents with abundant natural light and excellent indoor air quality. The building collects rainwater in a basement tank for watering roof gardens. Wastewater is processed for reuse in the air-conditioning system's cooling towers or for flushing toilets. The roof gardens not only provide a beautiful urban landscape but also assist in insulating the building to reduce heating and cooling loads. This interconnection of many of the green building measures in Solaire indicates that the project team carefully selected approaches that would have multiple layers of benefit, the core of systems thinking.[10]

Sustainable Design, Ecological Design, and Green Design

The issue of resource-conscious design is central to sustainable construction, which ultimately aims to minimize natural resource consumption and the resulting impact on ecological systems. Sustainable construction considers the role and potential interface with ecosystems to provide services in a synergistic fashion. With respect to materials selection, closing materials loops and eliminating solid, liquid, and gaseous emissions are key sustainability objectives. *Closed loop* describes a process of keeping materials in productive use by reuse and recycling rather than disposing of them as waste at the end of the product or building life cycle. Products in closed loops are easily disassembled, and the constituent materials are able to be recycled and worthy of recycling. Because recycling is not entirely thermodynamically efficient, dissipation of residue into the biosphere is inevitable. Thus, the recycled materials must be inherently nontoxic to biological systems. Most common construction materials are not completely recyclable but rather are *downcyclable* for lower-value reuse, such as for fill or road subbase. Fortunately, aggregates, concrete, fill dirt, block, brick, mortar, tiles, terrazzo, and similar low-technology materials are composed of inert substances with low ecological toxicity. In the United States, the 160 million tons (145 million metric tons [mt]) of construction and demolition waste produced annually make up about one-third of the total solid waste stream, consuming scarce landfill space, threatening water supplies, and driving up the costs of construction. As part of the green building delivery system, manufactured products are evaluated for their life-cycle impacts, to include energy consumption and emissions during resource extraction, transportation, product manufacturing, and installation during construction; operational impacts; and the effects of disposal.

LAND RESOURCES

Sustainable land use is based on the principle that land, particularly undeveloped, natural, or agricultural land (greenfields), is a precious finite resource and its development should be minimized. Effective planning is essential for creating efficient urban forms and minimizing urban sprawl, which leads to overdependence on automobiles for transportation, excessive fossil fuel consumption, and higher pollution levels. Like other resources, land is recyclable and should be restored to productive use whenever possible. Recycling disturbed land such as former industrial zones (brownfields) and blighted urban areas (grayfields) back to productive use facilitates land conservation and promotes economic and social revitalization in distressed areas.

ENERGY AND ATMOSPHERE

Energy conservation is best addressed through effective building design, which integrates three general approaches: (1) fully implementing passive design, (2) designing a building envelope that is highly resistant to conductive, convective, and radiative heat transfer, and (3) employing renewable energy resources. Passive design employs the building's geometry, orientation, and mass to condition the structure using natural and climatologic features, such as the site's solar *insolation* (or incoming solar radiation), thermal chimney effects, prevailing winds, local topography, microclimate, and landscaping. Since buildings in the United States consume 40 percent of domestic primary energy,[11] increased energy efficiency and a shift to renewable energy sources can appreciably reduce CO_2 emissions and mitigate climate change.

WATER ISSUES

The availability of potable water is the limiting factor for development and construction in many areas of the world. In the high-growth Sun Belt and western regions of the United States, the demand for water threatens to rapidly outstrip the natural supply, even in normal, drought-free conditions.[12] California is experiencing an epic drought that threatens not only the most agriculturally productive region of the world but also the economy of the state and perhaps the United States. Climate alterations and erratic weather patterns precipitated by global warming threaten to further limit the availability of this most precious resource. Since only a small portion of Earth's hydrologic cycle yields potable water, protection of existing groundwater and surface water supplies is increasingly critical. Once water is contaminated, it is extremely difficult, if not impossible, to reverse the damage. Water conservation techniques include the use of low-flow plumbing fixtures, water recycling, rainwater harvesting, and xeriscaping, a landscaping method that utilizes drought- resistant plants and resource-conserving techniques.[13] Innovative approaches to wastewater processing and stormwater management are also necessary to address the full scope of the building hydrologic cycle.

ECOSYSTEMS: THE FORGOTTEN RESOURCE

Sustainable construction considers the role and potential interface of ecosystems in providing services in a synergistic fashion. Integration of ecosystems with the built environment can play an important role in resource-conscious design. Such integration can supplant conventional manufactured systems and complex technologies in controlling external building loads, processing waste, absorbing stormwater, growing food, and providing natural beauty, sometimes referred to as *environmental amenity*. For example, the Lewis Center for Environmental Studies at Oberlin College in Oberlin, Ohio, uses a built-in natural system, referred to as a "Living Machine," to break down waste from the building's occupants; the effluent then flows into a reconstructed wetland (see Figure 1.6). The wetland also functions as a stormwater retention system, allowing pulses of stormwater to be stored and thereby reducing the burden on stormwater infrastructure. The restored wetland also provides environmental amenity in the form of native Ohio plants and wildlife.[14]

Figure 1.6 The Lewis Center for Environmental Studies at Oberlin College in Oberlin, Ohio, was designed by a team led by William McDonough, a leading green building architect, and including John Todd, developer of the Living Machine. In addition to the superb design of the building's hydrologic strategy, the extensive PV system makes it an NZE building. (Photograph courtesy of Oberlin College)

Rationale for High-Performance Green Buildings

High-performance green buildings marry the best features of conventional construction methods with emerging high-performance approaches. Green buildings are achieving rapid penetration in the US construction market for three primary reasons:

1. *Sustainable construction provides an ethical and practical response to issues of environmental impact and resource consumption.* Sustainability assumptions encompass the entire life cycle of the building and its constituent components, from resource extraction through disposal at the end of the useful life of the materials. Conditions and processes in factories are considered, along with the actual performance of their manufactured products in the completed building. High-performance green building design relies on renewable resources for energy systems; recycling and reuse of water and materials; integration of native and adapted species for landscaping; passive heating, cooling, and ventilation; and other approaches that minimize environmental impact and resource consumption.
2. *Green buildings virtually always make economic sense on an LCC basis, although they may be more expensive on a capital, or first-cost, basis.* Sophisticated energy-conserving lighting and air- conditioning systems with an exceptional response to interior and exterior climates will cost more than their conventional, code-compliant counterparts. Rainwater harvesting systems that collect and store rainwater for nonpotable uses will require additional piping, pumps, controls, storage tanks, and filtration components. However, most key green building systems will recoup their original investment within a relatively short time. As energy and water prices rise due to increasing demand and diminishing supply, the payback period will decrease (Kats 2003).[15]
3. *Sustainable design acknowledges the potential effect of the building, including its operation, on the health of its human occupants.* A 2012 report from the Global Indoor Health Network suggested that, globally, about 50 percent of all illnesses are caused by indoor air pollution.[16] Estimates peg the direct and indirect costs of building-related illnesses (BRIs), including lost worker productivity, as exceeding $150 billion per year (Zabarsky 2002). Conventional construction methods have traditionally paid little attention to sick building syndrome BRI, and multiple chemical sensitivity until prompted by lawsuits. In contrast, green buildings are designed to promote occupant health; they include measures such as protecting ductwork during installation to avoid contamination during construction; specifying finishes with low to zero volatile organic compounds to prevent potentially hazardous chemical off-gassing; more precise sizing of heating and cooling components to promote dehumidification, thereby reducing mold; and the use of ultraviolet radiation to kill mold and bacteria in ventilation systems.[17]

State and Local Guidelines for High-Performance Construction

At the onset of the green building movement, several state and local governments took the initiative in articulating guidelines aimed at facilitating high-performance construction. The Pennsylvania Governor's Green Government Council (GGGC) used mixed

TABLE 1.2

High-Performance Green Building as Defined by the Pennsylvania GGGC
A project created via cooperation among building owners, facility managers, users, designers, and construction professionals through a collaborative team approach.
A project that engages the local and regional communities in all stages of the process, including design, construction, and occupancy.
A project that conceptualizes a number of systems that, when integrated, can bring efficiencies to mechanical operation and human performance.
A project that considers the true costs of a building's impact on the local and regional environment.
A project that considers the life-cycle costs of a product or system. These are costs associated with its manufacture, operation, maintenance, and disposal.
A building that creates opportunities for interaction with the natural environment and defers to contextual issues such as climate, orientation, and other influences.
A building that uses resources efficiently and maximizes use of local building materials.
A project that minimizes demolition and construction wastes and uses products that minimize waste in their production or disposal.
A building that is energy- and resource-efficient.
A building that can be easily reconfigured and reused.
A building with healthy indoor environments.
A project that uses appropriate technologies, including natural and low-tech products and systems, before applying complex or resource-intensive solutions.
A building that includes an environmentally sound operations and maintenance regimen.
A project that educates building occupants and users to the philosophies, strategies, and controls included in the design, construction, and maintenance of the project.

Source: Pennsylvania GGGC (1999).

but very appropriate terminology in its "Guidelines for Creating High-Performance Green Buildings." The lengthy but instructive definition of high-performance green building (see Table 1.2) focused as much on the collaborative involvement of the stakeholders as it did on the physical specifications of the structure itself.

Similar guidance was provided by the New York City Department of Design and Construction in its "High Performance Building Guidelines," in which the end product, the building, is hardly mentioned, and the emphasis is on the strong collaboration of the participants (see Table 1.3).

The "High Performance Guidelines: Triangle Region Public Facilities," published by the Triangle J Council of Governments in North Carolina in 2001, focused on three principles:

1. *Sustainability*, which is a long-term view that balances economics, equity, and environmental impacts
2. *An integrated approach*, which engages a multidisciplinary team at the outset of a project to work collaboratively throughout the process
3. *Feedback and data collection*, which quantifies both the finished facility and the process that created it and serves to generate improvements in future projects.

Like the other state and local guidelines, North Carolina's "High Performance Guidelines" emphasized the collaboration and process, rather than merely the physical characteristics of the completed building. Historically, building owners assumed that they were benefiting from this integrated approach as a matter of course. In

TABLE 1.3

Goals for High-Performance Buildings According to the New York City Department of Design and Construction
Raise expectations for the facility's performance among the various participants.
Ensure that capital budgeting design and construction practices result in investments that make economic and environmental sense.
Mainstream these improved practices through (1) comprehensive pilot high-performance building efforts and (2) incremental use of individual high-performance strategies on projects of limited scope.
Create partnerships in the design and construction process around environmental and economic performance goals.
Save taxpayers money through reduced energy and material expenditures, waste disposal costs, and utility bills.
Improve the comfort, health, and well-being of building occupants and public visitors.
Design buildings with improved performance, which can be operated and maintained within the limits of existing resources.
Stimulate markets for sustainable technologies and products.

Source: Excerpted from "High Performance Building Guidelines" (1999).

practice, however, the lack of coordination among design professionals and their consultants often resulted in facilities that were problematic to build. Now the green building movement has begun to emphasize that strong coordination and collaboration is the true foundation of a high-quality building. This philosophy promises to influence the entire building industry and, ultimately, to enhance confidence in the design and construction professions.

Green Building Progress and Obstacles

Until recently considered a fringe movement, in the early twenty-first century, the green building concept has won industry acceptance, and it continues to influence building design, construction, operation, real estate development, and sales markets. Detailed knowledge of the options and procedures involved in "building green" is invaluable for any organization providing or procuring design or construction services. The number of commercial buildings registered with the USGBC for a LEED building assessment grew from just a few in 1999 to more than 6,000 registered and certified in late 2006. By 2015, the number of registered buildings had grown to over 69,000, and a total of over 27,000 buildings had been certified. The area of LEED certified buildings increased from a few thousand square feet in 1999 to 3.6 billion square feet (375 million m^2) in 2015 for commercial buildings alone. Federal and state governments, many cities, several universities, and a growing number of private-sector construction owners have declared sustainable or green materials and methods as their standard for procurement.

Despite the success of LEED and the US green building movement in general, challenges abound when implementing sustainability principles within the well-entrenched traditional construction industry. Although proponents of green buildings have argued that whole-systems thinking must underlie the design phase of this new class of buildings, conventional building design and procurement processes are very difficult to change on a large scale. Additional impediments also may apply. For example, most jurisdictions do not yet permit the elimination of stormwater infrastructure in favor of using natural systems for stormwater control. Daylighting systems do not eliminate the need for a full lighting system, since buildings generally must operate at night. Special low-emissivity (low-E) window glazing, skylights, light shelves, and other devices increase project cost. Controls that adjust lighting to compensate for varying amounts of available daylight, and occupancy sensors that turn lights on and off depending on occupancy, add additional expense and complexity. Rainwater harvesting systems require dedicated piping, a storage tank or cistern, controls, pumps, and valves, all of which add cost and complexity.

Green building materials often cost substantially more than the materials they replace. Compressed wheatboard, a green substitute for plywood, can cost as much as four times more than the plywood it replaces. The additional costs, and those associated with green building compliance and certification, often require owners to add a separate line item to the project budget. The danger is that, during the course of construction management, when costs must be brought under control, the sustainability line item is one of the first to be “value-engineered” out of the project. To avoid this result, it is essential that the project team and the building owner clearly understand that sustainability goals and principles are paramount and that LCC should be the applicable standard when evaluating a system’s true cost. Yet even LCC does not guarantee that certain measures will be cost-effective in the short or long term. Where water is artificially cheap, systems that use rainwater or graywater are difficult to justify financially, even under the most favorable assumptions. Finally, more expensive environmentally friendly materials may never pay for themselves in an LCC sense.

A summary of trends in, and barriers to, green building is presented in Table 1.4. They were generated by the Green Building Roundtable, a forum held by the USGBC for members of the US Senate Committee on Environment and Public Works in April 2002, and most still apply today.

TABLE 1.4

Trends and Barriers to Green Building in the United States

Trends

1. Rapid penetration of the LEED green building rating system and growth of USGBC membership
2. Strong federal leadership
3. Public and private incentives
4. Expansion of state and local green building programs
5. Industry professionals taking action to educate members and integrate best practices
6. Corporate America capitalizing on green building benefits
7. Advances in green building technology

Barriers

1. Financial disincentives
    - a. Lack of LCC analysis and use
    - b. Real and perceived higher first costs
    - c. Budget separation between capital and operating costs
    - d. Security and sustainability perceived as trade-offs
    - e. Inadequate funding for public school facilities
2. Insufficient research
    - a. Inadequate research funding
    - b. Insufficient research on indoor environments, productivity, and health
    - c. Multiple research jurisdictions

Source: Adapted from US Green Building Council. 2003. *Building Momentum: National Trends and Prospects for High-Performance Green Buildings*. Available at www.usgbc.org/Docs/Resources/ 043003_hpgb_whitepaper.pdf.

Trends in High-Performance Green Building

Even though the high-performance green building movement is relatively new, there have already been several shifts in direction as more is learned about the wider impacts of building and the accelerating effects of climate change. Fifteen years ago at the onset of this revolution, the use of the charrette was a relatively new concept, as were integrated design, building commissioning, the design- build delivery system, and performance-based fees. All of these are now familiar green building themes, and building industry professionals are familiar with their potential application.

Much has changed in a short span of time. Since 2008, energy prices have been erratic. Hydraulic fracturing (fracking) produced a rapid increase in oil and gas supplies in the United States. The result was equally rapid falling energy prices, which are causing havoc in the markets for renewable energy. Renewable energy had just become competitive with fossil fuel–based energy when the trend toward lower supplies of fossil fuel energy suddenly was reversed. However, the most significant environmental problem of our time, climate change, will only be exacerbated by short-term cheap energy. Within several decades, the world will be again faced with high energy prices plus the enormous and widespread impacts of climate change. This is a critical issue for green building, and thus the trend to NZE and net-zero-carbon buildings that rely on extremely high energy and very high energy performance.

Another major shift is the demand for and increased attention to transparency for the products that constitute the built environment. A wide range of new tools have become available, such as environmental product declarations (EPDs), health product declarations (HPDs), risk-based assessments (RBAs), and multiattribute standards. This is yet another indicator of the widening influence of the green building movement on the upstream activities of manufacturers and suppliers of built environment products.

New technologies, such as high-efficiency PV systems and building information modeling (BIM), are affecting approaches to project design and collaboration. Evidence is mounting that climate change is occurring significantly faster than even the most pessimistic models predicted. Some fundamental thinking about green building assessment has changed, and there is significant impetus toward integrating LCA far more deeply into project evaluation. The impacts of building location are being taken into account since it has become apparent that the energy and carbon associated with transportation is approaching the levels resulting from construction and operation of the built environment. The next sections address these emerging trends in more detail and provide some insights into how they are affecting high-performance green buildings.

TRANSPARENCY

The term *transparency*, when associated with the green building movement, is concerned with the open provision of information about: (1) building energy and water performance and (2) the impacts of the materials and products that compose the building. Building product transparency requires that manufacturers reveal product ingredients so that project teams will have information that allows them to decide if there are any potential toxicity problems with the chemicals that compose the product. Nonprofit organizations and industry associations are creating numerous tools designed to meet the demand of this relatively new movement. The trend toward product transparency and full disclosure is part of a larger trend in corporate sustainability in which large companies such as Walmart and Target are requiring their suppliers to disclose ingredients and to phase out certain chemicals of concern in their consumer products. HPDs, which became relatively mainstream tools in 2012, are one approach to addressing the demand for transparency. An HPD reports the materials or ingredients contents of a building product and the associated health effects. The content of this report and its format is governed by the HPD Open Standard^{TM}. HPDs have a standard format to allow users to become familiar with the location of key elements of information. It is voluntary and can be used by manufacturers to disclose information about product ingredients that they judge would be useful to the market. The HPD is designed to be flexible and allows manufacturers to deal with issues of intellectual property or supply chain communication gaps by letting them characterize the level of disclosure they able to achieve. In short this means that the HPD does not force the manufacturer to disclose proprietary or competitive trade information.

A complementary tool connected to transparency is the EPD. Whereas HPDs are designed to disclose human health impacts, EPDs provide detailed information on the environmental impacts of products. EPDs are third-party LCAs using a methodology spelled out in the international standards, ISO 14025. Similar to HPDs, EPDs have a standard format that makes them fairly easy to use by project teams or other stakeholders. Some of the impacts reported via EPDs include global warming potential, ozone depletion potential, and eutrophication. Although these tools provide enormous amounts of information about products, their actual utility is still being debated. The nub of the debate is about whether these products can be used to judge which products are best from a health and environmental standpoint and whether project teams have the knowledge and resources to utilize these tools effectively. HPDs generally are categorized as *hazard-based* tools because they use a hazard list to scan product chemicals for potential issues. An alternative to hazard-based approaches is RBA; such assessments include in the analysis standard toxicological approaches involving dose and exposure scenarios.

The other type of transparency that is rapidly emerging is building performance information. In the United States, large cities are leading the drive to make energy and water consumption data for all buildings openly available. In general, these cities require not only disclosure of the performance data but also require efforts to reduce energy consumption. On Earth Day 2009, Mayor Michael Bloomberg announced New York City's Greener, Greater Buildings Plan (GGBP), which requires the benchmarking and public disclosure of building energy performance and water consumption; periodic energy audits and building tune-ups known as *retro-commissioning*; lighting upgrades; submetering of large tenant spaces; and improvements to the city's building energy code. Roughly 80 percent of New York City's carbon footprint is connected to building operations, and the GGBP is designed to reduce the city's GHG emissions 30 percent by 2030.

In April 2015, Atlanta, Georgia, became the first southern city to pass legislation requiring the collection and reporting of energy use data in the city's commercial buildings. In Atlanta, the goal is a 20 percent reduction in energy consumption by commercial buildings by 2030, creation of more than 1,000 jobs annually for the first few years, and cutting carbon emissions in half from 2013 levels by 2030. The Atlanta Commercial Buildings Energy Efficiency Ordinance also encourages periodic energy audits and improvements to existing building equipment and functions (i.e., retro-commissioning).

A more extensive discussion of building product transparency can be found in Chapter 11; additional insights into energy reporting are included in Chapter 9.

CARBON ACCOUNTING

By virtually all accounts, climate change seems to be accelerating and lining up with the worst-case scenarios hypothesized by scientists. One unexpected event that is rapidly increasing levels of atmospheric CO_2, the primary cause of climate change, is drought, which causes, among other things, the death of rainforest trees. Researchers calculate that millions of trees died in 2010 in the Amazon due to what has been referred to as a 100-year drought. The result is that the Amazon is soaking up much less CO_2 from the atmosphere, and the dead trees are releasing all the carbon they accumulated over 300 or more years. The widespread 2010 drought followed a similar drought in 2005 (another 100-year drought), which itself put an additional 5.5 billion tons (5 billion mt) of CO_2 into the atmosphere (see Lewis et al. 2011). In comparison, the United States, the world's second largest producer of CO_2 behind China, emitted 6.0 billion tons (5.4 billion mt) of CO_2 from fossil fuel use in 2009. The two droughts added an estimated 14.3 billion tons (13 billion mt) to atmospheric carbon and likely accelerated global warming.

In the last major report by the Intergovernmental Panel on Climate Change in 2007, estimated sea level rises were just 7–23 inches (18–45 centimeters) by 2100. However, a mere four years later, a 2011 study presented by the International Arctic Monitoring and Assessment Program found that feedback loops are already accelerating warming in the Far North, which will rapidly increase the rate of ice melt. As a result, the panel now estimates that sea levels could rise by as much as 5.2 feet (1.7 m) by the end of the century. The only conclusion that can be reached by observing the many positive feedback loops influencing climate change is that all indicators point to a much higher rate of change than had been predicted.

The result of these alarming changes is that releases of CO_2 into the atmosphere are becoming an increasingly serious issue. Governments around the world are making plans to reduce carbon emissions, which entails tracking or accounting for carbon in order to limit its production. The built environment, with enormous quantities of *embodied energy*[18] and associated operational and transportation energy, is a ripe target for gaining control of global carbon emissions. It is likely that projects that can demonstrate significant reductions in total carbon emissions will be far better received than those with relatively high carbon footprints, which could conceivably be banned. New concepts, such as *low-carbon, carbon-neutral*, and *zero-carbon buildings*, are emerging in an effort to begin coping with the huge quantities of carbon emissions associated with the built environment. On the order of 40 percent of all carbon emissions are associated with building construction and operation, and it is likely that as much as another 20 percent could be attributable to transportation. Perhaps nowhere in the world has there been more interest and progress in low-carbon building than in the United Kingdom. The Carbon Trust was established by the government as a nonprofit company to take the lead in stimulating low-carbon actions, contributing to UK goals for lower carbon emissions, the development of low-carbon businesses, and increased energy security and associated jobs, with a vision of a low-carbon, competitive economy. We can expect to see control of carbon emissions and other measures to mitigate their impacts becoming an ever more prominent feature of high-performance green buildings. Chapter 12 provides details on how to account for the carbon footprint of the built environment.

NET-ZERO BUILDINGS

In the early 1990s, William McDonough, the noted American green building architect and thinker, suggested that buildings should, among other things, “live off current solar income”. Today, what seemed a rash prediction is becoming reality as the combination of high-performance buildings and high-efficiency, low-cost renewable energy technologies are providing the potential for buildings that, in fact, can live off current solar income. These are commonly referred to as NZE buildings. In general, these are grid-connected buildings that export excess energy produced during the day and import energy in the evenings, such that there is an energy balance over the course of the year. As a result, NZE buildings have a zero annual energy bill. The added bonus is that they are considered carbon neutral with respect to their operational energy.

An excellent example of an NZE building is the research support facility (RSF) designed and built for the National Renewable Energy Laboratory (NREL) in Golden, Colorado. The RSF, completed in 2011, is a 220,000-square-foot (20,450-m^2), four-story building with a PV system on-site. It is interesting to note that a 2007 NREL study concluded that one-story buildings could achieve NZE if the building roof alone were used for the PV system but that it would be extremely difficult for two-story buildings to meet this goal (Griffith et al. 2007). Clearly, much has been learned in a short time because the RSF has four stories, twice the limit suggested by NREL's own research. The Energy Use Intensity (EUI) of the RSF is just 32,000 BTU/ft^2/yr (101 kWh/m^2/yr), making it a very low energy building with the potential for producing enough PV energy to meet all its annual energy needs (see Figure 1.7A–D). The relatively narrow building floor plate, just 60 feet (19.4 m) wide, enables daylighting

Figure 1.7 (A) The NREL Research Support Facility in Golden, Colorado, is a four-story NZE building that combines low-energy design with high-efficiency photovoltaics to produce all the energy it requires over the course of a year. (*Source:* National Renewable Energy Laboratory)

Figure 1.7 (B) Ground view of the air intake structure that conducts outside air into the thermal storage labyrinth in the crawl space of the NREL RSF. (*Source:* National Renewable Energy Laboratory)

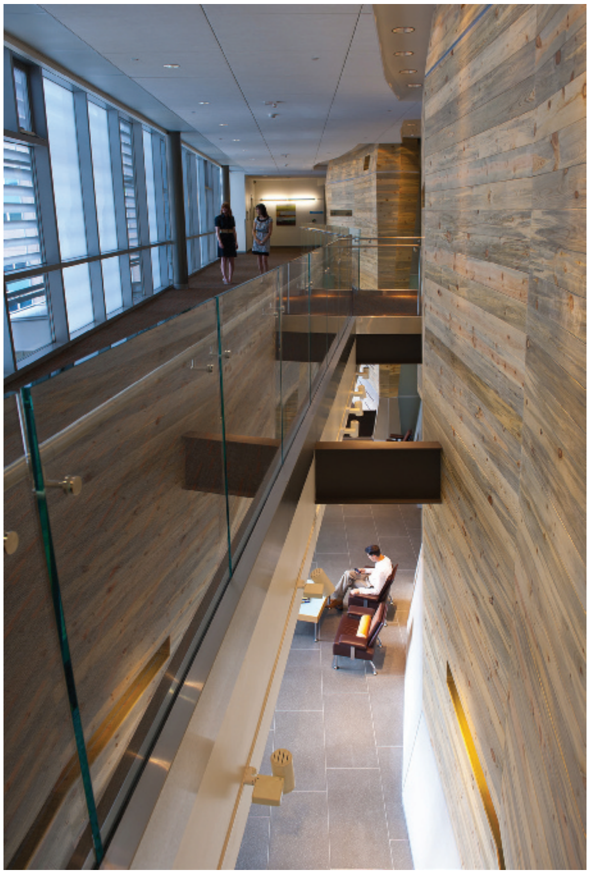

Figure 1.7 (C) The daylighting system for the NREL RSF was designed using extensive simulation. Shading devices were carefully placed on the exterior and interior to manage both direct and indirect sunlight, distributing it evenly to create a bright, pleasant working environment. (*Source:* National Renewable Energy Laboratory)

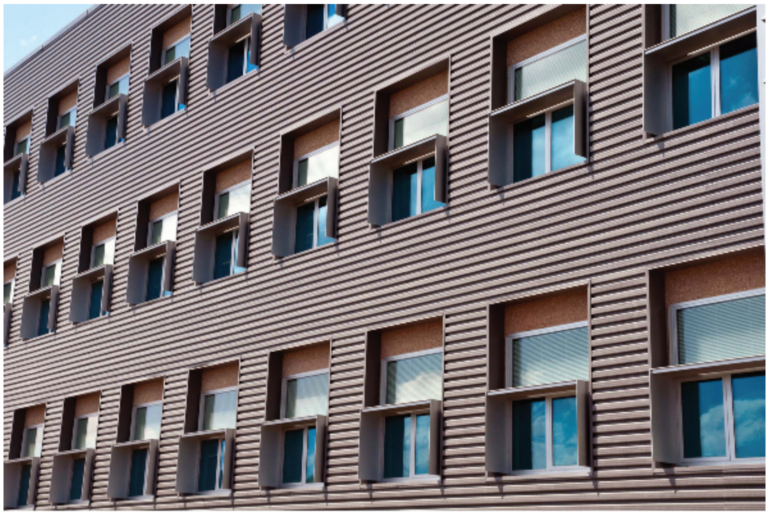

Figure 1.7 (D) The fenestration for the NREL RSF was designed to provide excellent daylighting while controlling glare and unwanted solar thermal gain through the use of shading devices, recessed windows, and electrochromic glass. Operable windows allow the occupants to control their thermal comfort and obtain fresh air. (*Source:* National Renewable Energy Laboratory)

and natural ventilation for its 800 occupants, and 100 percent of the workstations are daylit. Building orientation and geometry minimize the need for east and west glazing. North and south glazing is optimally sized and shaded to provide daylighting while minimizing unwanted heat losses and gains. The building uses triple-glazed operable windows and window shading to address different orientations and positioning of its glazed openings. The operable windows can be used by the occupants to provide natural ventilation and cooling for the building. Electrochromic windows, which can be darkened using a small amount of electrical current, are used on the west side of the building to control glare and heat gain. The RSF has approximately 42 miles (67 kilometers) of radiant piping embedded in all floors of the building to provide water for radiant cooling and heating the majority of the work spaces. This radiant system provides thermal conditioning for the building at a fraction of the energy costs of the forced-air systems used in most office buildings. A thermal storage labyrinth under the RSF stores heating and cooling in its concrete structure and is integrated into the building energy recovery system. Outdoor air is heated by a transpired solar collector system located on the façade of the structure. Approximately 1.6 MW of on-site PVs are being installed and dedicated to RSF use. Rooftop PV power will be added through a power purchase agreement, and PV power from adjacent parking areas will be purchased by the building through arrangement with a local utility. The RSF was awarded a LEED platinum rating in recognition of the success of its integrated design and the holistic approach of the project team.

The implementation of NZE is now national policy, and the US Department of Energy has programs in place with the objective that all new buildings will be NZE by 2050. In some local jurisdictions, such as Austin, Texas, new homes are required to be NZE by 2015. The ASHRAE-proposed building energy label, known as Energy Quotient, reserves its highest rating for NZE buildings. This important new trend appears to have significant momentum and will influence the direction of green building evolution.

BUILDING INFORMATION MODELING

The emergence of BIM as a design and visualization tool is an important trend for the building industry. Its three-dimensional modeling promises to provide owners with a far better representation of their projects, increase the quality of both design and construction, and increase the speed of construction. BIM makes the handling of complex projects with enormous information requirements far easier. One of the attributes of high-performance green building projects is their reliance on significant additional modeling, additional specification requirements, and the need to track numerous aspects of the construction process, such as construction waste management, indoor air quality protection during construction, and erosion and sedimentation control. Additionally, quantities of recycled materials, emissions from materials, and other data must be gathered for green building certification. BIM has the capability of accepting plug-ins that can perform energy modeling and daylighting simulation and provide a platform for the data required by green building certification bodies. BIM software makes it relatively easy to select the optimum site and building orientation to maximize renewable energy generation and daylighting and minimize energy consumption. BIM is an important and potentially powerful tool that can further increase the uptake of green buildings by lowering costs. Although not strictly relevant to green building certification, it makes the process far easier and less costly by providing "one-stop shopping" for information.

LIFE-CYCLE ASSESSMENT

Although a mature concept, LCA is growing in importance because it allows the quantification of the environmental impacts of design decisions that span the entire life of the project. In the past, LCA was used to compare products and building assemblies, which provided some indication of how to improve decision making but did not provide information about the long-term effects resulting from building operation. With the emergence of the German DGNB building assessment system, the environmental performance of the whole building—its materials, construction, operation, disposal, and transportation impacts—can be quantified and compared to baselines that have been compiled to allow comparisons. Designers can quickly consider a wide variety of alternative building systems, materials, and sites and compare them to the norms for the type of building being considered. For example, the global warming and ozone depletion potentials for various alternatives per unit of building area can be compared to find the least damaging outcome. The Australian Green Star building assessment system considers energy not in energy units but in CO_2 equivalents to focus on the impact of climate change. LCA affords the design team the capability of quickly evaluating their energy strategies to find one that improves on the baselines established for carbon or other parameters. In North America, LCA is rewarded to some extent in the Green Globes rating system. It is part of ANSI/GBI 01-2016, Green Building Assessment Protocol for Commercial Buildings, a standard based on the Green Globes rating system and promulgated by ANSI and the GBI. LCA was also included as a pilot credit in the LEED system, and it appears in the latest version. The state of California also included LCA as a voluntary measure in its 2010 draft Green Building Standards Code. In the future, as governments struggle to cope with reducing GHG emissions because the effects of climate change are causing economic problems and social dislocations, it is likely that LCA will become a mandatory area of evaluation for building design.

Book Organization

This book describes the high-performance green building delivery system, a rapidly emerging building delivery system that satisfies the owner while addressing sustainability considerations of economic, environmental, and social impact, from design through the end of the building's life cycle. A building delivery system is the process used by building owners to ensure that a facility meeting their specific needs is designed, built, and handed over for operation in a cost-effective manner. This book examines the design and construction of state-of-the-art green buildings in the United States, considering the nation's unique design and building traditions, products, services, building codes, and other characteristics. Best practices, technologies, and approaches of other countries are used to illustrate alternative techniques. Although intended primarily for a US audience, the general approaches described could apply broadly to green building efforts worldwide.

Much more so than in conventional construction delivery systems, the high-performance green building delivery system requires close collaboration among building owners, developers, architects, engineers, constructors, facility managers, building code officials, bankers, and real estate professionals. New certification systems with unique requirements must be considered. This book focuses largely on practical solutions to the regulatory and logistical challenges posed in implementing sustainable construction principles, delving into background and theory as needed. The USGBC's green building certification program is covered in detail. Other complementary or alternative standards, such as the GBI's Green Globes building assessment system, the federal government's Energy Star program, and the United Kingdom's BREEAM building certification program, are discussed. Economic analysis and the application of LCC, which provides a more comprehensive assessment of the economic benefits of green construction, also are considered.

Following this introduction, the book is organized into four parts, each of which describes an aspect of this emerging building delivery system. Part I, "Green

Building Foundations," covers the background and history of green buildings, the basic concepts, ethical principles, and ecological design. Part II, "Assessing High-Performance Green Buildings," addresses the important issue of assessing or rating green buildings, with special emphasis on the two major US rating systems, LEED and Green Globes. Part III, "Green Building Design," more closely examines several important subsystems of green buildings: siting and landscaping, energy and atmosphere, carbon accounting, the building hydrologic cycle, materials selection, and indoor environmental quality. In Part IV, "Green Building Implementation," addresses the subjects of construction operations, building commissioning, economic issues, and future directions of sustainable construction. Additionally, several appendices containing supplemental information on key concepts are provided. To support the readers, a website, www.wiley.com/go/sustainableconstruction, contains hyperlinks to relevant organizations, references, and resources. This website also references supplemental materials, lectures, and other information suitable for use in university courses on sustainable construction.

Case Study: The Pertamina Energy Tower: A Primer on Green Skyscraper Design

The world's population is likely to grow from 7 billion today to over 9 billion by 2050, with about 70 percent of the population dwelling in cities. Densely populated urban areas are the antithesis of the post–World War II era marked by suburban sprawl and migration away from the cities that dominated urban planning for over 60 years. Today economics and changes in people's attitudes toward lifestyle dictate a shift to large cities around the world. To meet the demand for built environment, whole ecosystems of skyscrapers are growing in the world's burgeoning urban areas and contributing to the emergence of a new urban form often referred to as vertical cities. The trend toward building more vertical cities is driven by global population growth, urbanization, and economics. Antony Wood, the executive director of the Council on Tall Buildings and Urban Habitat (CTBUH), a nonprofit organization that tracks skyscrapers, refers to this as **sustainable vertical urbanism**. Nowhere is this trend toward vertical urbanism more pronounced than in China, which has one-third of the world's largest buildings over 150 meters (492 feet). By 2020, China will boast six of the 10 tallest buildings in the world. In 2014, China dominated the growth in skyscrapers, with 58 of the 97 completed buildings being in Chinese cities. In their book *Vertical City: A Solution for Sustainable Living*, the architects Kenneth King and Kellogg Wong describe a future in which cities evolve into a complex array of skyscrapers, infrastructure, and services that include everything needed for a high quality of life. Space for parks, sports stadiums, libraries, theaters, restaurants, shopping malls, and even hospitals are provided, along with offices and work spaces for businesses.

The key to the vertical city is the skyscraper, and its design is being transformed by highly creative architects and developers who are helping propel the shift to a denser and taller built environment. The rate of construction, purpose, and approach to building skyscrapers are rapidly changing and evolving. Just after the 9/11 attacks on New York City in 2001, many pundits were forecasting that the formerly iconic skyscrapers would become obsolete because they were obvious targets for terrorists. However, in the period since the events of 2001, there has been a significant increase in the pace of skyscraper construction and a race to design and build ever taller structures. Between 1930 and 2001, the maximum skyscraper size increased by 230 feet (74 m). However, since 2001, due to the development of new materials, structural systems, and design tools, the height increase has been 1,234 feet (398 m) and led to the creation of a new category of skyscraper, the *supertall skyscraper*, a classification for buildings 984 feet (300 m) or more in height.

Prior to the mid-1990s, skyscrapers were designed to contain office space. However, the skyscrapers developed since that time are filled with hotels, condominiums, shopping centers, restaurants, theaters, and other elements of a typical downtown urban environment but arranged vertically. The design of skyscrapers increasingly is shifting to emphasize the buildings' relationships with people and the environment. Rather than commercializing every square meter of area, significant space is devoted toward creating a positive experience for occupants, in terms of both green space and extensive daylighting. Skyscrapers enhance the experience of living and working in the city and often contain offices and apartments plus all the amenities found in several typical blocks of a large city. In 2000, just five of the world's 20 tallest buildings were mixed use. By 2020, all *but* five of the tallest will be mixed use. It is clear that architects are responding to the demand for verticality by creating compelling new forms, enormous in scale, that draw attention as they change the skylines of the world's great cities. Towers that were once monolithic and repetitive edifices are becoming far more diverse, integrated, and connected.

Skyscraper designers face enormous challenges; not least among them are the enormous forces resulting from the sheer mass of materials used, which increases significantly with height. However, advances in materials, such as extremely high-strength concrete and steel, and more precise design tools coupled with faster computers are resulting in buildings that are far lighter than their predecessors. For example, the current tallest building in the world, the Burj Khalifa in Dubai, United Arab Emirates, which is more than 2,717 feet (828 m) in height, weighs half as much as the Empire State Building, which at 1,250 feet (381 m) is less than half as tall. The newest skyscrapers often incorporate very high compressive strength concrete that contains lightweight microfibers instead of reinforcing steel, saving considerable weight. Concrete structures can also be thinner and, unlike steel structures, concrete does not require fireproofing. Designing to accommodate wind forces also can be very challenging because winds 1,000 feet (323 m) above the ground may be traveling at up to 100 miles (160 kilometers) per hour, creating significant and complex forces, such as vortex shedding, that pull the structure in random directions. Today's enormous computing power and improved structural models have eliminated the need for engineers to design buildings with large safety factors because they are able to accurately model external forces and materials behavior. Three-dimensional printing also has contributed to the ability of engineers to rapidly test a wide variety of structural configurations in specialized wind tunnels to determine the best approach to minimizing wind loads. As a result, the quantity of materials needed to support the skyscraper is minimized.

Parallel to the growth in skyscrapers has been an accelerating shift to designing high-performance or green skyscrapers. In 2015, the US GBC announced that there were a record five iconic global skyscrapers being designed for certification with the LEED rating system. The result is that many of the features found in smaller green buildings, such as high levels of energy efficiency, low construction waste, abundant natural light, carbon-neutral buildings, and even NZE buildings, are finding their way into skyscrapers. Perhaps most significant of the newer skyscrapers emerging from the world's great architecture firms is the Pertamina Energy Tower in Jakarta, Indonesia, designed by Skidmore, Owings and Merrill (SOM), considered one of the premier designers of supertall category buildings. A 99-story structure with a height of 1,740 feet (530 m), the Pertamina Energy Tower provides a primer on the design of high performance green buildings (see Figure 1.8).

As a result of their unmatched experience with skyscrapers and in particular green skyscrapers, SOM has developed a well-thought-out and tested template for the design of high-performance skyscrapers that the firm has tested in a variety of projects. Among the projects that contributed to the evolution of the SOM approach is the Pearl River Tower in Guangzhou, China, a 72-story, 1,015-foot-tall (309-m) building completed in 2011. The 2.3 million square-foot (213,700-square-meter) building helped advance the state of the art in sustainable design by incorporating and testing the latest green technologies and engineering advancements. Its sculpted body directs wind to a pair of openings at its mechanical floors where

Figure 1.8 Rendering of the Pertamina Energy Tower, the world's first net-positive-energy building and an exemplar of high-performance buildings. (*Source:* SMILODON)

the prevailing winds drive vertical-axis wind turbines (VAWTs) that generate energy for the building. Other green features include solar PV panels, a double-skin curtain wall, a chilled ceiling system, under-floor ventilation, and daylight harvesting. The many lessons learned in its design and construction helped SOM further refine its green skyscraper design process. SOM applied the experience gained in the design of the Pearl River Tower and other green projects to the Pertamina Energy Tower, which was designed with a focus on high performance and sustainability. It is the first skyscraper that is net-positive energy—that is, on-site renewable energy provides more than 100 percent of the energy required to operate the building. Indeed, this building was designed with energy as the central criterion for measuring the success of its performance. As a result, the Pertamina Energy Tower's self-contained renewable energy system exceeds energy consumption by about 6 percent annually. This remarkable performance was achieved by reducing energy demand through a combination of active and passive strategies. The passive design strategies include a high-performance façade that allows daylight penetration while simultaneously minimizing cooling loads through optimized glazing and specially designed external shading fins. Natural light supplied by daylighting is important not only for reducing energy consumption but also for its positive benefits to human health. The active strategies include a high-efficiency ventilating and air conditioning system, high-efficiency light-emitting diode (LED) lighting fixtures, occupancy sensors that automatically dim or switch off luminaires, a demand-controlled ventilation system that provides the precise quantity of fresh outside air to meet occupant needs, a regenerative system that recovers energy during the braking cycle of the elevators, and double enthalpy wheels in the outside air-handling units that recover otherwise wasted energy.

The project team used a five-step process to design the Pertamina Tower. Step 1 was to design a baseline building to serve as a basis for testing ideas and hypotheses. Step 2 was to integrate passive strategies to reduce the project's energy demand. Step 3 focused on measures to increase efficiency and reduce energy demand through integrated active strategies. In Step 4, a central energy plant was designed to serve the energy needs of the building. Step 5 was to integrate on-site renewable energies into the building. This five-step process will be followed by the operational maintenance phase, which starts with the commissioning process and postoccupancy evaluation to optimize the building performance and to further reduce the building's energy consumption (see Figure 1.9).

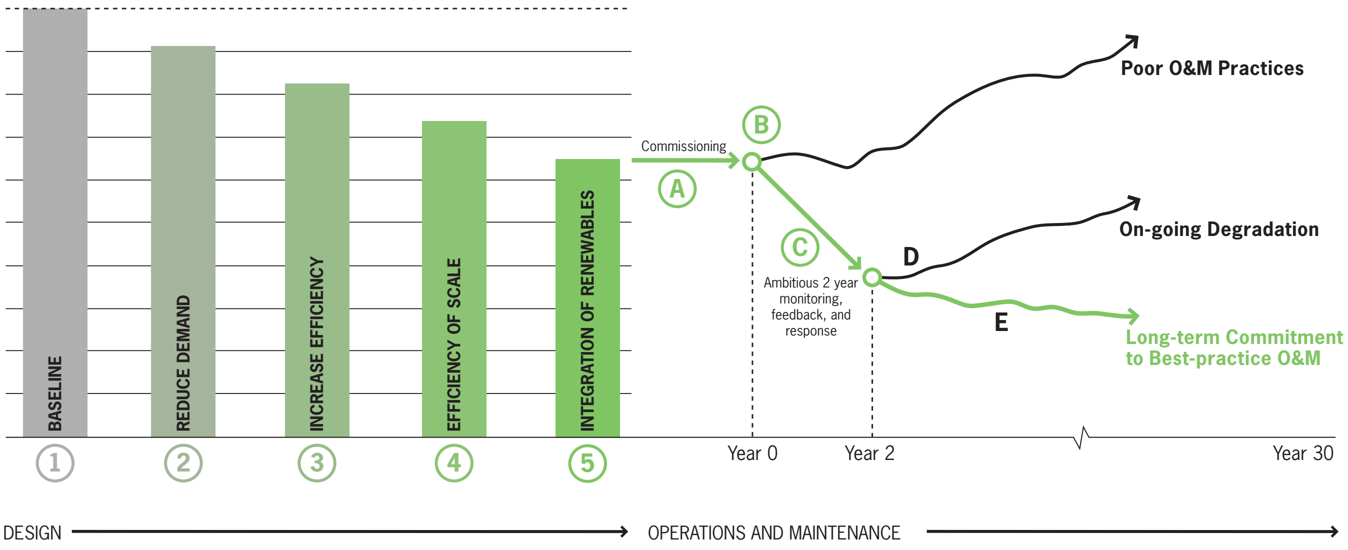

Figure 1.9 The five-step design process followed by SOM was applied to the design of the Pertamina Energy Tower. The period after occupancy is an enormous opportunity to capitalize on the building's high-performance design by fine-tuning and further improving the building's performance. (*Source:* SOM)

In Step 1 of the SOM design process, the project team calculated that the baseline energy consumption of the building was likely to be 250 kWh/m^2/yr (85,600 BTU/ft^2/yr). In this case, the base case is a building of the same type and size as the Pertamina Energy Tower that just meets the minimum requirements of the local building code. This level of performance is not atypical of skyscrapers, which tend to be more energy intensive than other building types. However, a high-performance skyscraper is expected to use considerably less energy through a process of integrated design, which requires extensive collaboration by all parties on the project team. In the case of the Pertamina Energy Tower, computer modeling of the actual building indicated that a reduction in energy demand of 60 percent to100 kWh/m^2/yr (34,000 BTU/ft^2/yr) could be achieved.

In Step 2, the incorporation of passive design features into the building, included detailed studies on how to best integrate the project with its environment to maximize energy savings. The Pertamina Tower is noteworthy for its rounded shape and notched corners on the east and west sides, the outcome of a parametric study to determine the form that would best minimize energy consumption. The idea was to study the relationship of the building to its environment to determine what shapes and features would produce the minimum energy demand. The analysis of the form of the building's footplate produced some significant and useful results. Starting with a conventional square shape as the base case for the 3,400-square-meter floor plate, the designers iterated through a variety of other options. A simple change in which the square shape of the base case building was rotated 90 degrees to a diamond configuration reduced peak cooling demand by 8 percent. Rounding the corners of the diamond reduced peak cooling by 8 percent, and also provided an overall savings of 9 percent in annual cooling. By shifting to the final notched and rounded shape, peak cooling was reduced by 49 percent and annual cooling was reduced by 30 percent, a truly significant decrease in energy demand (see Figure 1.10).

Passive design includes a detailed analysis of opportunities to harvest natural light and reduce solar loads through the design of the façade. The building is located about 6 degrees south of the equator. In this zone, the track of the sun directly over the building is virtually symmetrical over the course of a year. During the summer and winter solstices, the sun is directly overhead and does not cast a shadow. Day length does not vary much during the year and is always about 12 hours long. The location of the building produced some challenges but also some opportunities

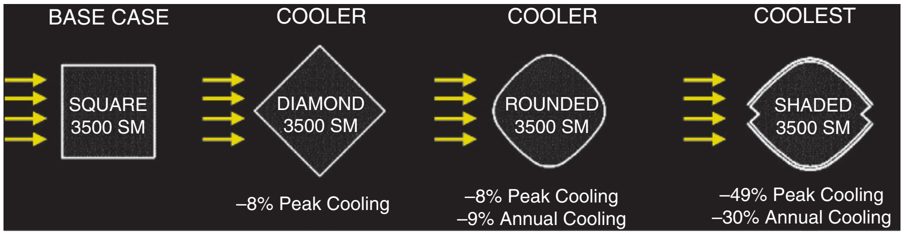

Figure 1.10 By optimizing the shape of the Pertamina Energy Tower's footplate, the design team was able to demonstrate enormous peak and annual energy savings. Note the notches on the rightmost shape, which are the east- and west-facing aspects of the tower. The façade in the notches is equipped with vertical fins to block intense early-morning and late-afternoon sun. (*Source:* SOM)

for passive design. The SOM design team ran an enormous number of calculations and simulations to determine the best approach to address the glare problem and minimize the solar thermal load (see Figure 1.11). The outcome of this effort was an external fin design that wraps around the building on each floor, controlling glare and solar loads (see Figure 1.12). The passive exterior fins are combined with automatic blinds controlled by sensors that open and close the blinds as the sun tracks across the building. The east and west ends of the buildings are equipped with vertical fins to counter the intense solar thermal radiation as the sun moves across the sky (see Figure 1.13).

Step 3 of the SOM design strategy initiates consideration of the cooling and electrical hardware of the building and components that complement the passive strategies. For example, an automated interior shading control system is used to optimize daylight harvesting, minimize artificial lighting, and maximize views. Zoned LED lighting is used throughout the building, along with occupancy sensors, to minimize electrical lighting energy. The core strategy for cooling the building is the use of active chilled beams on each floor in interior zones. Variable-volume fan coil units along the perimeter meet the varying solar thermal load and provide adequate control of humidity. Demand-controlled ventilation supplies the required ventilation air to the building in a precise manner based on the number of occupants present. Regenerative braking systems are used in the building's elevators to recover energy

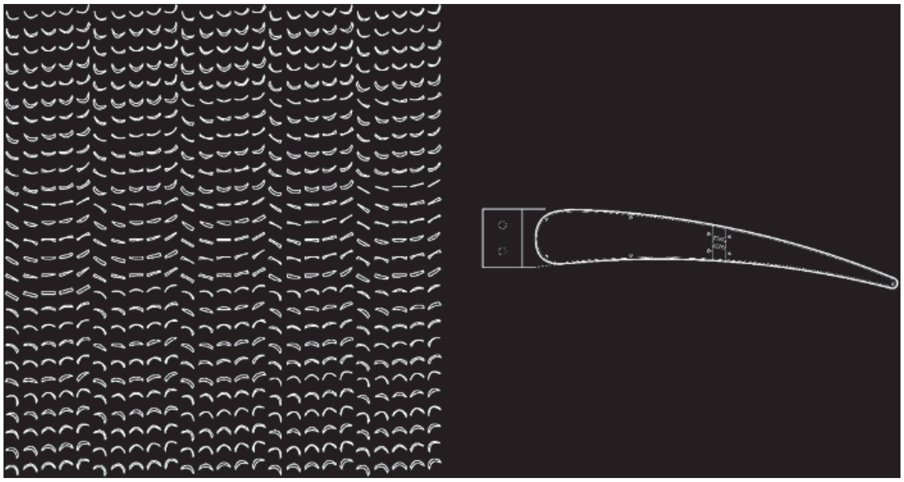

Figure 1.11 The SOM design team tested a wide variety of fin shapes to determine the optimum cross section for controlling glare and the solar thermal load for a building located on the equator. The selected shape is show on the right side of the illustration. (*Source:* SOM)

Figure 1.12 The actual designed fixed external fin system wraps around each floor of the building, terminating at the east and west notches. (*Source:* SOM)

that would otherwise be dissipated as heat. Exhaust air leaving the building is used to cool and dry hot fresh outside air through the use of an energy recovery system equipped with double enthalpy wheels located in the outside air-handling unit. The net result of all the passive and active strategies is that the EUI will be 60 percent less than the baseline of 250 kWh/m^2/year, or 100 kWh/m^2/year (see Figure 1.14).

Steps 4 and 5 of the SOM design strategy were accomplished in tandem. These involve the design of a central energy plant for the project and the integration of on-site renewable energy. Because of the significant reduction in EUI, the building has the potential for being designed to be energy self-sufficient—that is, an NZE building. Jakarta is located in a very active volcanic area, making geothermal energy a viable option for generating electricity and providing thermal energy for use

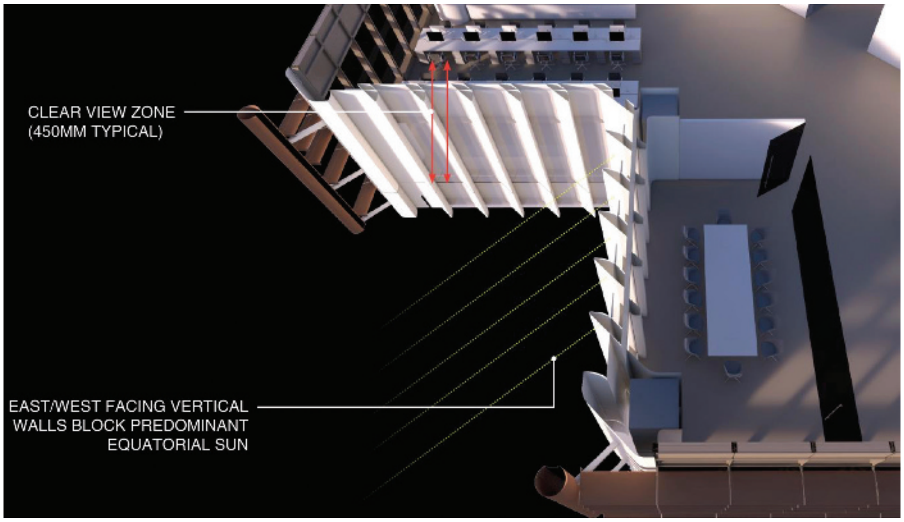

Figure 1.13 The fixed external fin system on the north and south faces of the building terminated at the notches on the east and west sides of the floor plate, where vertical fins block intense morning and afternoon heat. (*Source:* SOM)

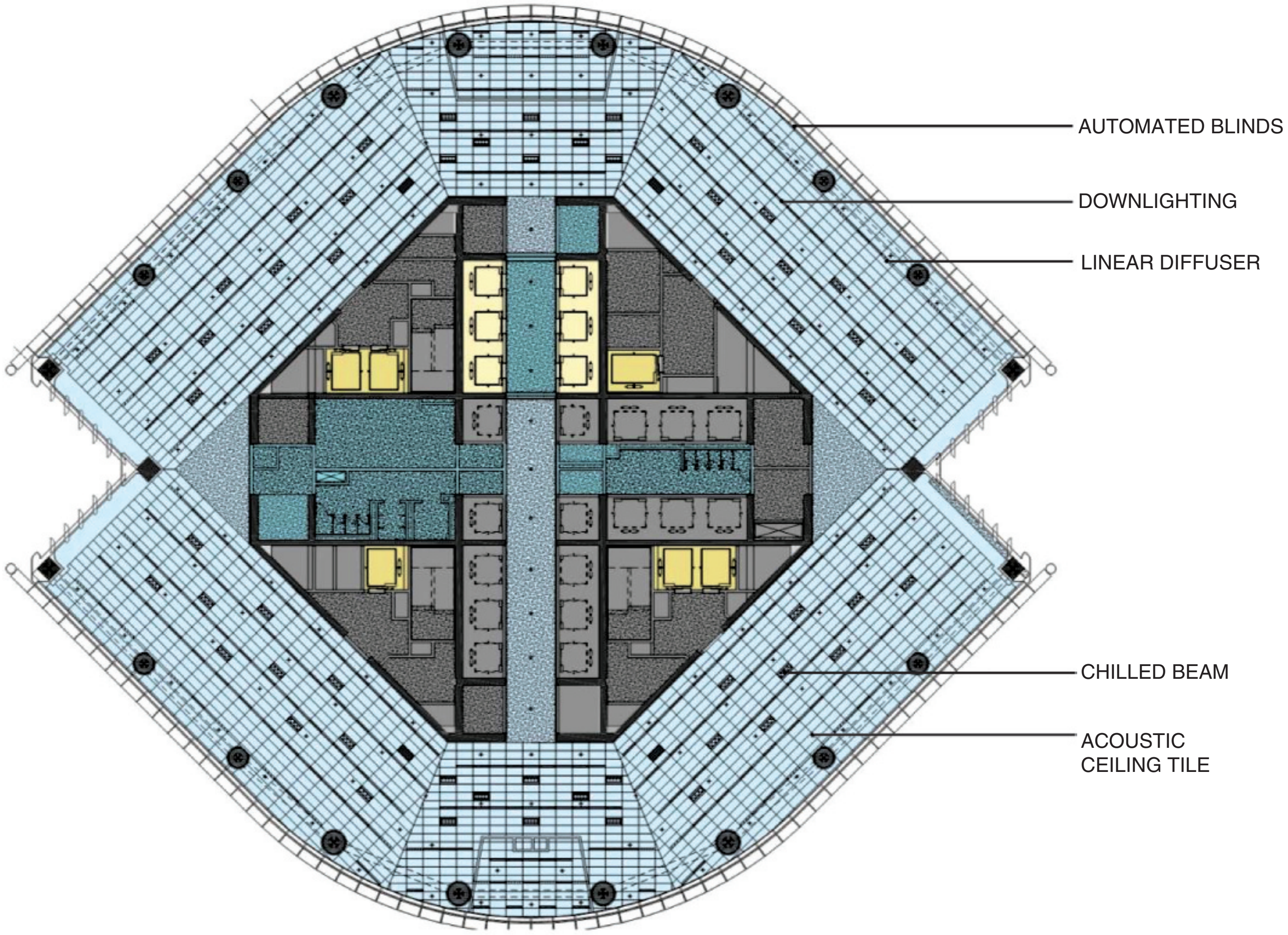

Figure 1.14 A combination of external and internal fins and blinds are used to control solar thermal energy and maximize daylighting during the course of the day. Three banks of chilled beams provide interior cooling, and perimeter fan coil units are employed to meet envelope loads and supply fresh outside air for ventilation. (*Source:* SOM)

in the building (see Figure 1.15). A geothermal binary cycle power plant is planned for implementation that will utilize a combined heat and power unit that can supply 4.2 MW of electricity and satisfy 100 percent of the site's annual electrical energy needs. High-efficiency centrifugal chillers that use green electricity produced by the binary cycle turbine will be tied into the geothermal fields and be used for cooling the tower. One thermal energy storage tank will be tied into the system so that the chillers can charge the tanks during low-cooling-demand hours for use when peak cooling is required, thereby maintaining a constant demand on the geothermal turbine that matches the 24/7 availability profile of the renewable resource (see Figure 1.16).

In addition to the geothermal energy, the Pertamina Energy Tower will capture energy from two other renewable sources, the prevailing winds and the sun. Solar PV panels that convert solar radiation into electricity will cover (18,800 ft^2 (1,750 m^2) of the pedestrian energy ribbon with state-of-the-art monocrystalline PV panels. Additional energy will be provided by VAWTs integrated into the building's crown and located at a height of 1,739 ft (530 m) to take advantage of the Venturi effect at this altitude. The crown design was developed using a comprehensive computational fluid dynamics study to thoroughly analyze the wind behavior at this elevation (see Figures 1.17 and 1.18). In short, in excess of 100 percent of the building's energy demand will be met by a combination of geothermal, wind, and solar radiation.

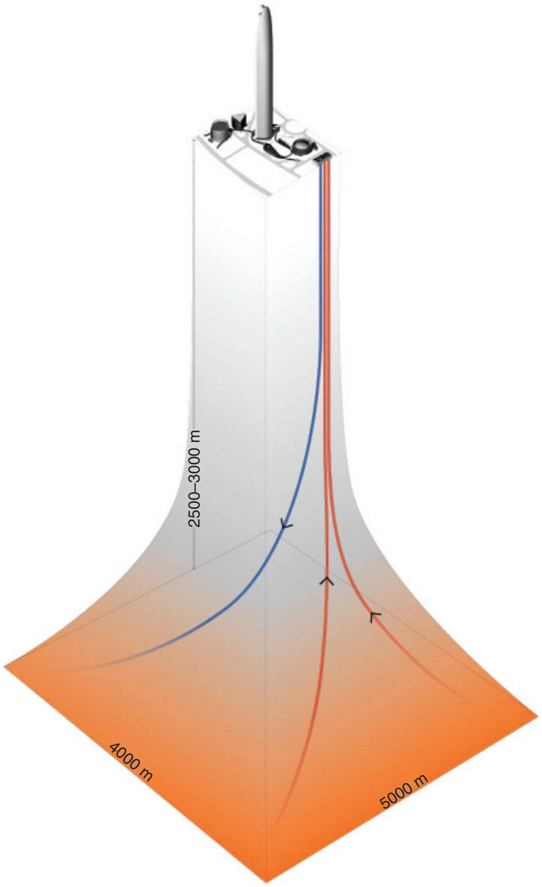

Figure 1.15 The Pertamina Tower will tap into the geothermal field located beneath the building and use heat exchangers to extract energy for electricity generation and cooling from the 150 ºC (300 ºF) energy source. (*Source:* SOM)

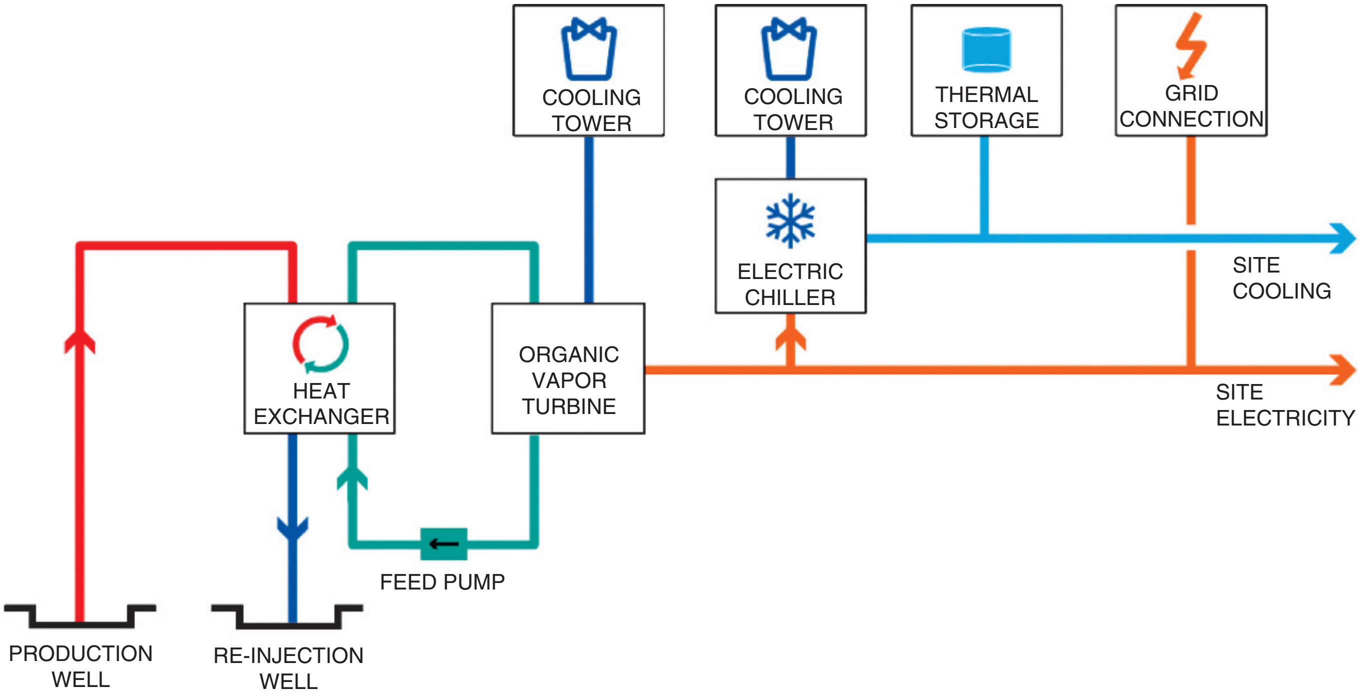

Figure 1.16 The geothermal energy system will use a 4.2 MW organic vapor turbine to generate electricity, electric chillers to generate chilled water, and a thermal storage system that will be charged during periods of low demand to meet high-demand peaks. (*Source:* SOM)

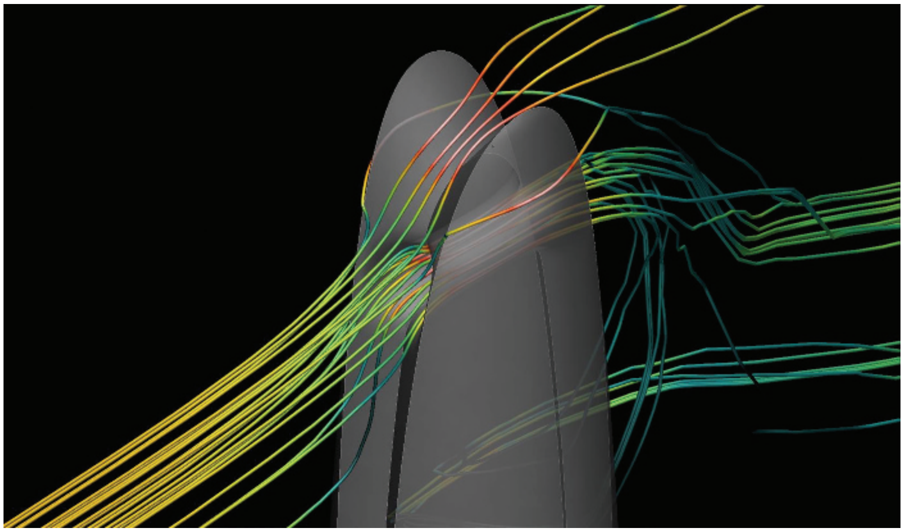

Figure 1.17 Winds at high levels above the ground present an opportunity to integrate wind turbines into skyscrapers. An opening in the, crown of the Pertamina Energy Tower is used to capture the energy of the prevailing wind and convert it into electricity using VAWTs. Computational fluid dynamics was used to model the behavior of wind around the building and design the wind energy system. (*Source:* SOM)

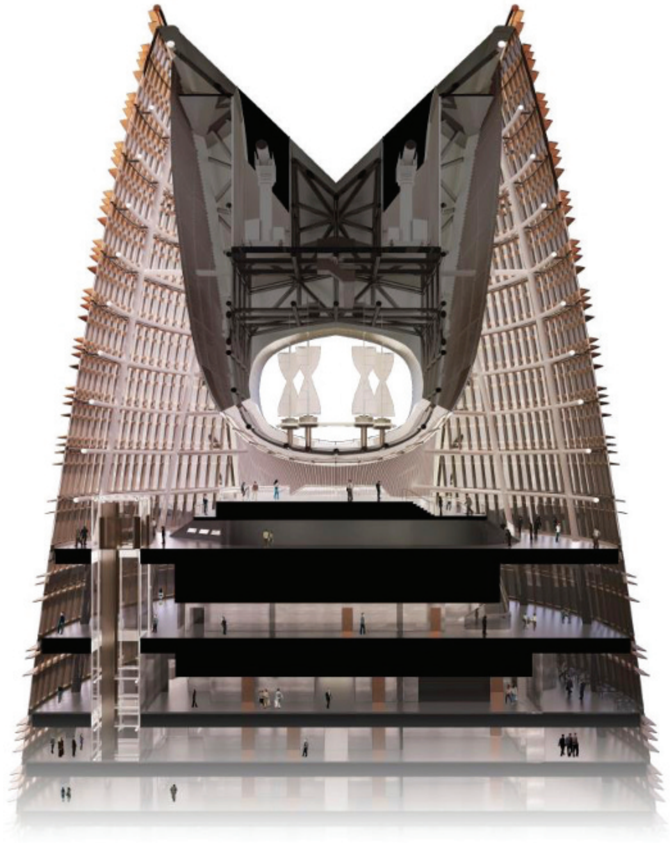

Figure 1.18 The opening in the crown of the building provides a platform for several VAWTs that provide significant renewable energy for the Pertamina Energy Tower. (*Source:* SOM)

The Pertamina Energy Tower represents a significant forward leap in the design of supertall skyscrapers. The design EUI of 100 kWH/m^2/year represents an enormous reduction in energy consumption—just 40 percent of the 250 kWh/m^2/year of a typical conventional, code-compliant building of this type. It is likely to be the first truly NZE skyscraper due to the strategy of tapping into the geothermal potential of its location in Indonesia. It also will have superior interior environmental qualities, such as excellent thermal comfort and views and extensive, glare-free natural light. The Pertamina project is the first to demonstrate that NZE is possible for very large buildings if an experienced team employs a disciplined design approach that uses past experience to inform future design.

Summary and Conclusions

The rapidly evolving and exponentially growing green building movement is arguably the most successful environmental movement in the United States today. In contrast to many other areas of environmentalism that are stagnating, sustainable building has proven to yield substantial beneficial environmental and economic advantages. Despite this progress, however, there remain significant obstacles, caused by the inertia of the building professions and the construction industry and compounded by the difficulty of changing building codes. Industry professionals in both the design and construction disciplines are generally slow to change and tend to be risk-averse. Likewise, building codes are inherently difficult to change, and fears of liability and litigation over the performance of new products and systems pose considerable challenges. Furthermore, the environmental or economic benefit of some green building approaches has not been quantified scientifically, despite the often intuitive and anecdotal benefits. Finally, lack of a collective vision and guidance for future green buildings, including design, components, systems, and materials, may affect the current rapid progress in this arena.

Despite these difficulties, the robust US green building movement continues to gain momentum, and thousands of construction and design professionals have made it the mainstay of their practices. Numerous innovative products and tools are marketed each year, and, in general, this movement benefits from enormous energy and creativity. Like other processes, sustainable construction may one day become so common that its unique distinguishing terminology may be unnecessary. At that point, the green building movement will have accomplished its purpose: to transform fundamental human assumptions that create waste and inefficiency into a new paradigm of responsible behavior that supports both present and future generations.

Notes

1. UNHSP and World Bank statistics are as quoted in Zayed (2014).
2. The energy consumption figures for buildings in the United States refer to purchased or metered energy.
3. The Architecture 2030 Challenge was started by Ed Mazria in 2002. A parallel effort known as the 2030 Challenge for Products was initiated in 2011 to reduce the contributions of building materials to climate change.
4. The 2030 Challenge is described at the Architecture 2030 website, http://architecture2030.org/2030_challenges/2030-challenge/.
5. The origin of the word *sustainability* is controversial. In the United States, sustainability was first defined in 1981 by Lester Brown, a well-known American environmentalist and for many years the head of the Worldwatch Institute. In “Building a Sustainable Society,” he defined a sustainable society as “one that is able to satisfy its needs without diminishing the chance of future generations.” In 1987, the Brundtland Commission, headed by then prime minister of Norway, Gro Harlem Brundtland, adapted Brown’s definition, referring to sustainable development as “meeting the needs of the present without compromising the ability of future generations to meet their needs.” Sustainable development, or sustainability, strongly suggests a call for intergenerational justice and the realization that today’s population is merely borrowing resources and environmental conditions from future generations. In 1987, the Brundtland Commission’s report was published as a book, *Our Common Future*, by the UN World Commission on Environment and Development.
6. The World Business Council for Sustainable Development (WBCSD) promotes sustainable development reporting by its 170-member international companies. The WBCSD is committed to sustainable development via the three pillars of sustainability: economic growth, ecological balance, and social progress. Its website is www.wbcsd.org.

7. In November 1992, more than 1,700 of the world's leading scientists, including the majority of the Nobel laureates in the sciences, issued the "World Scientists' Warning to Humanity." The preamble of this warning stated: "Human beings and the world are on a collision course. Human activities inflict harsh and often irreversible damage on the environment and critical resources. If not checked, many of our current practices put at serious risk the future that we wish for human society and the plant and animal kingdoms, and may so alter the living world that it may be unable to sustain life in the manner we know. Fundamental changes are urgent if we are to avoid the collision our present course will bring about." The remainder of this warning addresses specific issues, global warming among them, and calls for dramatic changes, especially on the part of the high-consuming developed countries, particularly the United States.
8. At the First International Conference on Sustainable Construction held in Tampa, Florida, in November 1994, Task Group 16 (Sustainable Construction) of the CIB formally defined the concept of sustainable construction and articulated six principles of sustainable construction, later amended to seven principles.
9. The *Whole Building Design Guide* can be found at www.wbdg.org.
10. Detailed information about Solaire can be found at www.thesolaire.com.
11. Primary energy accounts for energy in its raw state. The energy value of the coal or fuel oil being input to a power plant is primary energy. The generated electricity is metered or purchased energy. For a 40 percent efficient power plant, 1 kWh of purchased electricity requires 2.5 kWh of primary energy.
12. A description of the severe water resource problems beginning to emerge even in water-rich Florida can be found in the May/June 2003 issue of *Coastal Services*, an online publication of the National Oceanic and Atmospheric Administration Coastal Services Center, available at www.csc.noaa.gov/magazine/2003/03/florida.html. A similar overview of water problems in the western United States can be found in Young (2004).
13. An overview of xeriscaping and the seven basic principles of xeriscaping can be found at http://aggie-horticulture.tamu.edu/extension/xeriscape/xeriscape.html.
14. The Adam Joseph Lewis Center for Environmental Studies at Oberlin College was designed by a highly respected team of architects, engineers, and consultants and is a cutting-edge example of green buildings in the United States. An informative website, www.oberlin.edu/envs/ajlc, shows real-time performance of the building and its photovoltaic system.
15. "The Cost and Benefits of Green Buildings," a 2003 report to California's Sustainable Buildings Task Force, describes in detail the financial and economic benefits of green buildings. The principal author of this report is Greg Kats of Capital E. Several other reports on this theme by the same author are available online. See the references for more information.
16. See World Green Building Council (2015) for a detailed recent report on indoor air quality strategies in green buildings.
17. From "Ultra-Violet Radiation Can Cure 'Sick Buildings'" (2003).
18. The embodied energy of a product refers to the energy required to extract raw materials, manufacture the product, and install it in the building, and includes the transportation energy needed to move the materials comprising the product from extraction to installation.

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