PASSIVE SOLAR ARCHITECTURE
HEATING, COOLING, VENTILATION, AND DAYLIGHTING USING NATURAL FLOWS

David A. Bainbridge and Ken Haggard
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Two solar pioneers show how to design a building for comfort, joy, and sustainability.

No matter what climate you’re designing for, new buildings can be solar oriented, naturally heated and cooled, naturally lit, naturally ventilated, and made with renewable, sustainable materials. In a comprehensive overview of passive solar design—the resurrected solar strategy that is sweeping through Germany and rapidly regaining popularity in the United States—two of the nation’s solar pioneers give homeowners, architects, and builders the keys to successfully using the sun and climate resources for heating, cooling, ventilation, and daylighting.

Drawing on examples from decades of their own experiences and those of others, the authors offer readers overarching principles as well as the details and formulas necessary to successfully design a more comfortable, healthy, and secure places in which to live, laugh, dance, and be comfortable. Even if the power goes off. Passive Solar Architecture will also help readers understand “greener” and more sustainable building materials and how to use them, and explore the historical roots of green design that have made possible buildings that produce more energy than they use.

Fully illustrated with many diagrams and photographs, the book will help everyone involved in a building project best undertake a sustainable project, from planning and design, to building, remodeling, and operating the completed building.

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Buildings Matter for Ill...

_Sick building syndrome is a term used to describe situations in which building occupants experience discomfort and even acute health problems that appear to be related to time spent in the building._

—MOHAMED BOUBEKRI, 2008

**BUILDINGS MATTER.** We spend more and more of our lives inside them, and poorly designed, built, and maintained buildings are a common cause of human suffering, illness, and death. People are too often hot in summer, cold in winter, and face real danger if the power goes off. Many more suffer at work or at home from poor air quality. Sealed buildings, flawed building materials, and poor design lead to leaks and mold unless installation and maintenance are perfect—and they rarely are. In 1998, World Health Organization research suggested that 30 percent of all the new and remodeled buildings in the world were afflicted with sick building syndrome. The annual cost of poor indoor air quality in the United States alone has been estimated at $160 billion by the Department of Energy, more than the gross national product of most countries. In contrast, sustainable buildings, to those who live and work in them, pay large dividends as human comfort and health improve and productivity increases. The value of productivity gains alone is often a hundred times greater than energy savings.

Buildings are also a major user of materials and energy. They account for as much as a third of all the flow of materials (water, metals, minerals, et cetera) each year in the United States and are also responsible for 40 percent of the country’s greenhouse gas emissions. And this is not just a local problem. When Stefan Bringezu and co-workers computed the resource intensity of the fifty-eight sectors of the German economy, they concluded that buildings and dwellings consumed between 25 and 30 percent of the total nonrenewable material flow in Germany.

Buildings not only are material-intensive, but also require massive amounts of energy and water and are a source of many toxic and ecotoxic materials, including paints, plastics, cleaning solutions, pesticides, garbage streams, and copper, zinc, and lead leaching from roofing and pipes. Floods and fires release a wide range of toxins from buildings. Air pollution from buildings and from the power generation needed to heat and cool them causes far-reaching ecosystem damage and disruption locally, across the country, and around the world.

Why have we been so fuelish? As Amory Lovins and others have noted, small but important signals and incentives make it most profitable for designers, engineers, builders, and installers to create inefficient, costly, and unhealthful developments and buildings. This has been compounded by poor training in schools, particularly in architecture and engineering, lack of training for builders, and government subsidies that artificially reduce the cost of energy, water, and building materials.

Almost all of the adverse impacts of building can be avoided by good design and construction. New buildings in any climate can be solar-oriented, naturally heated and cooled, naturally lit, naturally ventilated, and made with renewable materials.

In most climates, proper building orientation can dramatically reduce building energy demand for heating and cooling at no cost increase. In a study of more sustainable home design (validated by actually building the home) in Davis, California, the home summer peak energy demand dropped from 3.6 kilowatt-hours (kWh) to 2 kWh, and annual energy use for heating and cooling dropped 67 percent. This improvement didn't cost anything; in fact, it reduced the cost of construction.

The goal of the sustainable building (also called green building) movement is to improve the comfort and health of the built environment while maximizing use of renewable resources and reducing...
The simple choice of window orientation can have large implications for cost, energy use, and comfort, yet these implications are rarely considered. Most attention in building codes is on reducing energy use for winter heating, but in many areas cooling is equally or even more important. Fortunately, design for passive solar heating in winter can reduce summer cooling demand as well, since facing south allows easy solar control in the summer with overhangs. The most common failing of building design is not orienting the house properly, something that has been well understood for more than two thousand years. As the Greek writer Aeschylus noted of the barbarians, “They lacked the knowledge of houses turned to face the sun.”

Besides discomfort, poor orientation is expensive to building owners, society, and the planet. The cost of a 50-square-foot west-facing window in Sacramento, California, is calculated to be $40,000 over a thirty-year period if you add up the added air-conditioning cost, the additional utility cost, and the related environmental cost of such a simple choice. If the three million houses built in California since 1980 had been well designed in regard to the simple problem of orientation, we could have reduced the critical summer peak energy demand by 3,000 to 6,000 megawatts at no additional cost. Sustainable design can pay big dividends!

**Fig. 0.2.** A sustainably designed building works well even when the power is off.
... or for Good

In a sustainable culture buildings will once again be seen as part of a beautiful place from planetary biomes to specific sites. These buildings will be part of a cyclic flow of materials and energy in an Environment without seams or waste.

—PLINY FISK III

THE VILLAGE HOMES subdivision in Davis, California, used proper solar orientation to reduce energy use for heating and cooling 50 percent back in the 1970s. The 500,000-square-foot ING bank in the Netherlands cost little more than conventional construction, but uses less than one-tenth as much energy, and absenteeism is 15 percent lower. A sustainably designed factory complex doubled worker productivity for the Herman Miller Corporation in Holland, Michigan. A very modest retrofit of a standard office building in San Diego reduced seasonal energy use for heating and cooling 70 percent and improved the comfort of those working there.

Increasing attention has been paid to sustainable building as a result of the US Green Building Council’s Leadership in Energy and

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**Fig. 0.3.** We all use buildings, and if they are designed right they can improve health and security and provide an effective and proactive approach to reducing global climate disruption.
Environment Design (LEED) program and other green building evaluation programs. While more green buildings are being built, they are only pale green and often perform little better than the buildings they replace, for they often neglect the most elementary feature of sustainable design: using the sun and climate resources for heating and cooling.

The benefits of sustainable design include comfort, health, economy, security and safety during power outages, as well as reduced impact on the planet. A well-designed building will keep its occupants warm in winter and cool in summer even when the power goes off. A sustainably designed building will also be able to provide emergency water supplies from its rainwater harvesting systems during a water-main break or natural disaster. And a passive solar water heater will provide hot water for showers and cleaning even when the power is off.

Building sustainable buildings has never been easier. Improved sensors and control systems can increase building thermal performance and resource use by better managing fans, pumps, valves, vents, shades, lights, and blinds, as well as making it easier to monitor buildings. Replacing the hidden mechanical meters used for energy and water with highly visible and easy-to-read water and energy meters in the lobby, living room, or as a display on your computer makes it much easier to understand and optimize building performance.

Better accounting that takes the true costs of a building—throughout its life cycle—into consideration is critical to make it clear that sustainable buildings are the best choice. When health and productivity are added to the mix, sustainable buildings are the best buy! Improving accounting for all costs is not going to be easy, as those who benefit from current subsidies are loath to give them up. But growing awareness of global warming, resource shortages, and energy insecurity are adding pressure for change.

A well-designed and well-constructed building should require minimal mechanical cooling, heating, and ventilation systems and limited artificial light during the day. And it can be built with renewable, locally sourced materials, which in turn can be manufactured and maintained without toxic chemicals. The built environment can become a source of satisfaction and joy rather than a polluting and often toxic prison. People enjoy sustainable buildings. They improve the quality of life. And sustainable designs add value from increased productivity from improved working and learning conditions. This book will help you find your path to sustainability!
ABOUT THIS BOOK

OUR GOAL in writing this book is to provide a comprehensive introduction and guide to the subject of passive solar architecture, a field the two of us have been working in for the past forty years. Our hope is to revive the name passive architecture as an umbrella term that includes in its purview all dimensions of green building and sustainability in the built environment.

Our paths first crossed in the 1970s. We were each working in one of the four passive solar “hot spots” in the country, Ken in San Luis Obispo and David at the University of California–Davis. (The other two were at Los Alamos and on the East Coast at MIT and Princeton.) By the 1980s, passive was a common term, and hundreds of passive buildings had been built. Performance and prediction modeling were developed, so that application of various architectural elements could be evaluated before construction to determine optimum design features.

However, with the election of Ronald Reagan in 1980, most federal support for solar energy was removed, an oil glut developed, energy prices shrunk, and the United States drifted backward toward its old wasteful energy ways. The passive architectural movement lost its immediacy, and most of the research and development was picked up by European countries, particularly the United Kingdom and Germany.

By the end of the first decade of this century, neglect and indulgence in regard to energy and building financing caught up with us in the form of the worst recession since the Great Depression. In addition, some began to recognize that looming problems such as peak fossil fuels, global climate disruption, and resource wars could only be addressed by shifting to a green economy.

At present, green architecture is very broadly defined and can mean different things to different people. Smart-growth concepts, healthy interiors, sustainably produced materials, energy conservation, life-cycle costs, new urbanism—all these and more are considerations for a green building. Stricter definition and quantification of green buildings is starting to occur with certification programs such as LEED (Leadership in Energy and Environmental Design), Green Globes, and others. These programs are based on checklists of prescribed points given for various green characteristics. With this situation, is the term passive architecture still relevant?

There are several reasons why the term passive is even more relevant than ever. One is that because of the breadth of green building and the greater difficulty that designers have in conceptualizing energy aspects than they do other green aspects, energy concerns in green buildings can often take second place, which is what happened in the early LEED checklists. There was a tendency to lump energy concerns under “energy efficiency” where they could be more easily dealt with by prescriptive standards. This type of simplified categorization misses the whole point of good passive architecture, which is a method of energy production as well as energy efficiency. Providing natural light by a well-designed atrium is energy production just as much as providing the same amount of light by electricity produced from a distant coal plant, except the passive approach is healthier and does not involve line loss to transport the energy, pollution, and other embedded costs. An energy-efficient building is a necessary prerequisite for a passive building, but energy efficiency by itself does not make a passive building. Therefore, we still need a term that allows the emphasis on producing thermal effects with building elements. Passive architecture fits the bill.

Green building really consists of three major concerns: sustainability, passive solar design, and triple-bottom-line accounting. All three topics and their interrelatedness are discussed in chapter 1. These are not static concerns, but a set of evolving techniques, all critical to obtaining the synthesis we call green building. Passive design must be a core consideration in a green building. We explore the latest developments and techniques for passive heating, passive cooling and ventilation, and natural lighting in chapters 2, 3, and 4, which are the heart of this book.

We see the shift to sustainable thinking and building as a continuum that contains starts, stops, and temporary reverses, but in general remains an evolution of building design and technology. Passive design is a necessary core element in green building because it embodies a shift from lightly differentiated design where discrete parts perform discrete functions to highly integrated design where one part contributes to many functions. This shift in the design process allows for dynamic synergy, where the whole is more than the sum of the parts, and the parts all contribute to the whole. Synergy
is more biological than mechanical; synergy is what will allow a sustainable culture where there is greater health, wealth, and equity because in the final analysis, systems with high synergy are more effective, reliant, and efficient.

The passive approach to building is not a fixed practice. If we look at its development over time, we see more and more functions being accomplished on-site using building elements. First there was heating, then cooling using the same building elements, then lighting, then electricity production. Now advanced passive buildings are going for water collection, carbon dioxide sequestration, and waste processing. What we are striving for is combining more and more production and use at the scale of the individual building. The harvesting of on-site resources is the focus of chapter 5.

In chapter 6, we invite some other voices to join us in looking at the big picture and at reimagining the present and the future. It is at the macro scale—where we can reconnect perceptions and assumptions about production and use—that passive architecture finds its cultural relevance. When building users can once again be more than just inhabitants of sealed boxes where energy production is out of sight and out of mind, then we can regenerate the awareness of energy and resources that is a necessary part of our transition from an industrial to a sustainable society.
Green buildings provide greater health and well-being by integrating principles of sustainability, passive design, and triple-bottom-line accounting.

The integrated design for this mixed-use passive solar complex features natural heating, cooling, lighting, and ventilation.
Integrated Design and Sustainability

Building sustainable and joyful buildings is not difficult or costly, but it does require a different approach. Designing and building good buildings demands a detailed understanding of the site and its microclimate, the orientation of the building and site with respect to the sun, and choosing and using materials, resources, and energy sustainably and wisely. This book works through the steps that are required for sustainable design, beginning with a definition of sustainability, fundamentals of energy and buildings, understanding site opportunities and constraints, and client requirements. The primary focus of this book is on using natural energy flows to meet the needs for heating, cooling, ventilation, and lighting, but supplemental materials extend the consideration of sustainability into materials, community, and other essential resource needs that can be met in full or in part by on-site resource capture.

Sustainability was defined at the United Nations Conference on the Environment in 1994 as “the ability to meet the needs of the present without compromising the needs of future generations.” More expansive goals were discussed, but this was the most that could be agreed upon. While the UN definition is widely used, it still isn’t specific enough. A working definition of sustainability must recognize that the environment and human activity are an interconnected, co-evolutionary whole. It is not just the protection of the environment that defines sustainability; the term must also encompass culture, economy, community, and family. As part of the whole, we must take into account how human activities affect natural processes and see how nature and natural flows are critically linked to our health and prosperity. Our contribution and participation in these processes must be restructured to sustain ourselves, other species, and the planet. Sustainability is local, regional, national, and global, and includes considerations of past, present, and future.

Sustainability is sometimes used in a narrow sense—as in “sustainable means profitable”—but we believe that a simple, single definition is not adequate to the task. Instead, to help shape and improve our designs we propose a working definition that is multidisciplinary. Sustainability must be understood by planning and design teams, citizens, and policy makers. A single definition won’t do, because sustainability is simple and complex, local and global, and based on actions taken today, past decisions and behavior, and the impacts and results from these choices extending for hundreds of years into the future. We have found it helpful to develop a working definition of sustainability with a spectrum of issues and ideas from relatively simple to more complex definitions (see figure 1.1).

For human survival and a livable future, the idea and application of sustainability must become part of an epochal cultural shift. The greatest barriers to understanding and embracing sustainability are residual biases from the fossil-fueled industrial era, when failed accounting and disconnection from nature led to potential catastrophe. It can be as hard for us to imagine what a sustainable culture of tomorrow might be as it was for the residents of a small horse-dominated farming town in Illinois in 1890 to envision the coming car-based culture of 1950. Their vision was restricted by their experience, and so is ours.

Fig. 1.1. Sustainability is a continuum, as seen in this working definition of the term for planning and design.
We can learn a great deal from studying and experiencing first-hand the best practices and communities that exist today. We can also learn from examining previous epochal shifts in cultural attitudes such as the transition from gathering and hunting to agriculture and more recently the abolition of slavery and voting rights for all. We can find good examples of sustainable management of local resources, notably a recent book by Arby Brown* on the Edo period in Japan, but this and other studies are far different in scale and perspective from the challenges we face in developing a sustainable global community. Failures of imagination can lead to philosophical traps; some of the most common are related to questions such as our place in nature, our interdependence with other cultures and ecosystems around the world, and the challenge of living within our means.

The question of our place in nature is critical. Aldo Leopold** was one of the first to address the problem:

*In short, a land ethic changes the role of Homo sapiens from a conqueror of the land-community to plain member and citizen of it. It implies respect for his fellow members, and also respect for the community as such. In human history we have learned that the conqueror role is eventually self-defeating. Why? Because it is implicit in such a role that conqueror knows, ex cathedra, what makes the community clock tick and just what and who is valuable, and what and who is worthless, in community life. It always turns out that he knows neither, and this is why his conquests eventually defeat themselves.

This is a critical step, but will not come easily to many people who have ignored and remain disconnected from the world.

Many people who have started to make this shift develop a sense of hopelessness, believing that we as a species are “bad” for the environment and that the slowness of our response to real and imagined crises dooms us. To them, humans are detrimental to nature—a species out of control—guilty just for being human. Many feel either that nothing can be done about our failures, leading to despair, or that we must sacrifice to atone for our sins. We should shiver in the dark, eat only beans and rice, and use less of everything. This view is equally flawed.

The problem is not us, but our ignorance and failure of imagination to understand how we could do better. We can be more comfortable, healthier, and secure by working with nature instead of fighting to subdue and conquer it. We have enough successful examples to show that by working with natural flows, renewable materials, and ecologically sound practices, we can exceed our current expectations with only 10 percent of the current negative impact or, better yet, with impacts that are positive. We know we need to change, but it is hard to get started. Guilt has never been an effective tool for driving change. Joy and satisfaction lead to more successful outcomes, and financial signals from true-cost accounting encourage improvements.

Balance, like sustainability, is a seemingly simple idea but in practice can be very complex. Our first impulse is to believe that a static balance must be achieved between humans and nature, our appetites and impact, and our economy and ecology. But what we need is dynamic balance and resilience to ensure the long-term stability of the complex systems that support us recover from perturbation. Certainly much of the industrial era has progressed with very little thought for consequences, and as William McDonough* has argued, we could hardly have done worse if we deliberately set out to do things as badly as possible, with the result being an out-of-control juggernaut of unbalanced, unhealthy, and destructive practices.

We need to be careful about how we define balance to avoid being caught in outdated attitudes or too narrow a focus. Balance is often defined by an accounting of inputs and outputs across the boundaries of a closed system that can be quantified, but an accurate accounting can be quite difficult to achieve for the complex world we live in. It is easy to fall for a single indicator that leads us astray. For example, the focus on energy conservation and stable interior temperatures in the 1970s led to sealed buildings that now cost the country billions of dollars a year in lost productivity and ill health.

Considering the complexity of living organisms and living systems, it should come as no surprise that achieving balance is complex and challenging. We need to focus more on our goal of healthy, happy, and productive people in a vital and resilient ecosystem—rather than oversimplifying indicators of balance, whether it is the temperature in a room or total global carbon emissions. Ecological systems, communities, families, landscapes, and heartbeats all

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* Sources mentioned or cited in the text are marked with an asterisk, and full citations are listed in appendix C, “References and Further Reading.”
dance to complex, collective, and often chaotic rhythm (“chaotic” in the modern scientific sense of unpredictable variations within prescribed limits, not in the literal sense of fearful disorder).

Passive Design

The pursuit of human comfort illustrates the flaw of seeking stability in inherently dynamic systems. We evolved in environments that varied in temperature, humidity, light, and wind conditions. Our activity levels, clothing, state of mind, mood, and other factors can also change, either inadvertently or deliberately. The development that began about 1950 of mechanical systems for heating and cooling buildings with heavily subsidized fossil fuels led to building standards that reflected the goals of the manufacturers of this equipment to sell more equipment, rather than the goal of meeting human needs. The ideal temperature was considered to be 72°F (see figure 1.2), and mechanical-systems controls were designed with the idea of making the balance between cold and hot as constant as possible. The buildings in which these mechanical systems were applied were not efficient. They were not well insulated, had very little thermal mass, and were oriented to minimize street, utility, and construction costs rather than to respond to sun angles or wind patterns. Therefore, the air conditioner or furnace had to come on fairly often to bring things back to the “ideal.” In reality, this type of temperature control is actually far from stable, as shown in figure 1.3.

Early attempts to provide natural conditioning of buildings with passive solar architecture ran up against the barrier of the static ideal enshrined in the building codes, which dictated that a building must be able to maintain a constant air temperature. The reality is of course far different, as any post-construction analysis will show, but this was ignored by codes and standards enforcement. The design of one of the first large passive solar buildings in California was blocked by interpretation of this static idea, despite the monitoring of existing buildings that showed all temperatures in offices in adjacent buildings were very unstable and often uncomfortable. In contrast, environmentally responsive passive solar buildings dance within prescribed limits of comfort, as shown in figure 1.4. The temperatures that dip outside the comfort zone can be eliminated by a very small backup mechanical system that is far less expensive in cost and energy use than that required to repeatedly adjust temperature as shown in figure 1.3.

Eventually, some regulators accepted the fact that temperature could be allowed to swing within a temperature band defined as the comfort zone, and passive solar buildings became more acceptable. A passive building is an integrated design approach that uses on-site energy sources and sinks to condition the interior by architectural rather than mechanical means. Experience around the world has demonstrated that we can provide most of the thermal conditioning needs of a majority of buildings with passive design.

Figs. 1.2–1.5. Passive design provides comfort without consuming nonrenewable resources in an effort to meet a flawed and unobtainable static ideal.
Triple-Bottom-Line Accounting

*The failure of the current worldwide economic system is in large part a failure of accounting.*

How did we get here? Many of our most pressing problems are the result of a mind-set that emphasizes parts and the short term at the expense of the whole and the long term. This bias creates specialized concentration on single-purpose concerns, often with disastrous consequences. This mind-set also contributes to the perverse incentives and distorting effects we list here; addressing these will encourage sustainable building.

- Recent architectural approaches evolved within a narrow framework that ignored the integration of multiple parts to achieve a whole. For example, Beaux Arts architecture of the nineteenth century emphasized art and history, and the resultant buildings all too often became shallow copies of the past rather than a response to contemporary needs. In the twentieth century, modernism became preoccupied with the function of space and circulation, but ignored human comfort and health, energy, and environmental impacts. Modern architecture became as narrow and fragmented as Beaux Art design and as unsustainable, often driven by abstract formulas and theories. The distorted view of architecture as sculpture has also contributed to the failure to embrace integrated, site-adapted designs that focus on health, comfort, and satisfaction. These may look good on paper or from a helicopter, but they can be untenable for occupants. The architect often plays the artist, and engineers are used to make the sculpture livable. The lighting engineer might be directed to design the lighting for minimal installed cost without considering possible use of daylighting (determined by the architect’s window decisions) or the cost of cooling to offset lighting heat gain (a problem for the mechanical engineer). The architect would often design the building without consulting anyone about the implications for natural heating, cooling, or daylighting. User comfort, health, and productivity are rarely an issue, a concern thought to be handled in the codes. Prospective occupants are rarely surveyed, and post-construction analysis is not done.

- Given current financial pressures, a developer in the United States must focus on minimal first cost without considering life-cycle costs, health, comfort, and productivity. Building owners usually pass all energy costs to leaseholders and feel little pressure to improve efficiency. Many large buildings are poorly operated and maintained. Building operation is not a highly valued or rewarding profession, and operators are often not treated well or given the resources they need to do their jobs well. Managers of flawed buildings often assume the energy demands are immutable and may reduce or fire maintenance staff to save money, further increasing life-cycle cost as poorly maintained mechanical systems add pollutants to indoor spaces and the moisture buildup and leaks lead to mold, rot, and increasing risk to health and productivity. The difference in building service life between the United States and Europe is related to differing economic incentives. Buildings in Europe have a lifetime that is typically double, but often four times as long as, that of a comparable building in the US.

- Subsidized power and material costs are also important. The estimated subsidies ($45 billion per year) for nonrenewable fuels have biased the market against renewable energy sources. If energy costs reflected real costs, electricity would

Reimagining architecture as a complex team effort that integrates art and engineering from the start to meet human and environmental needs and embracing sustainability is critical and will result in a new green architecture as different from modern architecture as modernism was from Beaux Arts.

Like architecture, economics has also devolved into a highly fragmented endeavor where many complexities and costs can be ignored by exiling them to the public and environmental realm as “externalities.” At the same time, obsolete subsidies from the past have become frozen through the dominance of lobbies and political contributions. The result is a rapidly crumbling economic edifice of flawed accounting, wasted resources, inefficiencies, obsolete subsidies, and the misplaced focus on financial manipulation and wasteful marketing. The effect of all of this on architecture and building is to further accentuate the disconnection between building impacts and costs described above.
cost four times as much as it does today. The separation of
users from production costs also has encouraged poor design
and very wasteful operation.

- Planning is still dominated by the post–World War II auto-
based suburban model that ignores sustainability concerns
despite the high and increasingly expensive infrastructural
cost of building. This approach to planning can severely limit
options for solar orientation, natural cooling, and meeting
infrastructure needs on-site. Good planning requires an inti-
mate understanding of the site, microclimate, air shed, waters-
hed, and bioregion.

- Incentives for minimal innovation are incorporated in percent-
age-based fees common for architects and engineers. These are
often fixed percentages and encourage use of standard plans
and details that are acceptable, but unoptimized. Liability fears
common in our litigious society may cause engineers to oversize
equipment to avoid lawsuits and callbacks, where a contractor
has to come back to respond to complaints of inadequate heat-
ing, cooling, ventilation, or lighting. Although more challenging
to put into practice, performance-based contracting fees related
to savings over base-case conditions drive design innovation.

- Failure to follow up on building performance is also perva-
sive. Building commissioning provides a critical first step and
is now required for LEED-rated buildings, but remains rare.
Building commissioning provides training for the new occu-
pants and managers and a management guidebook, just like
commissioning a naval vessel. Building performance after
completion is seldom monitored, although it is easy to do
this now that inexpensive automated sensors and recorders
are readily available. A recent review of rated LEED buildings
showed that many were not meeting performance expecta-
tions, illustrating the importance of monitoring.

- It’s ironic that with our high level of education and massive use of
information technology, ignorance of some very basic things is
still so widespread in the design professions. Topics such as solar
orientation and natural lighting are not complex or difficult, but
our society’s general level of abstraction and disassociation have
taken these commonsense relationships out of use. It used to be
rare for architecture students to visit or see a sustainable build-
ing or to work with sustainable building materials.

Many of these problems will be alleviated as we shift from a one-
dimensional economic viewpoint with a flawed accounting system
to a three-dimensional economic viewpoint with the more accu-
rate accounting we are now capable of undertaking. This is possible
owing to our greater ability to process, model, and evaluate information. This new way of factoring costs is called triple-bottom-line
accounting, a concept developed by UK business consultant John
Elkington in 1997. Triple-bottom-line economics differs from con-
ventional accounting because it attempts to include ecological and
cultural costs and benefits, as shown in figure 1.6. In a healthy soci-
ety, these factors should not remain in opposition to one another,
but should reinforce sustainable behavior, health, and happiness
(Bainbridge, 2009*). The use of triple-bottom-line accounting in
life-cycle design is most clearly articulated by William McDonough
and Michael Braungart,* who developed the diagram shown in fig-
ure 1.6. This diagram, when shown as a fractal, expresses the com-
plexity of the issues, the potential for integrated solutions, and the
infinite diversity of response that humans are capable of making.

Fig. 1.6. Triple-bottom-line accounting. The figure illustrates the
complexity of the balancing act required to integrate ecology, economy,
and social equity. Every little decision has implications for all three.
Green Architecture

Fig. 1.7. Green architecture. This diagram shows the roots, common terms, and continuing evolution of green building. The roots of the green building movement are sustainability, passive design, and triple-bottom-line accounting. This diagram shows the continuing evolution of concerns and techniques growing out of these roots and through synergetic design, becoming green architecture and sustainable building.
To address the problems with architecture and building, triple-bottom-line accounting means that costing must be revised to include all life-cycle costs over the thirty-, fifty-, or one-hundred-plus years of service life for construction, operation, and maintenance. All health and environmental costs created by hazardous materials and pollution, from production to construction and on through disposal or reuse of building materials, must be included. It should also include pollution-related costs from energy and water use and the impact of other material flows for maintenance and operation. With creative design and true-cost accounting, we will find that some of these costs are negative—but some can be positive. Life-cycle costing can lead to life-cycle design where savings can be achieved by developing synergies. Synergy occurs when the advantages of the whole far exceed the advantages of the parts. This is why a sustainable society offers greater wealth, health, justice, comfort, and joy.

The adverse impacts of our current way of doing things can be evaluated by periodically examining the ecological footprint of our planet, nations, communities, families, buildings, and materials. Mathis Wackernagel* and William Rees developed the concept of an ecological footprint to demonstrate the impact of our way of living through the amount of land area it takes to maintain present industrial lifestyles. We can do this at a very simple level by calculating our ecological footprint online using an eco-footprint calculator (see, for example, www.myfootprint.org).

Cultural Shift

Our goal in building sustainable buildings must always be to improve the comfort, health, and security of people. To do this, we need to rethink our approach to design and operation of the built environment while maximizing use of renewable resources and minimizing life-cycle costs. Improving comfort and health yield the biggest dividends. Energy and water use, waste minimization and recycling, ecosystem protection, and first cost are also important. Integrating systems is critical to meet multiple needs and goals, maximize benefits, and minimize costs. Optimizing design at the earliest stages can often dramatically improve performance at little or no additional cost.

The first step is proper orientation for solar heating and natural cooling. If possible, insulation should be placed outside the thermal mass. The only exception is in hot, humid climates where light frame or open buildings with optimized ventilation are the key to human comfort. Traditional homes in hot, humid areas often were placed on stilts to get more wind for ventilation cooling, or they had very high ceilings and paddle fans to keep air moving and double roofs to keep solar heating to a minimum.

This review of passive buildings using performance simulations showed that annual energy use for heating and cooling dropped from 53,802 BTU to 904 BTU (98 percent) for a super-insulated roof pond (98 percent) in El Centro, California, and from 48,525 BTU to 4,832 BTU (90 percent) for a super-insulated solar building in Denver with appropriate thermal mass. A building with just

### Table 1.1. Sustainable building performance, as measured by energy use for heating and cooling in BTU per square foot per year.

<table>
<thead>
<tr>
<th>Location</th>
<th>Nonsolar Stick-built</th>
<th>Solar Stick-built</th>
<th>Solar Straw bale (SB)</th>
<th>Percent reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling BTU</td>
<td>Heating BTU</td>
<td>Heating and cooling</td>
<td></td>
</tr>
<tr>
<td>Denver, CO [5673HDD, 625CDD]</td>
<td>7,450</td>
<td>41,075</td>
<td>48,525</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar Straw bale SB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooling BTU</td>
<td>2,686</td>
<td>1,816</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Heating BTU</td>
<td>13,474</td>
<td>3,016</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>Heating and cooling</td>
<td>16,160</td>
<td>4,832</td>
<td>90</td>
</tr>
<tr>
<td>Sb int* adobe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof pond</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Solar Straw bale SB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cooling BTU</td>
<td>11,387</td>
<td>553</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>Heating BTU</td>
<td>904</td>
<td>351</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Heating and cooling</td>
<td>53,802</td>
<td>98</td>
<td></td>
</tr>
</tbody>
</table>

*Calculations by J. Rennick and SLSG

*Straw bale with adobe interior for mass
good insulation and sufficient thermal mass usually achieves a 50 to 70 percent energy savings, but with good orientation and window placement, it can reach 80 to 90 percent.

The choices of materials also matter. They should be, insofar as possible, local, natural, and renewable. As Arne Naess* notes, “The degree of self-reliance for individuals and local communities diminishes in proportion to the extent a technique or technology transcends the abilities and resources of the particular individuals or local communities. Passivity, helplessness and dependence upon ‘megasociety’ and the world market increase.” Self-reliance is critical, as the building challenge is not simply for the developed countries—although their use of resources is disproportionately large—but must also include the billions of people who remain in poverty. Application of sustainable design principles can improve the lives of people in Geneva, London, Cape Town, Sydney, Los Angeles, and Lima, as well as the favelas and slums of the world’s growing megacities. The oldest occupied communities in the United States, the pueblos of New Mexico, reflect the importance of local, sustainable, and understandable materials. Building systems that employ locally available, safe, and easy-to-use materials such as straw bales and earth deserve special recognition because everyone in the community, including kids, can participate in construction. Community building through straw bale building workshops has created added benefits for this very efficient, sustainable building material (figure 1.8).

Fig. 1.8. To construct a small straw bale cottage in San Diego County, many people help a family create a new living space, while learning the techniques for building with straw bales and becoming part of a burgeoning sustainable building community.

There are many benefits to changing our cultural attitudes to planning and building, but to start, we would emphasize three key concerns: health, security, and economy.

Sustainable buildings are healthier: Fewer sick days, reduced allergies and irritations, fewer doctor visits, reduced medical expenditures, and better sleep—all these add value. Comfort adds quality to life, and comfort and health add to productivity gains in the office or factory. And as Ken found in surveys for a state office building design, people are aware of the problems and flaws in buildings. Many related how they hated their current space and were trying to transfer to different units where offices had more daylight and better ventilation.

More sustainable buildings also provide security and freedom from fear. Even if the power goes out in an ice storm, earthquake, hurricane, political dispute, or power-grid failure, homes will remain comfortable and livable. Commercial and industrial buildings remain inhabitable even when the power goes off, and workers can wrap up their work rather than groping their way through a dark and unpleasant building to get to safety outside.

The most important reason for change is for long-term prosperity. Better design can save money now and as long as the building is used. Money can be spent on more productive activities rather than simply going to the utility company. As the California blackouts of 2001 showed, we can’t count on nonrenewable energy resources. They will be more expensive in the future—perhaps much more expensive.

Energy costs for operating a sustainable building are low, and will remain low. This can be critical for retired people and institutions and is important for families and most businesses. Heating and cooling costs can be kept below $50 per month, in contrast with the rapidly rising utility bills many people experience today.

Sustainable buildings increase the quality of life. They improve health, speed learning (schools), increase sales (retail), improve patient outcomes (hospitals), and improve productivity (manufacturing and services). In commercial buildings, the return on investment for improvements on air quality alone has been estimated to be 60:1—far better than any Ponzi scheme! In central California, the revised design of a tract home led to reduced construction costs and a seasonal energy savings for heating and cooling of 70 percent. Rather than “freezing in the dark,” as the fossil-fool-funded opponents of renewable energy have argued, occupants and workers in sustainable buildings will be dancing in the sunlight!
**Energy Flows in Buildings**

It is sometimes helpful to go back and look at what was done before mechanical systems and energy consumption ruled the building comfort universe. Today you make the HVAC system whatever size is needed and buy the amount of energy required. The problem is today soon becomes tomorrow. Energy availability and cost will change. I am betting that some of these old lessons will become the basis for tomorrow’s buildings.

—Joseph Lstiburek, 2008

The physics of comfort and building performance are relatively straightforward. Unfortunately, most designers and builders have ignored these principles in recent years and simply added fossil-fueled space-conditioning systems to force bad buildings to provide reasonably tolerable conditions. We can do much better when we work with the sun and on-site climatic resources, but to do that we need to start by understanding and reconsidering some basic assumptions. The first of these is the elementary relationship among energy production, use, and efficiency.

**Energy Production, Use, and Efficiency**

Our society has so isolated production and use that very few people think about the impacts of their use of energy. We flip the light switch without considering the long chain of responsibility that leads back to the power plant, open-pit mine, and ravaged countryside. While we’ve become more efficient on the production side, we’ve become extremely wasteful on the use side. Just look around and notice all the high-quality energy being wasted by the massive use of electric lighting during the day inside buildings and often outside as well. We are not only lighting a majority of the earth at night, we are attempting to do the same during the day.

Passive design at this most basic level is the reuniting of these three: production, use, and efficiency at the scale of the building site. A *passive building* is defined as a building that:

1. Uses on-site energy sinks and sources.
2. Relies on natural energy flows with a minimum of moving parts.
3. Includes energy production as an integral part of the building design.

When we fail to consider the implications of our actions, we often do harm to others or the planet. Sometimes the simplest, most basic relationships become confused as we deal with complex social concerns such as energy regulations. For example, California’s...
well-regarded Title 24 building energy regulations have emphasized efficiency to the neglect of on-site production produced by passive means. Hence this code, the strongest in the nation, will not give credit for the most basic passive strategies such as thermal mass or night ventilation cooling. Likewise, the national LEED green building rating system with its linear checklist has an unintended bias against highly integrated passive design. Using linear analysis to evaluate a connected synergetic product will not work. Fortunately, both of these programs are evolving over time and will eventually be corrected to allow the basic relationships among production, use, and efficiency to be more accurately evaluated.

Building Metabolism

The scale of our buildings and artifacts on the earth have now gotten so large that we must now think of them more like living organisms that are part of ecological systems if we are to be a healthy part of the planet and not some self-destructive parasite.

—IAN McHARG

On a particular site, energy sources and sinks suggest how much energy is available for use in a building. It may seem that once the building’s use is determined, it should be relatively easy to determine the energy needed—the building’s load. In fact, however, determining load is one of the more challenging aspects of natural space conditioning. Loads are a product of the relationships of the building’s scale, metabolism, form, and human behavior. This is a complex problem because the relationship of these factors is not linear. To understand this complexity, consider the thermal loads of two different animals, a hummingbird and an elephant (see figure 1.13).

Animals, like buildings, need to maintain a relatively constant temperature. Heat to maintain this temperature is provided by the animal’s metabolism, and heat loss occurs mostly through the animal’s skin. Heat loss is therefore related to the skin’s surface area. A hummingbird is a very small animal, and the ratio of skin area to the volume of its body is very large. The hummingbird loses heat rapidly and must have a high corresponding metabolism to maintain a high enough interior temperature. Hummingbirds feed on the nectar of flowers, one of the most concentrated foods available in the natural world, and must eat often. In contrast, elephants, though vastly larger, have a low skin-area-to-volume ratio, with correspondingly lower heat loss. Thus, elephants can survive with less frequent meals of low-energy food like plant leaves.

Buildings act the same way. There are buildings like the hummingbird, with a large skin-to-volume ratio. These are called skin-dominated buildings, that is, buildings in which the building envelope
dominates the thermal loads. Corresponding to the elephant are the interior-load-dominated buildings, which are large enough for the internal loads to dominate their thermal character. Knowing these rather simple relationships destroys one of the myths of passive heating: that it is easier to heat small buildings than large buildings. Actually, in most temperate zones, the reverse is true. Heating larger buildings is usually easier because they produce much more internal heat, and their skin-to-volume ratio is small. Thus, if properly designed, they can often heat themselves largely by their own internal metabolism—metabolism being defined as heat generated inside the building by lighting, equipment, and people. Cooling, however, presents another set of challenges for large buildings.

In most temperate zones, heating, cooling, or combinations of the two are the limiting design factors for skin-dominated buildings. In interior-load-dominated buildings, heating is generally easier to accomplish than cooling, particularly if artificial lighting is not overused. Artificial lighting produces a great deal of heat, which is added to the cooling load. In many large, thick industrial-era buildings, lack of natural lighting is usually the limiting condition.

The recent bias has generally been toward interior-load-dominated buildings because they lend themselves to a single goal—maximum rental area for the lowest first cost. However, from an aesthetic, social, health, productivity, and environmental viewpoint, the typical interior-load-dominated building of the industrial era is disastrous. Skin-dominated buildings are usually more appropriate in temperate zones, because balanced natural heating, cooling, and lighting are easier to achieve within these buildings. In addition, social relationships are better when users feel less cut off from the exterior environment. They are also easier to daylight, and studies have shown they are healthier and more productive. The perceived density advantages of big, interior-load-dominated buildings are illusions, except to the building developer.

**Energy-Efficient Building**

Integration of many factors is the essential character of sustainable buildings. A passive sustainable building is one that is efficient enough to use the energy available from the sun and microclimate of the site to meet its needs. A sustainable building integrates production, use, and efficiency at the building site. Keeping integration in mind, this section deals with energy efficiency, an aspect of building, design, and construction that is a necessary prerequisite for a successful passive building. However, energy efficiency in itself does not create a passive building. The key is on-site energy production. This distinction is very important to avoid the confusion that exists with our present regulatory and evaluation structures, which recognize energy efficiency but do not consider energy capture or production at the building scale.

An efficient building must minimize heat loss or gain depending upon the season and its internal metabolism. Achieving this involves siting and orientation, which both affect solar use and control and air movement and control. It also requires energy-efficient construction with careful weatherization and appropriate construction materials.

**Fig. 1.13.** Thermal loads related to form: skin-dominated animal versus load-dominated animal.

**Fig. 1.14.** Thermal loads related to form: skin-dominated building versus load-dominated building.
Siting and Orientation: The Best Orientation?
Face the Equator!

Many designers find it uncomfortable to acknowledge the importance of facing the equator (south for the Northern Hemisphere, north for the Southern Hemisphere). This is because they feel this is an affront to their creativity. However, we would argue that this is an immutable cosmic relationship with multiple advantages. Failure to use these advantages is not an act of design freedom but a failure of the designer’s creativity and unwillingness to acknowledge the implications of his or her choices on the planet and future generations. Creative design can resolve design problems even for odd-shaped sites with important views in other directions or with other site limitations without giving up important advantages of good orientation.

There are three reasons for this cardinal rule:

1. If you wish to utilize solar radiation for heating or daylighting, facing the equator gives the best solar access. Horizontal sun from the east in the morning and the west in the evening is not very effective except for producing uncomfortable glare and summer overheating.

2. Conversely, if you wish to control solar radiation in the summer or fall, the same orientation is optimal because the sun is high in the summer and low in the winter and can therefore be easily controlled with simple horizontal overhangs that still allow the sun in during the winter.

3. If your site is in the tropics, the sun from the equatorial direction is very high year-round—and the climate is likely to be hot year-round as well. Therefore solar control is the main concern, and it’s still most easily done with horizontal overhangs on the side facing the equator.

Sun from the east and west is very difficult to control owing to its lower angles, which cannot be blocked by simple overhangs. The control of east or west sun is better accomplished through vertical fins, wing walls, louvered screens, or landscaping.

In this section, we concentrate on energy efficiency, but remember that orientation principles are important for energy production in passive solar buildings, for heating, daylighting, or electrical production.

Making optimum orientation a part of the design process is not difficult, but there are some basic things to consider. These are shown in detail on page 18.

Fig. 1.15. This south-facing building in the Northern Hemisphere collects solar radiation in the cold winter and yet is fully shaded on a hot summer day. Low horizontal sunlight in the morning and late afternoon is intercepted by wing walls below and vertical fins on the south-facing dormer.
Insulation

The second step in building or remodeling for energy efficiency is reducing unwanted conductive heat loss (or gain). Insulation is the key—not only for the walls and ceiling, but also for the foundation or slab perimeter, windows, doors, and the people inside. Most homes are woefully under-insulated. Typical wall-insulation levels are still R-13 to R-19 in many areas of the country, but they should be at minimum R-30, and R-50+ is much better. Straw bale buildings can offer R-40 walls at about the same cost as conventional buildings with R-19. Double-wall systems with cellulose insulation can also reach R-40 easily. Foam sheathing inside, outside, or both in- and outside of a wood-framed wall can also reach adequate levels of insulation, but sustainability and moisture questions remain. Insulation on massive walls of stone, concrete, brick, or earth should always be on the outside.

Ceiling or roof insulation is relatively easy to install and should generally be R-50+ in most temperate areas. Installation detailing is critical to avoid fire risks, properly ventilate attics and roof spaces, and ensure adequate weatherization.

Scrimping on insulation is penny-wise and pound-foolish because insulation is the least expensive component of standard construction. Adding more later is much more costly. The expensive part of upping insulation levels is not the insulation itself but creating the added cavity space required. It is also very important to provide a small but vented airspace above high levels of insulation in ceilings to avoid moisture buildup that can lead to mold problems. This is advisable even in relatively dry climates where this traditionally is not done with lower levels of insulation. The greater the amount of insulation, the greater the potential will be for condensation on its upper surface: Condensation occurs on the coldest surface.

Double-pane windows are commonly used, and high-performance windows or double-pane plus storm windows are usually cost-effective. Doubled single-pane windows might be the lowest-cost long-life window system in some parts of the world. Argon-filled high-performance windows are worth considering, as are the transparent insulating materials that can reach R-20, but these can be hard to obtain and costly in many areas.

Insulated drapes, blinds, and shutters are very effective on windows and skylights if they are well sealed. Interior shutters may cause overheating and failure of plastic skylight glazing or double-pane window seals. Exterior insulated blinds and shutters are preferred but more challenging to find (except in Europe) and more costly to build.

Weatherization

Infiltration losses are as important as conductive losses, and careful weatherizing is necessary. This includes both the obvious problems of weatherstripping doors and windows and also the more general problems of caulking and sealing building joints, access holes, and other areas where unwanted infiltration occurs. Infiltration may easily account for half of the heat loss in a well-insulated but poorly weatherized house. The infiltration rate on a typical house may be 1.5 air changes per hour, but can go significantly higher if the wind is blowing. With careful attention to detail the air exchange can be reduced to 0.2 changes/hour.

This low rate of air exchange can be unhealthy, especially if materials and operations inside the building include semi-toxic materials (deodorants, cleaning materials, smoking, off-gassing furniture and carpet, fixtures, decorations, air fresheners, and so on). The goal is to have controlled ventilation so the air comes in when and where you want it and is fresh and healthy. A super-insulated solar house will perform so well, it is often possible to have several windows slightly open almost all winter. In Europe, small trickle vents are being installed for fresh air. In very cold areas, an air-to-air heat exchanger is desirable for ventilation during the coldest periods. The heat exchanger warms the incoming fresh air with warm stale outgoing air. The low cost and efficiency (up to 90 percent) of this type of heat exchanger, coupled with very good insulation and a very tight building, allows a level of efficiency so high that residences in the difficult winter climates of Northern Europe can be heated by internal heat and solar gain.

Well-insulated, high-thermal-mass buildings were pioneered by Emslie Morgan, who designed the St. George’s School in Wallasey, England, in 1961. This building was heated for many years with only south-facing windows and energy from the students. In the 1980s with the advent of inexpensive air-to-air heat exchangers, super-insulated and super-weatherized buildings were built in Alaska, Canada, the continental United States, and Denmark. The rapidly growing Passivhaus movement in Germany and Northern Europe has demonstrated that super-insulated, super-weatherized buildings with heat-exchange ventilation can reduce heating costs 80 to 90 percent and cost only 5 to 7 percent more to build than standard residences. More than twenty thousand have been built in Northern Europe to date.
Fig. 1.16. The exterior and the performance of a solar-oriented, super-insulated, super-weatherized passive house in Darmstadt, Germany.

Energy-Efficient Materials

Most conventional building materials come with a very high lifecycle energy cost. Most are damaging to the environment, require the use of dangerous ingredients as well as massive amounts of energy and water, and have only a limited lifetime. But it doesn’t have to be this way if we consider buildings, materials, and construction in the context of energy and resource efficiency and on-site energy production. We need to understand three aspects of materials: their thermal characteristics, the embodied resources they contain, and their relation to the carbon cycle.

Thermal Characteristics of Building Materials

The most important thermal characteristics are insulation and thermal mass. These two are often confused, but the differences are critical to understanding energy flows in buildings. Insulation is the ability to resist heat flow. This is accomplished by providing trapped airspaces that reduce convection or reflective foils that slow radiation transfers across dead airspaces. Insulation effectiveness is measured in R-value, with the R standing for “resistance to heat flow.” Materials with high R-values are necessary for buildings to retain heat when the exterior temperature is cold or to retain “coolth” when the exterior temperature is hot.

Thermal mass provides the ability to store heat or coolth so that the interior temperature swings of the building are dampened. The measurement of a building’s response to both thermal mass and insulation is measured by a building’s time constant in hours. The time constant is the characteristic time it takes for the inside of a building to approach ambient conditions. The time constant of an uninsulated wood-framed house with gypsum wallboard is about half an hour, a passive building twelve hours, and a better passive building twenty-four hours; a totally optimized passive building might reach a time constant of eighty hours.

For skin-dominated buildings in temperate climates, both insulation and thermal mass are needed. One without the other will not produce an optimized building. Generally speaking, the building envelope should be well insulated, and interior surfaces and elements should have thermal mass. The trend for energy-efficient buildings has been to develop composite wall systems that have highly insulated exterior surfaces, and interior surfaces that provide thermal mass.

This is the opposite of traditional construction with heavy exterior walls, limited insulation often on the inside, and very lightweight interior walls.

Embodied Resources of Materials

Building materials not only influence the energy requirements of a building but also require energy and resources for their creation, shipping, and application. The energy costs of collection, processing, and transportation are called the embodied energy of a material, and can be determined by accounting for the energy requirements in sourcing, transporting, processing, distributing, using, maintaining, and eventually recycling the material. Materials such as aluminum and Portland cement have high embodied energy as a result of the considerable energy used in their production, while others like gypsum and earthen materials have low embodied energy.

In addition to embodied energy, building materials also require other resources and create other problems such as deforestation and air and water pollution. These factors are all considered in the Wuppertal Institute’s studies of the material intensity of the German economy (Schmidt-Bleek, 2000*). In Germany, buildings and dwellings accounted for 25 to 30 percent of the material flow of the economy. We don’t have this information for much of the US economy, but the figure is probably larger.
Fig. 1.17. **Burning rice fields aggravates asthma for local residents, increases health care costs, and generates greenhouse gases. A waste of an excellent building material.**

Dealing with true costs as discussed above requires a careful accounting for all the embodied costs of materials and is an important part of what’s called the life-cycle assessment of a building. There are two ways to look at life cycles. One is cradle-to-grave life cycle, in which we look at all the costs of materials through one complete cycle of use to disposal. The second is cradle-to-cradle resource cycles through several uses (McDonough and Braungart, 2002*). We design the building material to optimize the whole by adding value to cost, including value for the next cycles of use and/or supplementary values in the process of manufacture. This approach is referred to as life-cycle design and is an important part of the transformation of our industrial waste-based economy to a sustainable one. This more integrated approach can often find new uses for what are currently considered wastes. Rice straw is a good example of a waste that can be used to build high-performance passive solar buildings.

**Carbon Sequestration**

The climate crisis is upon us, caused by our profligate use of fossil fuels for more than 150 years. Our unfortunate delay in addressing this massive threat now forces us to respond with far-reaching efforts to avoid a catastrophe affecting everyone on the planet. There have been proposals for removing carbon dioxide from the atmosphere by scrubbing it from coal plants and burying it deep underground in geological formations that have been emptied by oil production, or by building gigantic scrubbing antennas into the sky, or by seeding large parts of the ocean with iron powder to produce plankton blooms that will take up carbon dioxide. The risk and expense of such schemes indicate the difficulty in which we find ourselves, but also reflect the reductionist industrial-era mind-set that perceives separate operations as a solution to an integrated systems problem.

It makes more sense to include the sequestration of carbon as a part of an existing human activity—building. To quote an old Chinese saying, “Why not ride the horse in the direction it is going?” We could start sequestering carbon at a rate far exceeding these expensive schemes to isolate or hide carbon at far less cost by making it an integral part of our building activity. Straw has a very low embodied energy cost and high carbon content, is presently considered a waste material, and is most commonly disposed of by field burning. By using straw in buildings, we improve building performance and reduce greenhouse gas emissions, reduce emissions from field burning (figure 1.17), and reduce methane emissions from rice straw decomposition in wet fields. This is a perfect example of a sustainable life-cycle design solution. By changing building design, we will have added a new value to construction addressing the climate problem while simultaneously creating less expensive, healthier buildings and reducing the pollution impacts of the field burning of straw.
Traditional Materials

The concern for sustainable buildings is changing the way we select and specify building materials and increasing the variety of available materials. The development of new, more sustainable materials is also proceeding rapidly. The desirability of traditional industrial materials such as steel, concrete, glass, milled lumber, gypsum board, and ceramics is being reevaluated. Steel has fared pretty well because much of it is recycled. Concrete has become less desirable because producing cement adds a large amount of CO₂ to the atmosphere (up to 15 percent of human-made greenhouse gases). The appropriate use of wood depends upon how it is grown and harvested, and certified wood should be considered. Aluminum is frowned upon because of its high embodied energy, but it is easily recycled. Vinyl and PVC plastics are avoided because of the toxic by-products emitted during their creation and when they burn in fires, and difficulties involved in reusing and recycling them. Gypsum wallboard has a bad reputation because it can become moldy if damp, but it has low embodied energy. Although it is relatively lightweight, it’s cheap enough to allow adding additional layers for greater thermal mass when needed. Wallboard with phase-change materials incorporated may offer the benefit of much-improved thermal storage. Straw board can be an excellent material for interior walls, but is not readily available in most of the world.

Traditional pre-industrial materials are being reconsidered because they have very low embodied energy and resources and high thermal-mass capabilities. These include the following materials.

- **Rammed earth**: Soil is the building material in rammed earth construction (see figure 1.18). Selected soils are moistened, placed in forms, and rammed to a high density and strength. This method of construction has been used for thousands of years. Parts of the Great Wall of China are rammed earth. The technique can be used for multistory buildings if done carefully. In modern times, rammed earth systems have been refined in France (called pisé) and other parts of Europe, where thousands of such buildings are found. The Miller passive solar house in Denver made good use of rammed earth in 1950. More recently, innovative builders like David Easton in California have developed methods of spraying on the dirt at high pressure to speed construction, but rammed earth walls can also be built with simple hand tools. The result is high-mass buildings with thick, dense walls 12 to 24 inches thick that are quiet and durable, with a beautiful finished surface.

- **Adobe**: The tradition of building with dried mud blocks, called adobe, also goes back thousands of years. Adobe walls are often very thick for larger buildings (between 36 and 72 inches) and between 14 and 24 inches for residential-scale buildings. Builders in Yemen reach up to ten stories with straw-reinforced...
Adobe blocks. Adobe blocks have also been used to build domes and arched structures in many areas. There are perhaps seventy-five thousand adobe homes in New Mexico, a relatively stable seismic zone. There are millions of adobe buildings in China, the Mideast, and Africa that, unfortunately, are not so seismically safe. Although techniques for seismic reinforcement have been developed, they are not widely used outside the United States. Thermal performance of adobe can be improved by adding more straw. The cost of building with adobe is high in the United States because it is so labor-intensive—often double the cost of a comparable straw bale wall.

Straw bale: Building with straw bales has been a marvelous success, far beyond what we imagined at the first straw bale building workshop in Elgin, Arizona, in 1989. The straw bale revival began after historic buildings from the early 1900s were rediscovered in the Great Plains. Straw bale buildings are surprisingly fire resistant once plastered, provide superior insulation (R-30 to R-45+), provide distributed thermal mass with their thick interior plaster skin, and create living spaces that are quiet and economical. In addition, straw bale buildings sequester carbon and are fairly easy to make earthquake-resistant. For these reasons, thousands have been built recently both at commercial and residential scales around the world. Natural plasters of mud and clay mixed with straw can be used in many circumstances for the finish surfaces on the bales, particularly on interior walls.

In the enthusiasm of rediscovery, there has been some misuse of these traditional materials. Keep the basic requirement for energy-efficient buildings in mind. Rammed earth and adobe have wonderful thermal mass but provide very little insulation, so in climates with wide external temperature variation they need to be insulated on the exterior. The most common method for doing this is to add a layer of polystyrene foam at the exterior surface just behind the weather skin.

Rammed earth and adobe walls are most effective thermally when used as interior walls within a well-insulated shell where their thermal mass is best utilized. From an energy- and resource-efficiency viewpoint, the optimum use of these materials is to have exterior walls of straw bale construction and interior walls of adobe or rammed earth. This has been validated by computer simulation studies of this arrangement for a variety of climates across the United States (Haggard et al., 2005*).

New Materials

Along with the rediscovery of traditional materials has come the development of a host of new materials for sustainable building. Nanotechnology has allowed the manufacture of microscopic containers of paraffin at the scale of the finest grade of sand. When paraffin melts or solidifies, the phase change enables large amounts of energy to be stored or released. These nanoparticles can be also added to concrete or plaster to create high-thermal-mass components that don't weigh very much. This material can also be added to gypsum so that lowly gypsum board can now become very inexpensive effective-thermal-mass interior material. Long-term studies of the health and ecological risks of nanoparticles have still not been done, but the hope is that they will prove safe.

The creation of new types of transparent insulation systems (see figure 1.23) that allow solar gain (insolation) and yet provide good

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*Haggard et al., 2005*
insulation with the same material are also noteworthy. Advances in the development of new glazings allow for either heat-rejecting glass or heat-receiving glass. Glazing with greater insulation value than ever before still retains visual characteristics needed for natural lighting. Aerogels allow very high insulation values yet still allow solar energy to pass through. There is also glazing that can change opacity with temperature, creating an automatic response to thermal conditions. Increasingly, there are photovoltaic materials that are also building components, and some can be custom-designed to produce different degrees of transparency while still producing electricity. Advances in waterproofing materials and techniques now allow the incorporation of landscape as a direct part of the building for green roofs, although detailing remains critical to avoid costly, bothersome leaks. Finally, with improvements in plastics we have the opportunity to more economically add water for desired thermal mass in tubes, tanks, or other containers. Beautiful tiles and ceramics can be created from a host of recycled material like crushed glass or various scrap.

As more appropriate technologies develop and we evolve a sustainable design culture, a range of materials, both old and new, will make the narrow vocabulary of the late industrial period look mundane and boring.

**Fig. 1.22.** Photovoltaic trellis, green roof, and natural lighting on the California Academy of Science, San Francisco.

**Fig. 1.23.** Transparent insulation.

**Fig. 1.24.** Thin tiles containing nanoscale capsules of phase-change paraffin provide lightweight thermal mass while acting as a light-diffusing element for a library.

**Fig. 1.25.** Glazing capable of changing from clear to opaque, controlled by electric current.
The Importance of Place

Scales of Place

With the first mission to the moon, we were able to see the earth in a new way for the first time. Today we can see the surface in remarkable detail by simply pulling up Google Earth on our computers. We have a fully integrated worldwide economy for the first time. We are for the first time just starting to realize we are changing the world’s climate in ways that are likely to be very costly.

To develop more sustainable designs, we need to start with this perspective of spaceship earth. We begin by considering our place in the biosphere and working down through smaller and smaller systems until we reach the site. Integrated understanding of the relationships among these inter-nested systems is our goal and a key element in creating sustainable designs.

**Biosphere:** The realm of life on earth. From the upper atmosphere to deep in the ocean and inside the earth’s surface, life exists and thrives in an area larger than previously thought.

**Biomes:** The major types of natural environments. Each biome consists of similar climatic, geological, and ecological characteristics that are considered unique. UNESCO’s Biosphere Reserve Program lists fourteen terrestrial biomes; the Köppen system of world climates lists seventeen.

**Bioregions:** Biomes further differentiated by topography, hydrology, smaller climate variation, or other factors are called bioregions.

**Watersheds:** The area drained by a particular drainage system is called a watershed. Large watersheds contain progressively smaller watersheds. Water is such a critical element for life that watersheds should be a very important design consideration.

**Airsheds:** An area determined by topography and wind patterns, much like a watershed. Humidity, temperature, pollen, and pollution flow and concentration are all affected by airshed characteristics.

**Ecosystem:** This is a much more specific area describing particular flora and fauna of a biome or bioregion.

**Ecotone:** The overlapping area where ecological communities meet is called the ecotone. Ecotones are important because they are usually biologically richer than a single ecological community, due to the edge effect.

**Landscape:** The visual surroundings as perceived by a viewer. In this context, it refers to the perceptual whole rather than just vegetation, and includes the effects of human activity.

**Settlement pattern:** Human settlement patterns have been more diverse than the industrial standards of a city, suburb, and country. Thus, the use of the term is more generic.

**Settlement:** A particular part of the general settlement pattern, usually politically or spatially defined.

**Complex:** A group of buildings, open space, and infrastructure creating a recognizable unit.

**Architecture:** Buildings and their adjacent spaces.

**Artifacts:** Human-made objects.

**Materials:** That which a place or object is constructed from.

**Compounds:** Building blocks of materials.

**Elements:** Building blocks of compounds. Compounds and elements can be in solid, liquid, or gaseous forms and can thus flow back into larger entities. If done in a non-designed, careless way, this can be in the form of waste or pollution. If done in an optimized design, they can take the form of a useful resource.

**Biomimicry:** A growing field of research that will play an increasing role in sustainable building design and construction; nature is seen as model, measure, and mentor.

Global industrialization has tended to homogenize place. One of the main tenets of modern architecture was that the same design could happen anywhere, which is why it’s sometimes called “international architecture.” To reconnect to place, we need to start with the recognition of the differences in place. We can begin by understanding biomes. A biome is an ecological community of plants and animals extending over a large natural area. As can be seen in figure 1.27, different biomes are largely the result of temperatures and rainfall, although topography and geology can play a role as well. To design sustainable architecture, we need to have an intimate feeling for the biome in which we are designing.
Global Reality:
Most people live in mud buildings
Most houses have thatched roofs
Most people have no HVAC
But all can be comfortable and healthy.

A healthy part of resource cycle or pollution?

Fig. 1.26 The progression from the micro to macro level of site development
Bio-Climatic Design

By comparing the indigenous architecture of similar biomes in different parts of the world, we can discover the traditional response to climate and place that are often remarkably alike despite different cultural traditions. Understanding our particular biome will help reveal natural resources that are available for green design. Straw bale construction was invented in the North American temperate grassland biome where trees are scarce and sandy soils formed weak turf and where native people created efficient buildings with native prairie grasses.

Bioregions

Within most biomes are smaller bioregions where place is further differentiated by topography, hydrology, microclimatic variation,
and other factors. Bioregions usually contain a series of inter-nested watersheds and variations of plant communities caused by slope, soil variations, and human activities. The boundaries between these are called ecotones, which are generally biologically richer than the adjacent plant communities owing to edge effects where the two communities are interlaced.

The microclimate interacts with the region’s geological foundation to shape the soils and vegetation that create the local bioregion. The bioregion may play a key role in siting, design, and construction. If the bioregion resources include rice, oat, or wheat straw, then a straw bale building may be more appropriate than a wood-framed or “stick-built” home. If adobe soils are common, and climates are warm in winter and cool in summer, then an adobe or rammed earth building may be a better choice.

If local streams run year-round, a microhydro generator may make more sense than a photovoltaic system. If it is windy, a wind turbine may make more sense. The bioregion will also influence water-use decisions, food production choices, and landscaping. The better the fit to the bioregion, the more sustainable the building will be.

This is the scale where human settlement patterns and community infrastructure start to become a factor. Transportation corridors, water systems, power plants, transmission lines, and waste disposal are common examples of community infrastructure. Up until recently, the cost of all these was relatively well hidden by subsidies at the federal and state level. However, with soaring costs of energy, scarcities of resources, impacts from climate change, and collapsing government budgets, these costs have not only increased dramatically but become more visible. At the same time, the adverse impact and disruption to various bioregions have become more dramatic and visible. Infrastructure costs are not trivial and are often greater than the construction costs of many projects they serve. All these factors are behind the increasing resistance of local communities to physical growth. Development has been destructive, but can be reshaped to restore ecosystems and communities, as shown in figure 1.29.

Green design (as defined on page 5) has the capability to dramatically reduce infrastructure costs by producing most of the energy needed on-site through passive design, conserving and producing water on-site, and potentially handling much of the waste on-site. As sustainable planning, appropriate technology, and green design are joined, they can also reduce transportation requirements, avoid disruption to the landscape, and even help with landscape and hence bioregional regeneration.

There is a common myth that sustainable design costs more. This is only true so long as costs such as infrastructure requirements remain hidden. In reality, with all things considered, sustainable design costs less. As more of these infrastructure costs become more apparent, green design will be seen to cost less and become more common. Sustainable design must integrate the large scales of biomes and bioregions as well as the small scale of materials and construction. This can be done no matter how restricted or constrained the building site is, because all sites have a natural history and all have a microclimate.

### Microclimate

Solar radiation, topography, wind, rainfall, and vegetation all interact and help shape the local microclimate. Even when architects and engineers try to consider climate factors, they often fail to acknowledge the wide variations in microclimate that may occur within a relatively small area—as seen in a study in Ohio, comparing a small valley with the state.

<table>
<thead>
<tr>
<th>Microclimate Factor</th>
<th>109 stations, Neotoma valley (0.6 km sq)</th>
<th>88 stations, Ohio (113,000 km sq)</th>
<th>Max difference, Neotoma to Ohio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Highest temperature</strong></td>
<td>75°F to 113°F</td>
<td>91°F to 102°F</td>
<td>-16 to +11°F</td>
</tr>
<tr>
<td><strong>January low</strong></td>
<td>14°F to -26°F</td>
<td>-6°F to -20°F</td>
<td>-6 to +20°F</td>
</tr>
<tr>
<td><strong>Frost-free days</strong></td>
<td>124 to 276</td>
<td>138 to 197</td>
<td>14–79</td>
</tr>
</tbody>
</table>

Wolfe et al., 1949*
The enormous differences in microclimate within this small valley illustrate the need to understand your local site. If the nearest weather station data is used, it may be off by 20 to 30°F in winter and summer, and solar radiation may be very different as well. A sustainably designed building that should work well can fail if it is not adjusted to suit local microclimate differences.

Radiation is usually the most important determinant of the microclimate. Both solar radiation and the heat radiated back to space are important. The radiation balance of a particular site will be determined by the sun’s path (a function of latitude), the topography (slope aspect and elevation), the landscape, the color and type of the land cover and surface, and the possible shading and wind modification from structures on bordering properties.

An east-facing slope will warm rapidly in the morning and then cool off in the afternoon, while a west-facing slope will be warmest in the afternoon and early evening. In fact, the west-facing slope will generally be the warmest part of the site since radiation is high at the same time the air temperature is high.

As a rough rule of thumb, you can displace the site in latitude by the angle of its north or south slope. For example, a south-facing 10° slope at 40°N latitude would have a solar potential similar to that of a flat site at 30°N latitude. Conversely, a north-facing 10° slope at 40°N latitude would have a microclimate similar to that of a flat site at 50°N latitude.

At higher elevations, the thinner atmosphere increases the radiation flux and can let more heat escape to space. The net effect is a cooling of between 3° and 4°F per 1,000 feet. The key factor that blocks outgoing radiation is water vapor. Clouds can increase night heat retention, while clear nights can lead to rapid cooling. Cold, dry nights and hot, dry days in the desert are the result of an atmosphere with very little moisture to block radiation flows.

Clouds and fog will limit heat gain. If morning fog is common, it can limit heat gain from east-facing windows in spring or fall during cool mornings. This may influence window and thermal-mass placement. Or summer coastal fog may provide considerable beneficial cooling during otherwise hot weather. If cloudy periods or fog are common in winter, then solar gain may be limited when it is needed most.

Plants can intercept almost all the sun’s energy before it reaches the ground, keeping the soil relatively cool all summer. Even leafless deciduous trees may block 40 to 70 percent of the sun’s energy in winter. Vegetation also blocks outgoing radiation, reducing nighttime cooling. The color and nature of the earth’s surface determine solar absorption and reflection. In 1809, Samuel Williams of Vermont demonstrated the changes in temperature and humidity in cleared and forested areas; the forests were 10°F cooler in summer and warmer in winter. Water evaporated 1.5 times faster in the open areas (Thoreau, 1993*).

The actual amount of direct radiation received on any spot will vary with the atmospheric content, cloudiness, and solar angles, which determine the sun path length. An average of about a third of the extraterrestrial radiation that hits the outside of the earth’s atmosphere reaches the earth’s surface as direct solar radiation.

Solar radiation that reaches the earth after reflection or refraction is known as diffuse radiation. The amount will vary with the atmospheric content, cloudiness, and solar angles. On average, about a quarter of the extraterrestrial solar radiation reaches the earth as diffuse radiation. On a cloudy day, diffuse radiation may account for almost all of the energy received at the surface. It is often assumed to be uniformly distributed over the sky for simplicity, but the distribution is in fact far from uniform; diffuse radiation is usually much stronger near the sun disk’s position in the sky. On a clear, bright day with a few big clouds, radiation may reach a peak as direct solar radiation is augmented with reflection from bright clouds.

The total of the diffuse and direct components of solar radiation, figure 1.30, reaching the ground is known as the *global radiation*.

Reflection occurs when radiation bounces off a surface. This can be either specular or diffuse reflection, figure 1.31. A mirror or still water exhibits specular reflection, while snow or white paint exhibits diffuse reflection. The term *reflectance* is used to describe the ability of a given surface to reflect radiation. The reflectance of a surface is generally given as a ratio of the reflected to the incident radiation,
expressed as a percentage. Reflectance is often different for specular and diffuse radiation. Table 1.3 lists specular and diffuse reflectance of common surfaces in visible wavelengths. Fresh snow can improve south-window-wall performance significantly—often important during the cold, clear days that often follow a big winter storm.

**Table 1.3 Direct and diffuse reflection vary by surface.**

<table>
<thead>
<tr>
<th>Specular</th>
<th>Surface</th>
<th>Diffuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>65–95%*</td>
<td>Fresh snow</td>
<td>75–95%</td>
</tr>
<tr>
<td>60%*</td>
<td>Old snow</td>
<td>40–70%</td>
</tr>
<tr>
<td>60%*</td>
<td>Dry sand</td>
<td>35–45%</td>
</tr>
<tr>
<td></td>
<td>Wet sand</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>Meadow</td>
<td>12–30%</td>
</tr>
<tr>
<td></td>
<td>Grass</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>Dark soil</td>
<td>7–10%</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>Red brick</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>Tarpaper</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>Aluminum foil</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>White paint (new)</td>
<td>75–80%</td>
</tr>
<tr>
<td></td>
<td>White paint (old)</td>
<td>55%</td>
</tr>
</tbody>
</table>

* Low angle

Adding the direct and diffuse and reflected radiation gives us the total solar radiation. This is particularly important for natural heating systems in the higher latitudes where a snowy surface in front of the south-wall collector may add 30 percent to the total solar radiation in the winter.

The reflectivity of the surface determines how much radiation is absorbed. But the type of surface and its moisture content determine what the effect of heat radiation will be. A walk around town after sunset illustrates this clearly. The parking lots and west-facing walls of concrete buildings have stored much of the sun's energy and will re-radiate it for several hours, but the west walls of wood-framed buildings are soon cool. Buildings with ivy-covered west walls will remain even cooler, thanks to the solar control and evaporative cooling by the plants. Trees shade the ground and also absorb energy for photosynthesis and transpire large quantities of water vapor. Temperature differences of 10°F or more may occur between areas with and without trees.

**Design with Climate**

Many architects will put the same house or commercial building design in any climate and simply change the size of the mechanical systems. Sustainable design, however, must consider the local site, microclimate, and bioregion.

A sustainable building for Phoenix, Arizona, won't be the same as one for Denver, Colorado, because of obvious climatic and bioregional differences. It may also be built differently because the most appropriate locally available building materials are not the same.

**Sun Path and Orientation**

Solar radiation is the dominant factor in almost all sustainable building designs. It is critical in heating, cooling, and daylighting. To use solar energy effectively, we use our knowledge of the sun's path and the nature of solar radiation to capture heat when we want it, shed heat when we don't, and gather light.

**Solar Geometry**

Through years of teaching and practice we have found the most important, basic, simple things are often the most neglected. This is too often true with solar geometry. Therefore, we have put on one page all you need to know to deal with solar geometry in design besides standard orthographic projection.

**Wind and Airflow**

The orientation of slopes also influences local wind patterns, which in turn help determine temperature. Winds driven by convective currents during the day help to cool valley slopes. At night, dense colder air settles to valley floors. Cold-air drainage can create very cold areas, and houses located in these spots may have very high heating demand compared with neighbors 20 feet higher. Buildings and fences in cold-air drainages must be carefully designed to prevent damming the flow and creating a reservoir of freezing air that can lead to damage to landscape plants and crops and higher heating bills.

Water bodies, which absorb and store solar radiation well, help to stabilize the surrounding microclimate. The leeward side of a lake is always milder than the windward side. This influence is minor for small bodies of water, and even for Lake Michigan the 10°F temperature reduction extends inland less than a mile. But cool ocean breezes can reach far inland during the summer.
To predict the sun’s location, follow these easy steps:

1. Locate true south. If you use a compass, be sure to correct for magnetic declination in your area as shown on the map.
2. Find the right chart for your latitude.
3. You can now see where the sun will be located at any time of the year, month, day, and hour.

*Fig. 1.32. Solar geometry.*
Topography is a major factor in determining site wind patterns. Hilltop homes experience the highest wind speeds. They are also most vulnerable to wildfires. A house on a hillcrest will be more exposed to cooling breezes in the summer, but also to winter gales. The choice of house location, window type and placement, roof shape and overhangs, and even building materials are influenced by the site topography, wind speeds, and patterns.

If a cold strong northwest wind blows across your region in winter, then building your house in a northeast–southwest valley may be a good idea. Or if a cooling sea breeze approaches from the southwest in a very hot climate, then a site that channels this wind to the site will make it easier to keep cool. Low places can be subject to cold-air drainage and flooding.

**Analyze Your Own Site**

You can learn a lot by simply being observant, looking at and feeling the environment of your site. Visit as often as possible, in both fair weather and storms. Which direction is the wind blowing from? What is the wind speed? What is the temperature? When does the last snow melt? Where does the frost remain in the morning? It’s easy to install your own weather station on-site using data loggers and weather instruments. Then compare your temperature and wind with the local meteorological station—you may be surprised to see how different your microclimate is from the “standard.”

A basic instrument package might include a temperature data logger (as low as $40 from Lascar) and a handheld wind recorder (as low as $50 from LaCrosse) or a complete weather station for $1,000 to $2,000. This might seem like a large investment, but the potential savings far exceed even the highest-cost weather station. An infrared thermometer ($80 to $100), which reads the temperature of surfaces, can be very informative as well. Use it to better understand the influence of radiation, orientation, and moisture on radiant surface temperatures.

The development of a local site climate profile begins with a study of existing climate data. These are increasingly available online, from NOAA, individual states, and others. This background information is helpful, but then you need to do your own detective work. How does your site compare with the nearest weather station? Tuning into the uniqueness of your site is critical.

**Site Selection**

The choice of building site should take into account microclimate and other specific site characteristics. Shown in figure 1.33 are many of these aspects for choosing a site for residential-scale construction. The specific criteria for a given site will depend on the use, occupants, regulations and code requirements, material availability and cost, microclimate resources, ecosystems, and many other factors. Each chapter includes a discussion of site-related considerations.

A common mistake in residential site selection is to locate the building at the highest spot. The top of the hill is the worst location because it increases weather exposure and wildfire risk, maximizes noise dispersal and impact from others, and is most visually disruptive for others. The military crest or, as Frank Lloyd Wright called it, the Taliesin (“shining brow” in Welsh) is a better location with reduced fire risk, less extreme winds, and reduced visual and noise impact.

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Fig. 1.33. Many factors affect site selection. Hill town siting recognizes many of these considerations. This is Gangi, central Sicily.
We build structures to improve our comfort by controlling our personal microclimate. The goal is to be much more comfortable and healthy than we would be living under a tree or in a cave. This has not always been the case with modern buildings, but naturally heated, cooled, daylit, and ventilated buildings can provide this level of comfort, health, and mental well-being. They also improve our ability to learn (in schools), to heal (hospitals), and to work (offices and manufacturing facilities).

Yet all too frequently buildings are not comfortable, healthy, or joyful. Some buildings we have looked at over the years actually would provide fewer hours within the comfort range over the course of a year than you could enjoy by living outside under a tree. These terrible buildings may decrease the temperature extremes, but they store the day’s heat to make hot summer nights unbearable; or they retain the night’s cold in winter long after the sun is up and it has become comfortable outside. Few people will find joy working in a cubicle in a room with no windows, a sealed air system delivering a steady stream of smelly plasticizers and chemicals from the out-gassing of building materials, furniture, and fixtures, as well as fungal spores and decay by-products and other allergens.

Although the simple term human comfort covers a complex subject, involving all the methods of heat transfer (radiation, conduction, convection, evaporation) as well as many psychological and physiological factors, it’s not that hard to get it right. Human comfort for this book is defined as “that range of microclimate conditions under which a person feels good.” The comfort range varies depending on the type of activity engaged in, health, clothing, past experience and adaptation, expectations, and body type.

A resident in a rural area may find lower temperatures more comfortable than an urban dweller. And a thin, inactive elderly man may feel cold and uncomfortable in a room described as very comfortable by a young, fit woman. Living rooms may feel comfortable when much cooler than bathrooms, particularly when the bathroom floor is tile and feels cold. Not everyone will want the same conditions, so the goal is to provide individual controls and opportunities for everyone to be as comfortable as possible.

Human comfort also is influenced by and influences our thermo-regulation systems, involving a complex interaction of autonomic and voluntary responses, mental attitude, and clothing. These govern the rate of heat loss or gain from the body and the rate of heat production. The comfort condition is usually met when these are balanced. Our regulatory systems are also influenced by many factors including temperature, humidity, radiation, air movement, clothing, metabolism, and acclimation. Comfort or discomfort can be created in many ways.

On a winter night, for example, large single-pane cold windows and leaky walls can create chills in the living room even when the air temperature is 75°F. The same room could be very comfortable
at 65°F if the radiant temperatures of interior surfaces are warm, a high-performance window is used, and the building is draft-free.

Comfort in summer depends on the same interactions, only in summer we would like low radiant temperatures for interior surfaces, quiet but steady air circulation, low humidity to improve evaporation, and no heating from direct sunlight. Effective use of microclimate resources can provide summer comfort with natural forces in virtually any environment, even in the hottest deserts.

If a house is working well enough to provide comfort for the clothes that the owner wishes to wear and the activities planned, then it is a comfortable home. By wearing shorts and a light shirt in summer or a vest in winter, the comfort range can be extended. Table 1.4 shows that clothes make a big difference, and many of the perceived comfort differences between men and women are related to the clothes they are expected to wear. A commercial building will have to be cooler in summer to provide comfort for men who wear suits and ties, but these lower temperatures can cause women in skirts and lighter blouses to be continually cold and perhaps to sneak in an electric heater under their desks.

**Table 1.4. Chart of clo values for common clothing options.** Clothing thermal properties are described by a unit called the clo, a dimensionless number equal to the total thermal resistance of the clothing from the skin to the outer surface of the clothing.

<table>
<thead>
<tr>
<th>Attire</th>
<th>clo value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nude</td>
<td>0</td>
</tr>
<tr>
<td>Shorts</td>
<td>0.1</td>
</tr>
<tr>
<td>Shorts, open-neck short sleeve shirt, sandals, light socks</td>
<td>0.3–0.4</td>
</tr>
<tr>
<td>Long trousers, open-neck short sleeve shirt</td>
<td>0.5</td>
</tr>
<tr>
<td>Typical business suit</td>
<td>1</td>
</tr>
<tr>
<td>European heavy suit, vest, cotton long underwear</td>
<td>1.5</td>
</tr>
<tr>
<td>Chinese winter wear</td>
<td>2</td>
</tr>
<tr>
<td>Outdoor winter wear</td>
<td>3–4+</td>
</tr>
</tbody>
</table>

In winter, warmer clothes make it possible for a building to be cooler, yet still remain comfortable. Chinese rural residents found indoor winter temperatures of 52.7°F comfortable, while urban Chinese felt 57°F was better. These compare with temperatures of 71.4°F in urban Iran, 71.2°F in Italy, and the historic US goal of 72°F. These differences reflect differing expectations, adaptation, and clothing. Lower interior winter temperatures can help reduce the stress of going outside on a cold winter day. One of the worst feelings after trudging through the snow and cold is entering a building that is blistering hot, which results in sweating, evaporative cooling, and perhaps a chill.

In summer, 80 percent of the people may feel comfortable at 86°F in tropical climates with outdoor mean monthly air temperatures of 95°F, according to revised thermal comfort standards based on field research by Brager and de Dear (2000*).

Clothes make the man, so the saying goes. But clothes often make discomfort the rule or demand high energy inputs for cooling and heating. More appropriate clothing choices can make a big dent in our national energy bill. President Obama has set an excellent example by wearing less formal clothing and being shown without his suit jacket.

Shifting to business attire that allows businessmen to wear shorts (like Bermuda does), or polo shirts and slacks could significantly reduce energy costs for cooling around the world. Eliminate the wool or polyester business suit and tie and shift to linen, bamboo, or silk fabric.

Furniture also matters. A mesh chair will provide more comfortable conditions on a hot day, while a deep padded chair will reduce heat loss on a cold winter day. In hot climates, a mesh chair is more appropriate; in a colder climate a deep padded chair will be better. In temperate climates, the choice of chair type may be made to suit individual preference.

Air temperature is most commonly talked about as the determinant of comfort, but it is just part of the comfort equation. As a general rule, in dwellings thermal radiation will be about equal in importance to the combined effects of air temperature, humidity, and air motion. The influence of thermal radiation explains why natural heating, cooling, and ventilation systems are so delightful.

The ideal system for human comfort is one with radiant temperature in the comfort range on all surfaces. This has been known for a very long time and was practiced by the Romans and Chinese in buildings with radiant walls, floors, and ceilings heated by air. These hypocaust systems are being used again in Europe. Ancient Persian systems provided very effective cooling with natural energy flows, wind catchers, and evaporation from fountains to provide uniform temperatures in protected spaces. Courtyards and fountains provide many of the same benefits today in Italy, Spain, and the Middle East.
The renewed interest in cooling and heating panels for radiant temperature control is also encouraging. Changing the radiant temperatures can be more effective in providing comfort than simply working with air temperature. The fiction that a fixed air temperature is a provider of comfort never made sense, and although codes still focus on air temperature, the concerns are beginning to shift toward comfort instead. Not everyone can be comfortable, but with good design the predicted mean comfort vote (PMV) can be maximized and the predicted percentage of dissatisfied people (PPD) can be minimized.

A natural heating, cooling, and ventilation system will typically include only a couple of surfaces that are directly heated by the sun, but radiant exchange within the building and across distributed thermal mass help deliver very stable temperatures that allow internal radiant exchange to equilibrate. These uniform radiant temperatures can provide comfort even if the air temperature varies considerably from 72°F. In fact, with good radiant temperatures it may be comfortable with air temperatures in the low 60s in winter or in the low 80s in the summer.

Comfort zones also vary depending on adaptation, experience, and expectation. In figure 1.35, you can see the changes for residents of different zones. As these show, in hotter climates, the comfort zone can be displaced up as much as 18°F. In colder climates, this can be displaced down an equivalent or greater amount, and Arctic dwellers may work outside in shirtsleeves when the temperature is far below freezing.

Natural variation in perceived comfort is common, and is characterized by a normal distribution, with most people clustered in the same area. There are outliers, and some people can feel comfortable far outside the norms. For clients of custom homes, it is always good to determine what they prefer. Skin and basal temperatures can be a good quick check. David, for example, has a consistent body temperature near 96.6°F instead of 98.6°F. This is just a 2°F difference, but if we compare the differences between basal air temperature of 72°F, it is 8 percent different, a significant difference.

**Comfort Range**

Our comfort range also varies with our activities, health, nutrition (low iron can lead to cold hands and feet), when we last ate, age, and time of day. However, in some tests there has been very little difference between young and elderly subjects when the activity levels are comparable. Sensitivity to cold in elderly people may reflect reduced activity more often than increased sensitivity. A good salsa CD and some dancing around the house could be just the ticket to warm up on a winter day. A hyperkinetic person may be much warmer than a meditative and very still person.
When we are sleeping, many people prefer cooler temperatures and a good comforter, and can be quite comfortable at 60°F or less. By adding bed curtains and canopies, sleepers in the old days stayed warm even in very cold, damp, and breezy homes and castles. The canopies limited drafts, captured air warmed by sleepers, and improved the radiant environment. These same features can help improve comfort in homes where thermal performance is less than ideal and where whole-house retrofits would be too costly.

If we graph our comfort zone over a winter day, it might look something like the diagram in figure 1.37. This assumes winter clothing is being worn: pants, long sleeves, warm socks, and a vest.

With solar orientation, sufficient thermal mass and an efficient building shell, natural heating, and ventilation can provide full comfort in most climates without using any fossil fuels. Natural heating without fans, boilers, and furnaces can also improve the quality of indoor air and eliminate unwanted noise, vibration, and cost!

In a well-designed naturally heated building the balance of solar gain, thermal mass, and insulation will usually provide such good performance that windows can be left open to provide sufficient fresh air for those who wish it on all but the coldest days. This also allows different family members or workers to adjust their space to their desired comfort condition. This sense of control also adds to the feeling of comfort, even when it does not provide fully comfortable conditions. This same sense of control is more difficult to provide in a sealed building. However, just as with lighting, surveys show that most people prefer operable windows and will use them wisely, but some people are passive and will rarely operate windows or even blinds.

Natural cooling with solar orientation, solar control, and microclimate-adapted cooling (radian, evaporative, or convective) can provide cooling almost everywhere on a summer day. Using the cooling strategies in this book can improve comfort throughout the cooling season.

This comfort is readily apparent and is usually one of the first comments a visitor will make during a visit to a naturally heated, cooled, and ventilated building. This comfort and quiet is in marked contrast with mechanical or artificial space-conditioning systems.

**Comfort Problems with Artificial Heating and Cooling**

**Heating**

Forced-air heating systems are most common in the United States. While they may theoretically be able to maintain the air temperature at 72°F, they often have trouble reaching all areas of a building. The resulting cold pockets and hot pockets lead to discomfort. In addition, the hot air quickly rises to the ceiling, leaving the floor too cool and the ceiling too warm with resulting imbalance in radiant temperatures, often 15°F or more. A large cold window in a room heated with air temperatures above 75°F may still be uncomfortable to someone sitting nearby. Tall glass-walled office buildings create even more difficult conditions to balance temperatures. Workers on the lower floors on the north side may be freezing while occupants of south and west upper floors are baked in the afternoon.

Forced-air heating increases convective cooling of occupants as well as providing an irritating, drying wind (more colds), noise (more stress and less sleep), vibration, and breezes. The ducts and the air movement also stir up dust and can bring mold into the living space from ducts and return pathways in walls, attics, and basements.

Radiant heating systems are usually more comfortable, although they also suffer from problems absent in natural systems. The most common variant is the radiant floor, which is usually run with hot water. This type of system works fairly well and is considered one of the more comfortable systems by people who have never experienced natural heating and cooling. But leaks and repairs can be costly and frustrating to fix.

Radiant ceilings are also used, often using electric resistance heating panels, and while they are often more comfortable than forced-air systems, here the problems are worse than for a radiant floor. The overheated area is near the head (one of the dominant heat-exchange areas for humans) while the floor remains cool. In addition, air heated on the surface has nowhere to go, so it forms a pool of hot air near the ceiling.

**Fig. 1.37.** *Daily variation in comfort expectations.*
Cooling

Air conditioners work well for cooling and moving air, but it takes a great deal of energy to do it. They also provide a very cool stream of air that may be too cool to be comfortable if you are in it. In many cases they cannot cool the room enough to lower the radiant temperatures of the walls, ceiling, and windows, so the room is noisy and breezy, but not comfortable. Oversizing of air conditioners often leads to repeated on–off cycling that is irritating and inefficient. Air-conditioning is also expensive, requiring power at the most expensive peak period. As time-of-use billing becomes more common, this will dramatically increase the cost of air-conditioning. Air conditioners condense out water, and stopped drains often lead to mold problems. And air conditioners leak CFCs and HCFCs, gases that are both implicated in global warming and attack the atmospheric ozone layer, leaving us more vulnerable to potentially deadly UV radiation.

Evaporative coolers (sometimes pejoratively called swamp coolers) use evaporation of water across a pad/filter to reduce outside air temperatures to a comfortable level for indoor comfort. These can be very effective in areas with low humidity, and may be run with solar panels. But on hot humid days, they provide little relief. Indirect evaporative coolers are better and are finally becoming more available on the market. Some of these are twice as efficient as an air conditioner, and because they do not add moisture to the air they provide better comfort even in humid areas.

Ultimate Comfort

There is no doubt that a building with a very energy efficient shell and natural heating, cooling, and ventilation systems (if well designed) is the most comfortable building possible. People who get to visit, live, or work in one of these buildings will often exclaim they are “More comfortable than ever before.” They are not mistaken. Comfort is good for health, and the human body recognizes what is good for it. Balanced radiant temperatures are ideal for health. The quiet comfort of naturally heated and cooled homes can improve sleep quality, and research has revealed how important sleep is for health and mental well-being.

Natural light is increasingly recognized as important for health as well. Daylight can help minimize problems with seasonal affective disorder. Daylighting has been shown to improve students’ learning performance in schools, speed recovery of people in hospitals, and increase worker productivity. The “Greenhouse” factory of the Herman Miller Corporation in Holland, Michigan, helped double productivity and paid the additional cost of good design back in a matter of months. Good building design also increases shopper satisfaction, and large retailers and others are starting to adopt better building practices to improve profitability.

Natural heating, cooling, and ventilation should be used for all new buildings, and a retrofit effort needs to be started for the many appallingly bad buildings we now live and work in. Windows, solar tubes for daylighting, roof monitors, and other features can bring light and fresher air into dark sealed buildings and improve the quality of life. Solar and climatically adapted retrofits can reduce heating and cooling costs and improve comfort in almost any building.

Health

The benefits of good building can be realized with improved health. Less stress, less drying air in winter, less mold, fewer allergens, and better sleep add up to better health all year. When more comprehensive studies are finally done on the benefits of good design, they will be as dramatic as the benefits found in analyses of daylighting on learning and productivity. In sustainable buildings, fewer days are lost to absenteeism and ill health. It is not uncommon to see sick days decline 12 to 20 percent.

Joy

If you feel very comfortable and are healthy, it is easier to feel joy. Naturally heated and cooled buildings are more joyful buildings. They are quiet, feel good, and help harried parents, children, and workers recover from the day’s stressful activities and the bad buildings we now work in, go to school in, or shop in. Working hard and effectively is much easier and more satisfying in a comfortable and enjoyable building.

Comfort Outside

The same principles determine the comfort conditions outside. Good design can improve comfort outside and can improve conditions for pedestrians and bicycle commuters. This can encourage more commuters to choose these more sustainable options. Solar orientation can create comfortable winter spaces, and effective use of microclimate resources can create cool havens in summer. This
helps keep people outside and interacting in the community. The mean radiant temperature is very important outside and should be a factor for all landscape and city design.

Many traditional designs of outdoor space were effective for improving comfort. From the shaded streets and souks of desert cities to the toldos, fountains, and landscaping of courtyards in Italy and Spain, we can find excellent examples of solutions for outdoor comfort. Sadly, most American cities have been built for cars, not people, and microclimate has not been considered in design and development.

**Occupant Program and Preferences**

*Rather than to exclude people from making design decisions because they are ignorant, the most feasible solution is to educate them.*

—ROBERT SOMMER

The most important factor in building design should be the comfort, security, and happiness of the occupants. Sadly this is usually neglected when the client is not the occupant—and even when clients will be occupants, they are often not consulted on critical factors. The growing number of studies on productivity and health benefits of sustainable buildings is encouraging more careful consideration of the occupants even when the client is a developer with first cost and financing pressure as a primary concern. Working to meet client desires or preferences can be challenging even when the client will be the occupant, and the architect and designer is concerned about meeting needs and wants. Anyone with much project experience can recognize the challenge, which includes developing a program that clarifies client preferences, needs and wants. See the “Program Considerations” sidebar.

The development of the program for the building should be thorough, articulated clearly, and refined as the project progresses. In most cases it will take time to educate the clients, clarify preferences and requirements, and isolate important drivers of design decisions. Arranging visits to both very good and very poor designs can be helpful in clarifying client needs and preferences. Monitoring performance of existing spaces where clients live or work can also be instructive.

## PROGRAM CONSIDERATIONS

- Use patterns—annual, season, vacation only.
- Living pattern—cooking, relaxing, working, sleeping, interacting, individual time.
- Daily-use pattern—early riser, late sleeper, night owl.
- Temperature and clothing preferences.
- Bedding choices and preferences.
- Lighting preferences.
- Bathing preferences, time and type (shower, tub, furo, inside/outside).
- Privacy preferences.
- Sound preferences.
- Ventilation preferences.
- Security preferences.
- Ceiling height.
- Clothes washing and drying (clothesline?).
- Building-material/color preferences.
- Flooring preferences. Tile or carpet? Can floor mass be effective or not?
- Landscaping preferences—gardening, flowers, colors, food production.
- Waste management preferences, recycling, composting.
- Storage requirements.
- Rainwater harvesting.
- Gray-water use.
- Desired involvement in building operation—none to intensive.
- Allergies and asthma issues—ventilation/building-material choices.
Program Example

Figure 1.38 shows an example of sustainable issues as an integral part of programming for the zero-energy building illustrated in the preface on page ii.

Six basic issues regarding sustainability based on the idea of cyclic rather than linear processes are included. A key question is always:

How much does the client wish to push to advance the state of the art of sustainable design? Some techniques to allow efficient cycles at this scale exist and have been tested exhaustively (marked with O on the chart). Others are developed but are not common enough to be available without extra expense (marked by O). And finally, there are some that, although examples exist, are more adventurous from a technical and regulatory viewpoint (marked by *).

Fig. 1.38. Programming based on cyclic rather than linear processes for sustainable design.
Passive Considerations in Programming

Passive considerations for heating, cooling, ventilation, and daylighting need to be part of each phase of work, starting with programming. Leaving passive considerations out of the early phases of work and attempting to graft them on later (figure 1.39) results in less cost-effective integration. Attempting to add passive solar and sustainability elements at the end of a project’s design or construction often hinders success and is like adding a sail to a powerboat after the boat has been launched.

The myth that passive solar buildings cost more to build has been fueled by this lack of attention and commitment to passive strategies throughout the design and construction process. In reality, passive solar buildings can be similar in cost to conventional buildings and may cost less because they can reduce the need for expensive mechanical systems, which can make up to a third the total cost of a building. Reducing mechanical systems a backup role saves in up-front capital costs as well as operating costs.

The importance of the programming phase of work as a prerequisite to the later phases cannot be overestimated, as it greatly affects each successive decision.

Fig. 1.39. The cost of incorporating sustainability concerns at different phases of design and implementation.
Resulting Costs and Aesthetics

Costs

When green design considerations are integrated at the beginning of the design process, there may be no premium in construction first cost and dramatic savings in life-cycle cost. This is illustrated in the example on pages 80–81.

Passive solar systems can often reduce the cost of a building by utilizing components that are already in the budget (windows, overhangs, mass) and minimizing or eliminating the mechanical support systems that are needed in a nonsolar or anti-passive solar building. To realize these savings passive solar design should be a key factor in city street layout and subdivision design.

Within any section of this book, the cost for a given result will depend on the skill of the designer and the client’s choices. A low-cost canvas or shade cloth cover to control summer overheating from a west-facing window might cost less than $1/square foot, while a high-end motorized exterior shutter might cost $36/square foot or more.

As we tell clients, overall building costs vary as much or more. Straw bale passive solar homes have been built for less than $10/square foot (in areas without building codes) and for more than $300/square foot. Typically, they will cost about the same as a conventional custom building—less than a super-insulated building made using double-stud or truss walls, and considerably less than an adobe house.

California’s Sustainable Building Task Force quantified the value of resource savings in table 1.5 (Kats et al., 2003*). In October 2002, the David and Lucille Packard Foundation* released their Sustainability Matrix and Sustainability Report, developed to consider environmental goals for a new 90,000-square-foot office facility. The study found that with each increasing level of sustainability (including various levels of LEED), short-term costs increased, but long-term costs decreased dramatically.

A second, older study conducted by Xenergy* for the City of Portland identified a 15 percent life-cycle savings associated with bringing three standard buildings up to USGBC LEED certification levels (with primary opportunities to save money associated with energy efficiency, water efficiency, and use of salvaged materials).

<table>
<thead>
<tr>
<th>Category</th>
<th>20 year NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Value</td>
<td>$ 5.79</td>
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<tr>
<td>Emissions Value</td>
<td>$ 1.18</td>
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<tr>
<td>Water Value</td>
<td>$ 0.51</td>
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<tr>
<td>Waste Value (construction only) - 1 year</td>
<td>$ 0.03</td>
</tr>
<tr>
<td>Commissioning O&amp;M Value</td>
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<tr>
<td>Productivity &amp; Health Value (Certified &amp; Silver)</td>
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<tr>
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<td>Less Green Cost Premium</td>
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<td>Total 20-year NPV (Certified &amp; Silver)</td>
<td>$ 48.87</td>
</tr>
<tr>
<td>Total 20-year NPV (Gold &amp; Platinum)</td>
<td>$ 67.31</td>
</tr>
</tbody>
</table>

Life-Cycle Costs

The most important savings from passive solar design comes in reduced life-cycle costs (LCC). Energy savings of 70 to 90 percent at little or no added construction cost can quickly become significant. If we add in the avoided external costs, the savings go up even faster.

Fig. 1.40. Life-cycle cost of a commercial building over thirty years.
For example, a typical American home used more than 50 mBTUs for heating every year. If this is one of the thirty-one million all-electric homes, the direct cost would be somewhere around $1,600 year for a nonsolar house with almost $200 of external costs for emissions of carbon dioxide, nitrogen oxides, sulfur oxides, and particulate matter less than 10 microns. Over a hundred years, the all-electric nonsolar home would cost $180,000, while the passive solar homeowner would save $172,000.

Savings in commercial buildings are comparable, but the advantages are even greater. A daylit, comfortable, health-giving passive solar building will increases sales and productivity. In many cases, the productivity gains outweigh energy savings 20:1 or more.

Substantial research supports the health and productivity benefits of green features, such as daylighting, increased natural air ventilation and moisture reduction, and the use of low-emitting floor carpets, glues, paints, and other interior finishes and furnishings. In the United States, the annual cost of building-related sickness is estimated to be $58 billion. According to researchers, green building has the potential to generate an additional $200 billion annually in the United States in worker performance by creating offices with improved indoor air quality (CEC, 2008*).

Note that $200 billion is larger than the size of the entire Canadian construction market, which was $156 billion in 2006. As this potential benefit becomes more widely understood, countries with a comprehensive range of green products will have a competitive advantage in the global marketplace.

Aesthetics

Passive solar design is architecture, and architecture is involved with aesthetics. The question of what aesthetics is has been asked for a long time, from Plato to Tolstoy to Wright to Hundertwasser (see Haggard, Cooper, and Gyovai 2006). Plato felt that aesthetics dealt with perfection, which could exist only the mind. The more modern interpretation by Tolstoy was that aesthetics was the result of honest emotion, an approach more related to ours. Frank Lloyd Wright championed organic architecture as a reinterpretation of nature’s rules to suit humans, and to provide harmony with the materials chosen and the site. And Hundertwasser argued that aesthetics came from using organic forms and reconciling humans with nature. All steps along the way to integrated, sustainable design. So the question continues, what are the aesthetics of passive solar architecture? Historically, architectural aesthetics have dealt with three qualities: harmony, proportion, and scale. These three have been used to create architecture composed of:

**Sequence:** *The movement of things.*  
**Rhythm:** *The repetition of things.*  
**Order:** *The constructive nature of things.*  
**Form:** *The shape of things.*  
**Theme:** *The primary story told by the composition.*  
**Feeling:** *The emotion conveyed by the story.*  
**Clarity:** *The clear communication of any or all of the above.*

The aesthetic goal in any composition is to achieve synergy, where all the elements are so well composed that the whole exceeds the sum of its parts, giving the composition a transcendent quality. This quality has been achieved by all great architecture.

The theme for passive solar architecture could be comfort, which is discussed throughout this book. However, the next level of comfort would be health: personal health, community health, and planetary health.

With comfort and health comes the feeling of rightness, rightness that supports health and comfort. Successful passive solar design can create comfort and contribute to health. In addition to being successful aesthetically, it must be clear in its communication of these qualities through its feeling of rightness.

Aesthetically successful passive buildings have an intense but peaceful feeling of this rightness that is communicated by the building itself without words or description.

Modern architecture using the theme of industrial progress became the architecture of the twentieth century. Passive solar architecture using the theme of comfort, health, economy, and sustainability is becoming the architecture of the twenty-first century.
Sustainable design can be beautiful as well as comfortable, healthful and economical. Residential and commercial projects by SLSG.