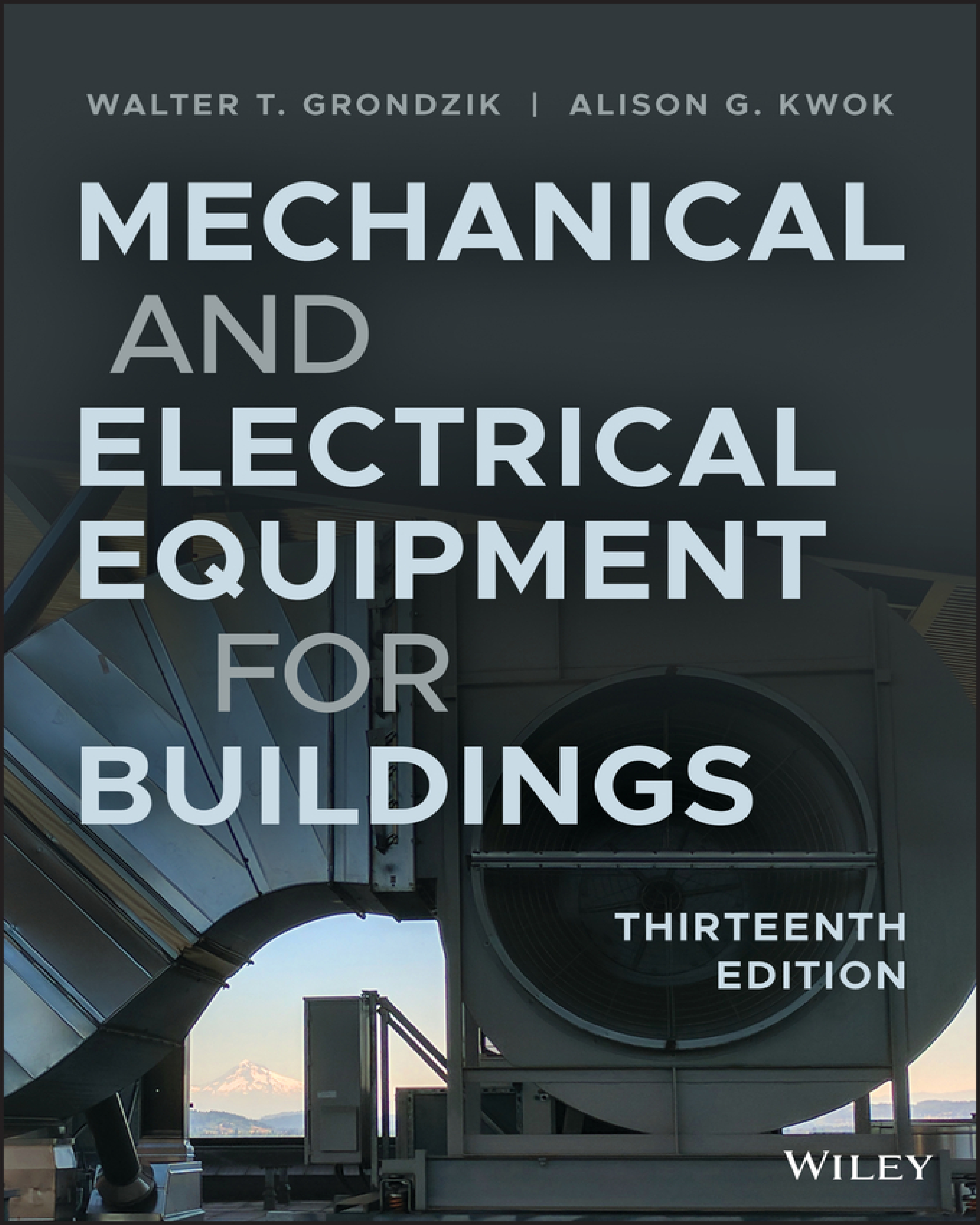
WALTER T. GRONDZIK | ALISON G. KWOK

MECHANICAL AND ELECTRICAL EQUIPMENT FOR BUILDINGS

THIRTEENTH EDITION



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Mechanical and Electrical Equipment for Buildings

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WILEY

Part opener pages are from the drawing set for the Lillis Business Complex at University of Oregon, designed by SRG Partnership, Portland, OR.

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Preface

EIGHT DECADES AND A FEW GENERATIONS have passed since the first edition of *Mechanical and Electrical Equipment for Buildings* was published in 1935. At its birth, this book was 429 pages long. Now, in the 13th edition, the book is more than 1800 pages, an increase of 400%. This expansion gives pause to our publisher and strengthens the arms of students—but, more seriously, it reflects the growing complexity of building design and the burgeoning knowledge base that confronts today's designers. Many new topics have been added over the years, and a few have disappeared; computer simulations are now routinely used in system design; new standards, codes, and guidelines offer challenges to designers; equipment and distribution systems have undergone major changes; mechanical cooling has become commonplace; fuel choices have shifted (coal has moved from an on-site to an off-site energy source). In recent editions, the book has increasingly added discussions of "why" to its historic focus upon "how-to."

Most of the systems presented in this book consume energy and embody materials. Some systems consume water. As global society has moved from its early reliance on renewable energy sources (wind, water, and horsepower) to today's seemingly unbreakable addiction to nonrenewable fossil fuels, it has also added vastly to its population and increased its global per capita energy use. The resulting environmental degradation (primarily evident in air and water quality) has spurred efforts to reverse this decline. Governmental regulations are a part of such efforts, but this book emphasizes the investigation of alternative fuels and design approaches that go beyond those solutions currently deemed "acceptable" to society. Designers are encouraged to take an aggressive leadership role in mitigating environmental degradation.

On this note, it is becoming increasingly clear that climate change is well under way. The distressing measured value of 400 ppm of atmospheric CO_2 has been reached. We may not know the precise extent to which our insatiable carbon-based energy consumption is responsible for pushing the world to this new reality. However, it seems professionally irresponsible to believe that human actions have had no effect. It is very clear that the world's supply of fossil fuel is diminishing, that the consumption of these fuels dumps massive quantities of CO_2 into the air, and that there will be future consequences for all buildings (and their occupants) that today rely so thoroughly on nonrenewable energy sources.

The buildings of today contribute to negative global consequences that will impact future generations, and our approach to mechanical and electrical systems must consider how best to minimize and mitigate—if not negate—such negative environmental impacts. Thus, on-site resources—daylighting, passive solar heating, passive cooling, solar water heating, rainwater, wastewater treatment, photovoltaic electricity—share the spotlight with traditional off-site resources (natural gas, oil, the electrical grid, water and sewer lines). On-site processes can be area-intensive and labor-intensive and can involve increased first costs that require years to recover through savings in energy, water, and/or material consumption. Off-site processes are usually subsidized by society, often with substantial environmental costs that accrue to the commons. On-site energy use requires us to look beyond the building, to pay as much attention to a building's context as to the mechanical and electrical spaces, equipment, and systems within.

Throughout the many editions of this book, another trend has emerged. Society has slowly moved from systems that centralize the provision of heating, cooling, water, and electricity toward those that encourage more localized production and control. Increased sophistication of digital control systems has encouraged this trend. Further encouragement comes from multipurpose buildings whose schedules of occupancy are fragmented and from corporations with varying work schedules that result in partial occupancy on weekends. Another factor in this move to decentralization is worker satisfaction; there is solid evidence that productivity increases with a sense of individual control of one's work environment. Residences are commonly being used as office work environments. Expanding communications networks have made this possible. As residential designs thus become more complex (with office-quality lighting, zoning for heating/cooling, sophisticated communications, noise control), our nonresidential work environments become more attractive and individual.

Air and water pollution problems stemming from buildings (and their systems and occupants) are widely recognized and generally condemned. The interest in green design on the part of clients and designers may help to mitigate such problems, although green design is hopefully just an intermediate step in the journey to truly sustainable solutions. And no, we are not designing sustainable solutions today—despite the claims about sustainable this and sustainable that filling the Internet, conference presentations, and professional journals.

Another pervasive pollutant affecting our quality of life is noise. Noise will impact building siting, space planning, exterior and interior material selections—even the choice of cooling systems (as with natural ventilation). Air and water pollution can result in physical illness, but so can noise pollution, along with its burden of mental stress.

This book is written primarily for the North American building design community and has always emphasized examples from this region. Yet other areas of the world, some with similar traditions and fuel sources, have worthy examples of new strategies for building design utilizing on-site energy and energy conservation. Thus, buildings from Europe and Asia appear in this 13th edition, along with many North American examples. The names of these buildings (and associated researchers and designers) have been included in the index of this edition. Design standards presented in this book are generally reflective of practice in the United States; this is a result of our experiences, but also reflects a desire not to burden readers by listing the many, many variations in design standards that exist across the globe,

Building system design is now widely undertaken using computers, often through proprietary software that includes hundreds of built-in assumptions. This book encourages the designer to take a rational and pragmatic approach to system design: to verify intuitive design moves and assumptions and to use computers as tools to facilitate such verification, but to use patterns and approximations to point early design efforts in the right direction (and catch the occasional garbage-in/garbage-out simulation result). Hand calculations have the benefit of exposing all pertinent variables and assumptions to the designer. This in itself is a valuable rationale for conducting some portion of an analysis manually. Rough hand-calculated results should point in the same direction as results obtained with a computer; the greater the disparity, the greater the need to check both approaches. This is not to disparage the use of simulations, which are valuable (if not indispensable) in maximizing the benefits of complex and sometimes counterintuitive systems.

This book is written with the student, the architect- or engineer-in-training, and the practicing professional in mind. Basic theory, preliminary design guidelines, and detailed design procedures allow the book to serve both as an introductory text for the student and as a more advanced reference for both professional and student. This work is intended to be used as a textbook for a range of courses in architecture, architectural engineering, and building/construction management.

A "MEEB 13" website provides supporting materials to enhance learning about and understanding of the concepts, equipment, and systems dealt with in this book. As with previous editions, a 13th edition instructor's manual has been developed to provide additional support for those teaching with the book. The manual, updated by Jennifer Lee and Troy Peters (with input from Tom Collins), outlines the contents and terminology in each chapter; highlights concepts of special interest or difficulty; and provides sample discussion, quiz, and exam questions. The manual is available to instructors who have adopted this book for their courses.

Mechanical and Electrical Equipment for Buildings continues to serve as a reference for architectural registration examinees in the United States and Canada. We also hope to have provided a useful reference book for the offices of architects, engineers, and building managers.

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ALISON G. KWOK

Visit **www.wiley.com/go/meeb13e**
for the expanding set of learning resources that accompany this book.

Acknowledgments

Many people and organizations have contributed knowledge, materials, and insights to the several editions of this book. We begin this acknowledgment with those from whose work we have borrowed at length: Baruch Givoni, John Tillman Lyle, Murray Milne, William McGuinness, and Victor Olgyay; Architecture 2030, ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers), the American Solar Energy Society (ASES), the Illuminating Engineering Society of North America (IESNA), the International Living Future Institute (ILFI), the National Fire Protection Association (NFPA), Passive House Institute United States (PHIUS), the U.S. Green Building Council (USGBC), collective wisdom from the Society of Building Science Educators (SBSE), the creative talents and expertise of numerous architects, engineers, consultants, and design professionals, and the many equipment manufacturers whose product information and photographs are used to illustrate the book.

We owe a great debt to the insight and technical knowledge compiled into MEEB over the many years (spanning the 8th and 9th editions) during which Benjamin Stein and John Reynolds were sole authors of this book. This knowledge remained in place as they transitioned out of their roles as primary authors (during the 10th and 11th editions) and still provides a core around which we have revised, updated, and developed new material for this edition.

Numerous professionals provided valuable assistance in assembling materials and clarifying ideas and details. These include Michael Bonn (Ankrom Moisan); Mike Steffen (Walsh Construction); Jeff Becksfort (PAE); Walker Macy (Landscape Architects, Orchards at Orenco); Charles Salter (Charles M. Salter Associates, Inc., Skywalker Ranch Technical Building); Carl Sterner (Sterner Design, LLC, Iowa Nest); James Lowe (Ball State University Facilities Planning and Management, BSU Ground Source Heat Pump system); Pete Munoz and Jean Wisenbaugh (Biohabitats); Kyle Andersen (GBD Architects); Mitch Dec, Brightworks (formerly at Glumac); Chris Lowen and Rob Schnare (Glumac); Charles Brucker (PLACE, Hassalo on 8th); Michael Utzinger and Joel Krueger (Aldo Leopold Legacy Center), Vikram Sami and Jim Nicolow (Blue Ridge Parkway Destination Center), Craig Christiansen (NREL research reports), William Lowry (climate of cities), Daniel Panetta (AIWPS and recycling at California Polytechnic, San Luis Obispo), Dr. Jonathan Stein (computer applications), John A. Van Deusen (vertical transportation), and Martin Yoklic (cooltower performance analysis). In addition, Peter Clegg (Feilden Clegg Bradley Studios); Guy Nevill and Max Fordham (The Hive); Robert Schnare and THA (Mercy Corps); Ron Rochon and Jim Hanford of Miller Hull Partnership; Denis Hayes, Bullitt Foundation (Bullitt Center); Julia Lau and David Lung (International Commerce Centre). Donald Corner, Lee Eckert, Tisha Egashira, Bruce Haglund, Toshi Woudenberg, Erica Ling, and Thomas Collins kindly contributed images that enhance the book.

We are very pleased to include illustrations by talented students in this thirteenth edition. These include Sharon Alitema, Kelli Kimura, Alisa Kwok, Nathan Leigh, Martin Lee, Achyuthan Ramaswamy, and Alexa Thornton—who met weekly for many months to do peer reviews of more than 200 illustrations. We continue to thank those who assisted with illustrations for the 12th edition: Zeta Fernando, Tyler Mavichien, Wesley Thompson, Karen Tse, and Ayush Vaidya; the 11th edition: Lisa Leal, Nathan Majeski, and Jonathan Meendering; the 10th edition: Dain Carlson, Amanda Jo Clegg, Eric Drew, Erik Winter, and (again) Jonathan Meendering; and the 8th edition: Michael Cockram. These are former students (now professionals) who embraced the principles and concepts of environmental technology in their design work and therefore clearly understood what they were drawing. We also acknowledge the many architects and engineers who provided illustrations of their buildings and design artifacts that appear in many of the chapters—citations to these firms and individuals are found throughout the book.

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Much of the work involved in producing a manuscript is accomplished by dedicated supporting personnel. We are truly grateful to an experienced and trusted production team: Ayush Vaidya (months of file coordination, chapter updates, project and database management) and Karen Tse (chapter updates, on-call assistance, file management).

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PART I

THE BUILDING DESIGN CONTEXT

The design of mechanical and electrical equipment for buildings is often not considered until many other important design decisions have already been made. This is sometimes a result of a relay-race type of design process, whereby decisions are handed off sequentially from architect to consulting engineer. In some cases, active systems are considered to have a corrective function, permitting a building design to work on a site and in a climate that were essentially ignored during early design phases. Such is the power of fossil-fueled systems; however, such power comes with a price—both economic and environmental.

The chapters that comprise Part I encourage designers to use the wonderfully flexible building design process to full advantage, and to include site and climate—as well as the owner's project requirements for thermal, visual, and acoustical comfort and indoor air quality—in their earliest design thinking. Chapter 1 discusses the building design process and the roles played by codes, costs, and project objectives in shaping a final building design. The critical importance of clear design intents and criteria is emphasized. Principles to guide environmentally responsible design are given. Chapter 2 discusses the relationship of energy, water, and material resources to buildings, from design through demolition. The concept of environmental footprint is introduced as an ultimate arbiter of design decision making. Chapter 3 encourages designers to view a building site as a collection of renewable resources, to be used as appropriate in the lighting, heating, and cooling of buildings.

CHAPTER 1

Design Process

IN MARCH 1971 VISIONARY ARCHITECT MALCOLM WELLS published a watershed article in *Progressive Architecture*. It was rather intriguingly and challengingly titled "The Absolutely Constant Incontestably Stable Architectural Value Scale." In essence, Wells argued that buildings should be *benchmarked* (to use a current term) against the environmentally regenerative capabilities of wilderness (Fig. 1.1). This seemed a radical idea then—and remains so even now, almost 50 years later. Such a set of values, however, may be just what is called for as the design professions slowly but inevitably move from *energy-efficient* to *green* to *sustainable* design in the coming decades. The main problem with Wells's "Incontestably Stable" benchmark is that most buildings fare poorly (if not dismally) against the environment-enhancing characteristics of wilderness. But perhaps this is more of a wakeup call than a problem.

As we sit firmly in the first quarter of the twenty-first century, *Progressive Architecture* is no longer in business, Malcolm Wells has sadly passed away, mechanical and electrical equipment has improved, simulation techniques have radically advanced, and information exchange has been revolutionized. In broad terms, however, the

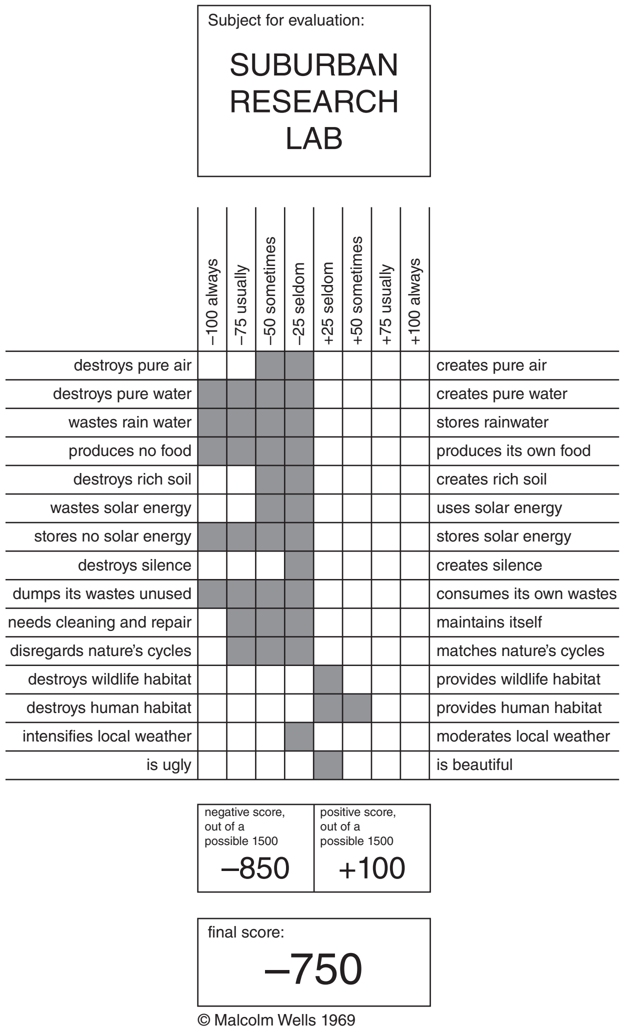


Fig. 1.1 *Evaluation of a typical project using Malcolm Wells's "absolutely constant incontestably stable architectural value scale." The value focus was wilderness; today it might well be sustainability. (© Malcolm Wells. Used with permission from Malcolm Wells. 1981.* Gentle Architecture. *New York: McGraw–Hill.)*

design process has changed little since the early 1970s.

The immediacy of climate concerns on the design, construction, and operations of buildings *mandates* a change in the underlying values and philosophy of the design process to build a low-carbon, more resilient future. Bill Bordass (Usable Buildings Trust, United Kingdom) offers a clear "multiplier effect" to achieving low-carbon buildings. The approach began in the early 1990s when he was reporting on office energy case studies, which then led to the first edition of the *Energy Consumption Guide 19* for offices. The idea further developed for the PROBE studies (1995–2002) and was formalized in 1997 (Field et al., 1997), in *CIBSE TM22—Energy Assessment and Reporting Methodology: The Office Assessment Method* (1999), and a report *Flying Blind* (October 2001).

Bill discovered that most decision makers were more receptive to a simple three-step hierarchy. We embrace this by introducing specific chapters in this book as Bill Bordass has summarized it in three steps: 1) Cut **energy demand** by 50% by designing a passive building that is well oriented for thermal and lighting (MEEB, Chapters 1–13), then 2) cut **energy supply** another 50% by specifying energy-efficient equipment (MEEB, Chapters 14–17), and finally 3) reduce the **carbon content** 50% of the remaining energy supplied to the building (MEEB, Chapter 29).

To meet the challenges of the coming decades, it is critical that designers consider and adopt values appropriate to the nature of the problems being confronted—both at the individual project scale and globally. The many chapters in this book give us strategies and validation for understanding building systems, and also integrate water, acoustics, and fire in the remaining sections. Nothing less makes sense.

1.1 INTRODUCTION

The design process is an integral part of the larger and more complex building procurement process through which an owner defines facility needs, considers architectural possibilities, contracts for design and construction services, and uses the resulting facility. Numerous decisions (literally thousands) made during the design process will determine the need for specific mechanical and electrical systems and equipment, and very often will determine eventual owner and occupant satisfaction. Discussing selected aspects of the design process seems a good way to start this book.

A building project typically begins with predesign activities that establish the need for, feasibility of, and proposed scope for a facility. If a project is deemed feasible and can be funded, a multiphase design process follows. The design phases are typically described as conceptual design, schematic design, and design development. If a project remains feasible as it progresses, the design process is followed by the construction and occupancy phases. In fast-track approaches (such as design-build), design efforts and construction activities may substantially overlap.

Predesign activities may be conducted by the design team (often under a separate contract), by the owner, or by a specialized consultant. The product of predesign activities should be a clearly defined scope of work for the design team to act upon. This product is variously called a *program*, a *project brief*, or the *owner's project requirements*. The design process converts this statement of the owner's requirements into drawings and specifications that permit a contractor to then convert the owner's (and designer's) wishes into a physical reality.

The various design phases are the primary areas of concern to the design team. The design process may span weeks (for a simple building or system) or years (for a large, complex project). The design team may consist of a sole practitioner for a residential project or 100 or more people located in different offices, cities, or even countries for a large project. Decisions made during the design process, especially during the early stages, will affect the project owner and occupants for many years—influencing operating costs, maintenance needs, comfort, enjoyment, and productivity.

The scope of work accomplished during each of the various design phases varies from firm to firm and project to project. In many cases, explicit expectations for the phases are described in professional service contracts between the design team and the owner. Often there is close collaboration between the client and design firm. A series of images illustrating the development

Fig. 1.2 *The Iowa Nest, under construction during the winter. (Photo © Sterner Design, LLC; used with permission.)*

of the Net Zero Iowa Nest Residence (Fig. 1.2), a high-performance residence under construction in southeast Iowa, is used to illustrate the steps of the building project that will offer a durable, ultra-low energy, and comfortable, residence year-round.

The story of this remarkable project and its design process is jointly chronicled by the designer and owners in the blog http://www.iowanest.com. The team set out with five primary goals: 1) Net Zero Energy: the building will produce as much energy as it uses on an annual basis; 2) Conventional Cost: the house is designed to achieve the same cost (per square area) as conventional new residential construction in Iowa; 3) Passive Cooling/No Air Conditioning: achieving thermal comfort during the hot and humid summer season; 4) Integrated with the Land: increase biohabitat and age gracefully in the landscape; 5) 200-Year House: use of durable materials and careful detailing to control water and moisture. Conceptual design (Figs. 1.3*a* and 1.3*b* and 1.4) outlines a solution to the owner's program that meets the budget and captures the owner's imagination so that design can continue.

Fundamental decisions about the proposed project should be made during conceptual design (Figs. 1.5 and 1.6) (not that things can't or won't change). During schematic design (Figs. 1.7 and 1.8), the conceptual solution is further developed and refined. It is worth noting that the design team ended up not going with a ground source heat pump shown in the "waterfall" diagram (Fig. 1.8). The team was able to use a cost-effective system because of good envelope and passive design. The heating loads were too small for a ground source heat pump to be practical. The best way to net zero energy use turned out to be a less-efficient electric radiant heating system and slightly larger photovoltaic array—all possible

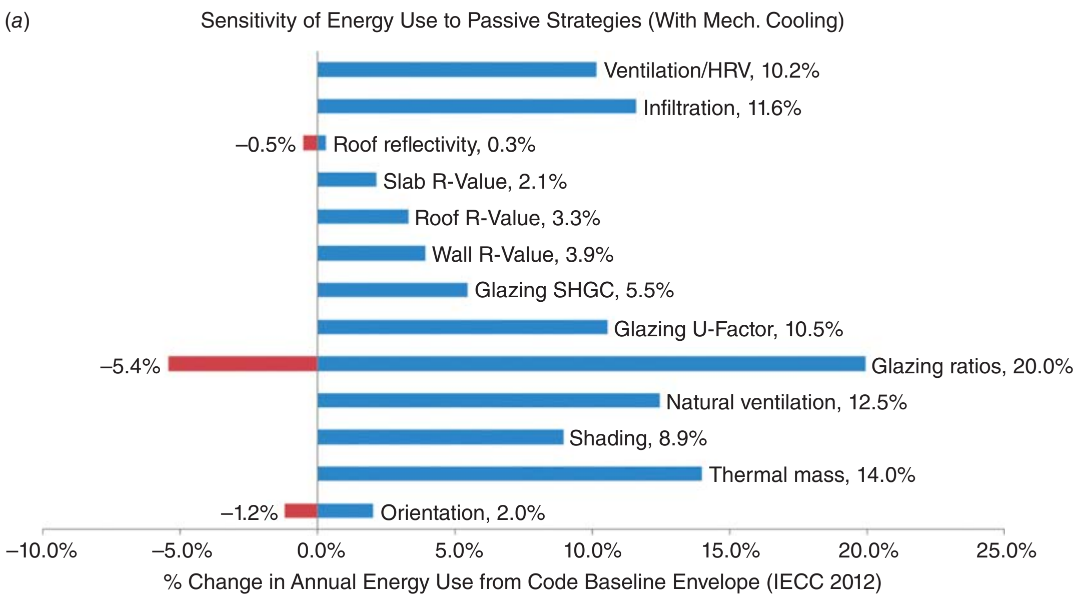


Fig. 1.3 *Several analyses compared potential passive strategies to a code-compliant baseline envelope (a) using mechanical cooling for percentage change in annual energy use; and (b) without mechanical cooling for percentage change in annual hours where the air temperature is above 82.4°F (28°C). (© Sterner Design, LLC; used with permission.)*

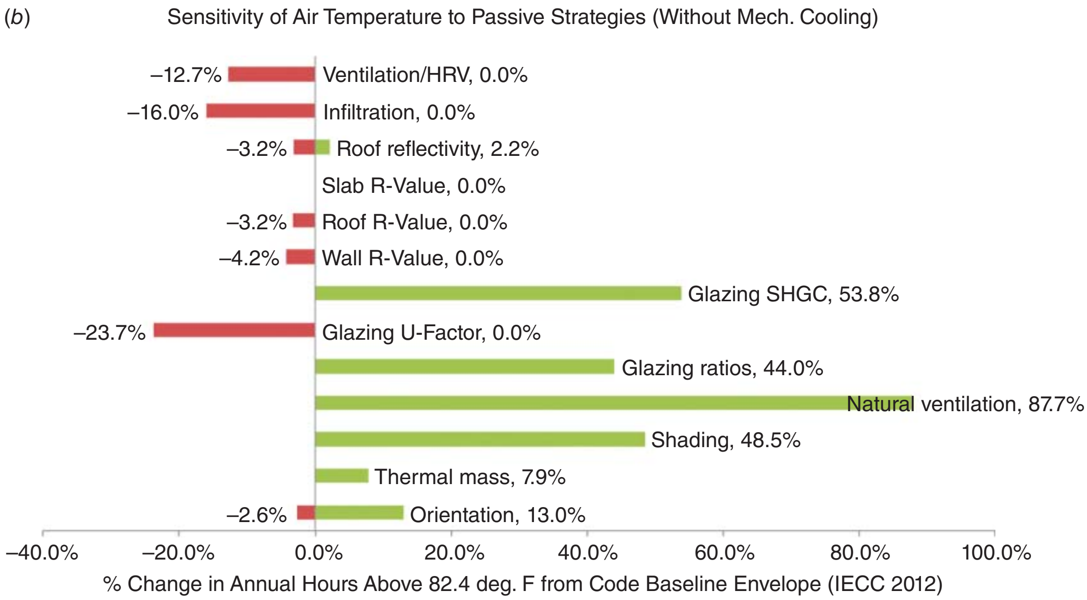


Fig. 1.3 *(continued)*

because of excellent integrated design. During design development and construction documentation (Fig. 1.9), all decisions regarding a design solution are finalized, and construction drawings and specifications detailing those innumerable decisions are prepared.

The construction phase (Figs. 1.9 and 1.10) is primarily in the hands of the contractor (and the owner and friends) although design decisions have determined what will be built and may dramatically affect constructability. One specific example of this: airtightness is often treated as a "detail" to be figured out during construction documentation. The experience of the design of the Iowa Nest confirmed that basic design moves can have a significant impact in making airtightness goals more or less easy to achieve. In this case, the air barrier was defined early in design, and the design ensured that critical areas would be accessible for air sealing during construction. The building owners/occupants are the key players during the occupancy phase. Their experiences with the building (utility bills, comfort, and beauty) will clearly be influenced by design decisions and construction quality, as well as by maintenance and operation practices. A feedback loop that allows construction and occupancy experiences (lessons learned—both good and bad) to be used by the design team on future projects is essential to good design practice. In this residence, the designer and owner are actively tracking temperature and relative humidity and will track energy use and production as well, to understand whether the building is performing as intended. We look forward to the unfolding story and documentation on the blog.

1.2 DESIGN INTENT

Design efforts should focus upon achieving a solution that will meet the expectations of a well-thought-out and explicitly defined design intent. A design intent is simply a statement that outlines an expected high-level outcome of the design process. Making such a fundamental statement is critical to the success of a design, as it points to the general direction(s) that the design process must take to achieve success. Design intent should not try to capture the totality of a building's character; this will come only with the completion of the design. It should, however, adequately

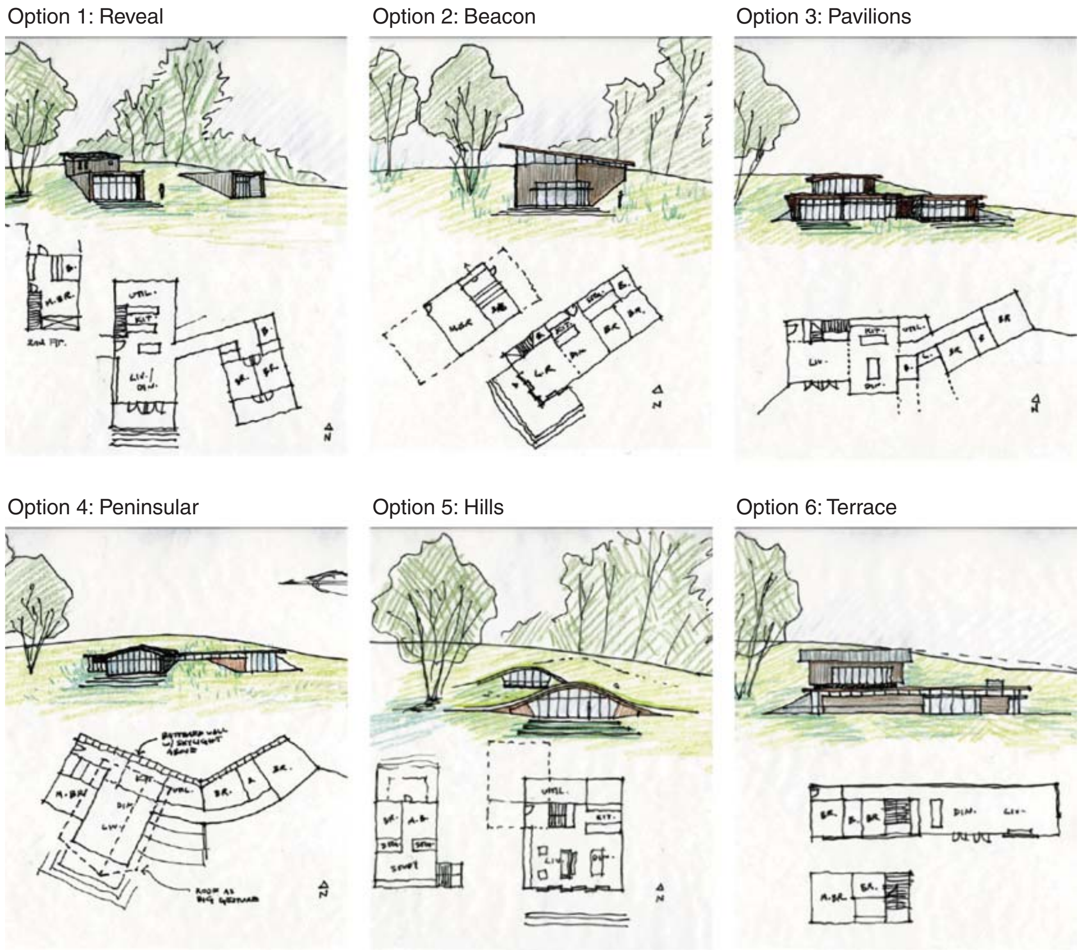


Fig. 1.4 *Design iterations began using hand sketches with attention to earth berming and daylighting zoning. (© Sterner Design, LLC; used with permission.)*

express the defining characteristics of a proposed building solution. Example design intents (from among thousands of possibilities) might include the following:

- The building will provide outstanding comfort for its occupants.
- The design will consider the latest in information technology.
- The building will be carbon neutral.
- The building will provide a high degree of flexibility for its occupants.
- The design will integrate health and wellness for the occupants.
- The design will address adaptation and resilience.

Clear design intents are important because they set the tone for design efforts, allow all members of the design team to understand what is truly critical to success, provide a general direction for early design efforts, and put key or unusual design concerns on the table. Professor Larry Peterson, former director of the Florida Sustainable Communities Center, has described the earliest decisions in the design process as an attempt to make the "first, best moves." Strong design intent will inform such moves. Weak intent

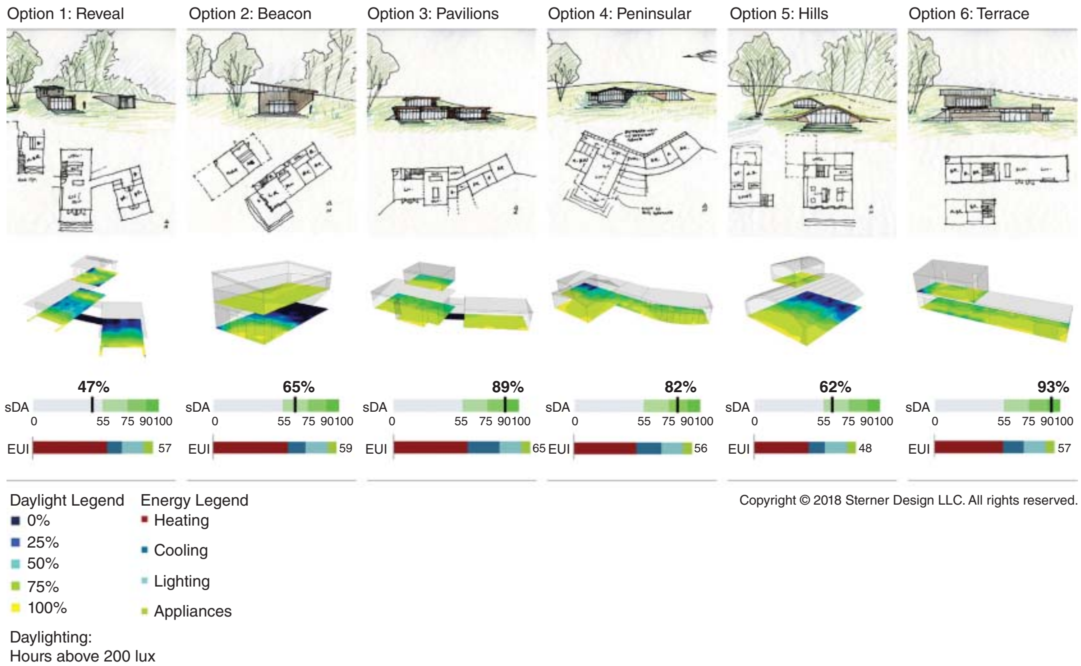


Fig. 1.5 *The design concept was further refined by comparing the different design iterations for daylight and energy performance using Sefaira analysis. Early analysis rarely dictates the selection of a concept, but can nevertheless inform design moving forward. This conceptual study showed a strong correlation between earth berming and low energy use. (© Sterner Design, LLC; used with permission.)*

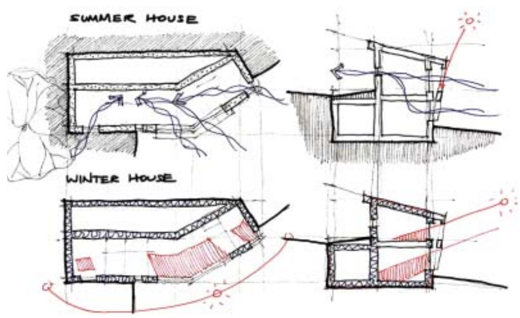


Fig. 1.6 *Conceptual sketches for shading and natural ventilation strategies at the Iowa Nest suggest in fairly strong terms the "first, best moves" for design direction, yet details are left to be developed in later design phases. There is a clear focus on shading, ventilation, earth berming, insulation, and passive solar design even at this stage—a focus that was carried throughout the project. (© Sterner Design, LLC; used with permission.)*

will result in a weak building. Great moves too late will be futile. The specificity of the design intent will evolve throughout the design process. *Outstanding comfort* during conceptual design may become *outstanding thermal, visual*, and *acoustic comfort* during schematic design.

1.3 DESIGN CRITERIA

Design criteria are the benchmarks against which success or failure in meeting design intent is measured. In addition to providing a basis against which to evaluate success, design criteria will ensure that all involved parties seriously address the technical and philosophical issues underlying a project's design intent. Setting design criteria demands the clarification and definition of many intentionally broad terms used when crafting design intent statements. For example, what is really meant by *green*, by *flexibility*, by *comfort*? If such terms cannot be benchmarked, then there is no way for the success of a design to be evaluated—essentially anything goes, and all solutions are potentially equally valid. Setting design criteria for qualitative issues (such as *exciting*, *relaxing*, or *spacious*) can be especially challenging, but equally important (and possible). Design criteria should be established as early in the design process as possible—but certainly no later than the schematic design phase. Because design criteria will define success or failure in a

Fig. 1.7 Schematic design renderings for the Iowa Nest. As design thinking and analysis evolve, so does the specificity of a proposed design. Site development has progressed, and the building elements begin to take shape. (© Sterner Design, LLC; used with permission.)

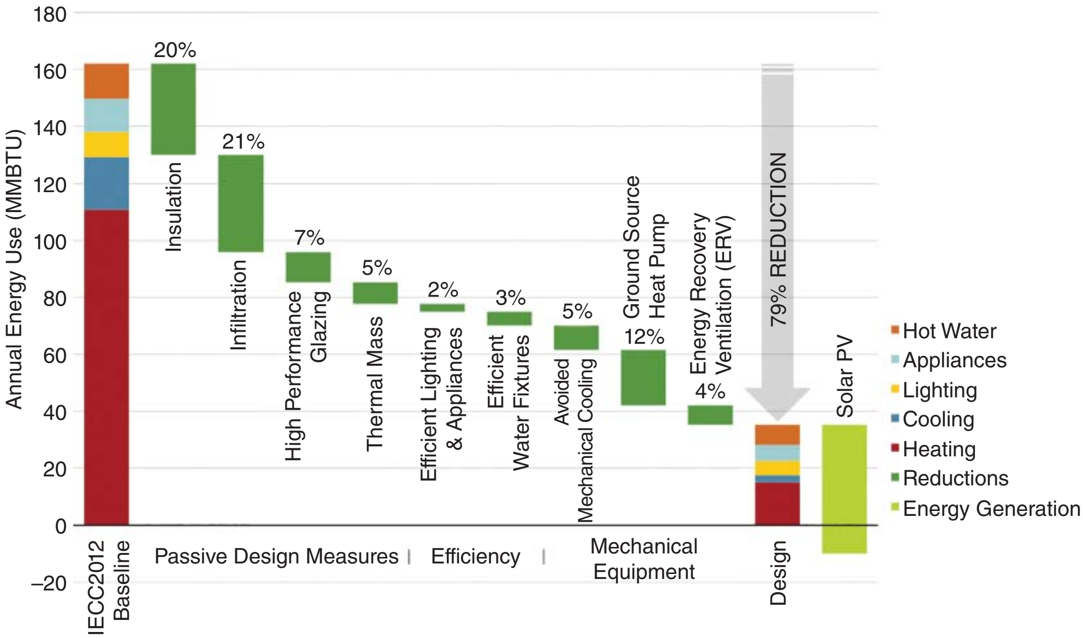


Fig. 1.8 Further analysis examined potential passive strategies (insulation, reducing infiltration, use of high-performance glass, thermal mass), efficiency strategies (electric lighting, appliances, water fixtures), high-performance mechanical equipment (no air-conditioning, ground source heat pump, and ERV) which drove the estimated annual energy use to almost 80% less than a baseline building. (© Sterner Design, LLC; used with permission.)

specific area of the building design process, they should be realistic and not subject to whimsical change. In many cases, design criteria will be used both to evaluate the success of a design approach or strategy and to evaluate the performance of a system or component in a completed building. Examples of design criteria might include the following:

- Thermal conditions will meet the requirements of ASHRAE Standard 55.
- The power density of the lighting system will be no greater than 0.7 W/ft^2.
- The building will achieve a LEED® Platinum certification.
- Fifty percent of building water consumption will be provided by rainwater capture.
- Background sound pressure levels in classrooms will not exceed RC 35.

1.4 METHODS AND TOOLS

Methods and tools are the means through which design intent is accomplished. They include design methods and tools, such as a heat loss calculation procedure or a sun angle calculator. They also

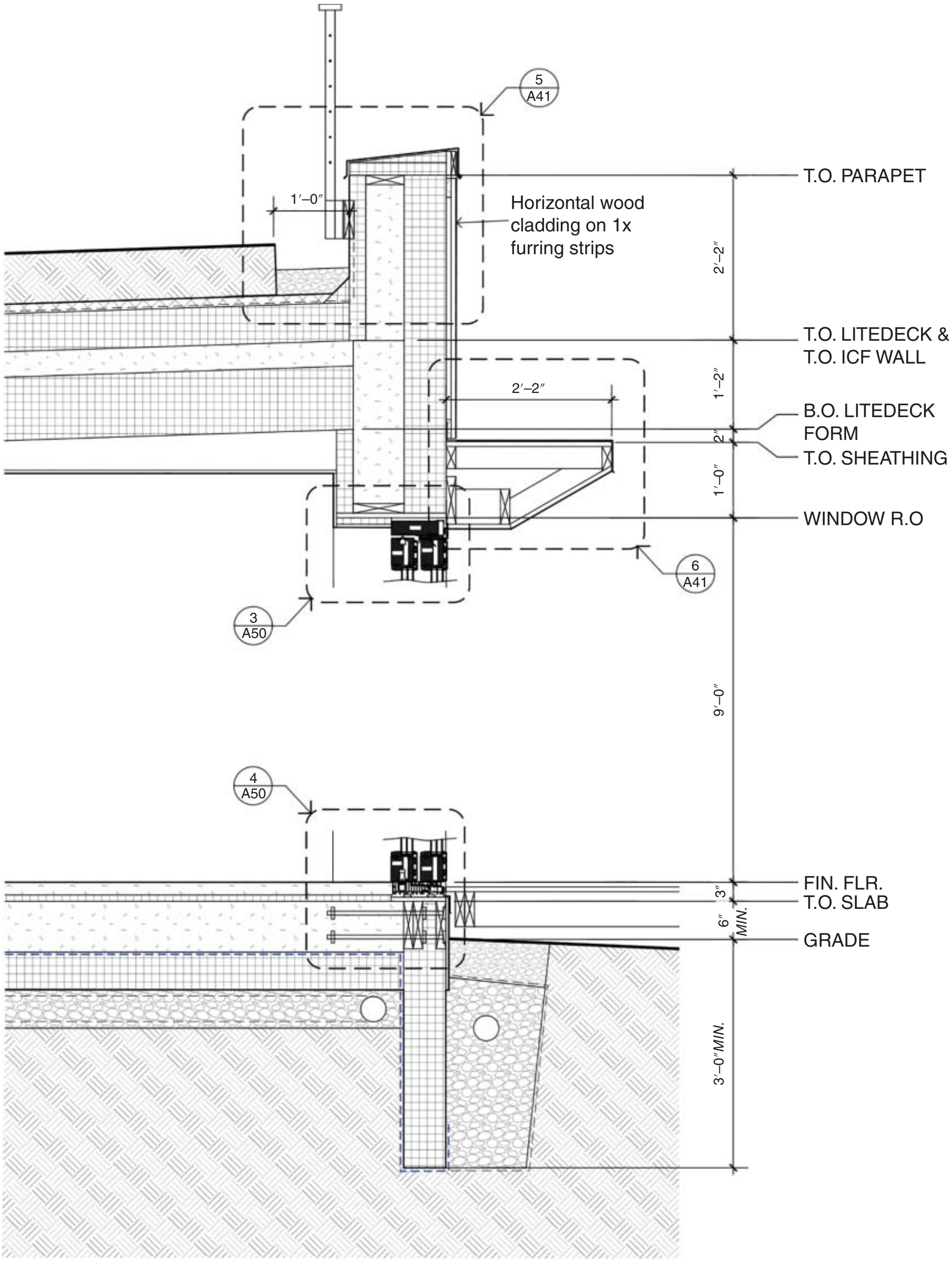


Fig. 1.9 *During design development, construction details converting an idea into a building evolve. This drawing illustrates the development of working details for the enclosure used in the Iowa Nest, resulting in an insulated enclosure: R-28 slab, R-45 walls, and an R-70 roof. (© Sterner Design, LLC; used with permission.)*

(a) (b)

Fig. 1.10 (a) Construction phase photo of the west wall of the Iowa Nest. Design intent becomes reality during this phase, showing the shading of a deciduous tree on the west window on a summer day and (b) the shading of the high-performance, triple-pane sliding doors on the south-facing façade. (Photo © Carl Sterner; used with permission.)

include the components, equipment, and systems that collectively define a building. It is important that an appropriate method or tool be used for a particular purpose. It is also critical that methods and tools (as means to an end) never be confused with either design intent (a desired end) or design criteria (benchmarks for success).

For any given design situation, there are typically many valid and viable solutions available to the design team. It is important that no reasonable solution be overlooked or ruled out as a result of design process short circuits. Although this may seem unlikely, methods (such as fire sprinklers, electric lighting, and sound absorption) are often included as part of a design intent statement. Should this occur, all other possible (and perhaps more desirable) solutions are ruled out by direct exclusion—if electric lighting is seen as an *intent*, then there is no place for daylighting. This does not serve a client or occupants well, and is also a disservice to the design team.

This book is a veritable catalog of design guidelines, methods, equipment, and systems that serve as means and methods to desired design ends. Sorting through this extensive information will be easier with specific design intent and criteria in mind. Owner expectations and designer experiences will typically inform design intent. Sections of the book that address fundamental principles will provide assistance with establishment of appropriate design criteria. Table 1.1 provides examples of the relationships between design intent, design criteria, and tools/methods.

1.5 VALIDATION AND EVALUATION

To function as a knowledge-based profession, design (architecture and engineering) must reflect upon previous efforts and learn from existing buildings. Except in surprisingly rare situations, most building designs are unique, comprising a collection of elements not previously assembled in precisely the same way. Most buildings are essentially a design team hypothesis: "We believe that this solution will work for the given situation." Unfortunately, the vast majority of buildings exist as untested hypotheses. Little in the way of performance evaluation or structured feedback from the owner and occupants is typically sought. This is not to suggest that designers do not learn from their projects, but rather that little research-quality, publicly shared information is captured for use on other projects. This is not an ideal model for professional practice from the perspective of society at large.

Bill Bordass, with the Usable Buildings Trust in the United Kingdom, has occasionally presented the Society of Building Science Educators (SBSE) listserv with summaries of lessons learned through extensive post-occupancy evaluation (POE) studies of buildings. This chapter is an appropriate place

TABLE 1.1 Relationships between Design Intent, Design Criteria, and Design Tools/Methods

Issue	Design Intent	Possible Design Criterion	Potential Design Tools	Potential Implementation Method
Thermal comfort	Acceptable thermal comfort	Compliance with ASHRAE Standard 55	Standard 55 graphs/ tables or comfort software	Passive climate control and/or active climate control systems
Lighting level (illuminance)	Acceptable illuminance levels	Compliance with recommendations in the *IESNA Lighting Handbook*	Hand calculations or computer simulations	Daylighting and/or electric lighting
Energy efficiency	Minimal energy efficiency	Compliance with ASHRAE Standard 90.1	Handbooks, simulation software, manufacturer's data, experience	Envelope strategies and/or system and equipment strategies
Energy efficiency	Outstanding energy efficiency	Meet the requirements of the ASHRAE 50% *Advanced Energy Design Guide* for the building type	Handbooks, simulation software, manufacturer's data, experience	Envelope strategies and/or system and equipment strategies
Green design	Obtain green building certification	Meet the requirements for the Living Building Certification	International Living Future Institute materials, experience	Any combination of approved strategies to obtain sufficient petals

to digest some of the design recommendations that flow from these findings. Bordass notes that building design features tend to have four attributes, sometimes possessing these attributes simultaneously:

- Physical: Fit and forget—if the designer and contractor have done a good job, the feature does its job and users can take it for granted.
- Administrative: Fit and manage—the feature needs looking after, and the question arises: Are the vigilance demands clear to the client and the operator? Often design features turn out to be more demanding on the operator than is realized at the time of design.
- Behavioral: Implement and internalize—the users have to understand the feature to make effective use of it. Often, however, the design intent is not clear, the feature has not been properly delivered, how it should be used has not been explained to the occupants, and use does not make sense or go with the flow of occupancy, even if explained.
- Perverse: Risk and freedom—often design features have both good and bad effects; it is easy for designers to get excited by the good ones and forget about the bad ones.

An intriguing recommendation, based upon the results of the Usable Buildings Trust POE studies is: "Keep it simple and do it well, and only after that begin to be clever." This guidance can be illustrated in the following sets of words to guide the wise designer (Bordass, et al., 2001):

- Process before product—then product and back to process
- Passive before active
- Simple before complicated
- Better before more
- 80 before 20 (use design time wisely)
- Robust before fragile
- Self-managing before managed
- Efficient before elaborate
- Trickle before boost
- Intelligible before intelligent
- Usable before alienating
- Forgiving before demanding
- Assets before nuisances
- Response before provision
- Off before on
- Cellular before open
- Experience before hope
- Thought before action
- Horses before carts

(a) Conventional Validation/Evaluation Approaches

Design validation is very common, although perhaps more so when dealing with quantitative concerns than with qualitative issues. Many design validation approaches are employed, including hand calculations, computer simulations and modeling, physical models (of various scales and complexity), and opinion surveys. Numerous design validation methods are presented in this book. Simple design validation methods (such as broad approximations, lookup tables, or nomographs) requiring few decisions and little input data are typically used early in the design process. The later stages of design see the introduction of more complex methods (such as computer simulations or multistep hand calculations) requiring substantial and detailed input.

Building validation is much less common than design validation. Structured evaluations of occupied buildings are rarely carried out. Historically, the most commonly encountered means of validating building performance is the post-occupancy evaluation (POE). Published POEs have typically focused upon some specific (and often nontechnical) aspect of building performance, such as way-finding or productivity. The building commissioning process and evaluative case studies of projects are finding more application as approaches to building validation. Third-party validations, such as ENERGY STAR certified buildings and the Leadership in Energy and Environmental Design (LEED) rating system, are popular approaches.

(b) Commissioning

Building commissioning is a proven approach to quality assurance. An independent commissioning authority (an individual or, more commonly, a team) verifies that design decisions and related building assemblies, equipment, and systems can meet the owner's project requirements (design intent and criteria). Verification is accomplished through review of design documents, observation of component installation, and detailed testing of equipment and systems under conditions expected to be encountered with building use. Historically focused upon mechanical and electrical systems, commissioning is currently being applied to numerous building systems—including envelope, security, fire protection, and information systems. Active involvement of the design team is critical to the success of the commissioning process (ASHRAE, 2013; Grondzik, 2009).

(c) Case Studies

Case studies represent another approach to design/construction validation and evaluation. The underlying philosophy of a case study is to capture information from a particular situation and convey the information in a way that makes it useful to a broader range of situations. A building case study attempts to present the lessons learned from one case in a manner that can benefit other cases (future designs). In North America, the Vital Signs and Agents of Change projects have focused upon disseminating a building performance case study methodology for design professionals and students—with an intentional focus upon occupied buildings (à la POEs). The American Institute of Architects and the U.S. Green Building Council have developed case studies dealing with design process/practice. In the United Kingdom, numerous case studies have been conducted under the auspices of the PROBE (Post-Occupancy Review of Buildings and Their Engineering) project.

1.6 INFLUENCES ON THE DESIGN PROCESS

The design process may appear to revolve primarily around the needs of a client and the capabilities of the design team—as exemplified by the establishment of design intent and criteria. There are several other notable influences, however, that affect the conduct and outcome of the building design process. Some of these influences are historic and affect virtually every building project; others represent emerging trends and affect only selected projects. Several of these design-influencing factors are discussed below.

(a) Codes and Standards

The design of virtually every building in North America will be influenced by codes and standards. *Codes* are government-mandated and -enforced documents that stipulate minimum acceptable building practices. Designers usually interface with codes through an entity known as the *authority having jurisdiction*. There may be several such authorities for any given locale or project (fire protection requirements, for example, may be enforced separately from general building construction requirements or energy performance requirements). Codes essentially define the minimum response that society deems acceptable for dealing with a particular building design issue. In no way is code compliance—by itself—likely to be adequate to meet the needs of a client. On the other hand, code compliance is indisputably necessary.

Codes may be written in prescriptive language or in performance terms. A *prescriptive* approach mandates that something be done in a certain way. Examples of prescriptive code requirements include minimum R-values for roof insulation, minimum pipe sizes for a roof drainage system, or a minimum number of hurricane clips per length of roof. The majority of codes in the United States are fundamentally prescriptive in nature. A prescriptive code defines means and methods. By contrast, a performance code defines outcomes. A *performance* approach presents an objective that must be met. Examples of performance approaches to code requirements include a maximum permissible design heat flow through a building envelope, a minimum design rainfall that can be safely drained from a building roof, or a defined wind speed that will not damage a roof construction. Some primarily prescriptive codes offer performance "options" for compliance. This is especially true of energy codes and for smoke control requirements in fire protection codes.

Codes in the United States are continually in transition. Each jurisdiction (city, county, and/or state, depending upon legislation) is generally free to adopt whichever model code it deems most appropriate. Some jurisdictions (typically large cities) use homegrown codes instead of a model code. Historically, four model codes (the *Uniform Building Code*, the *Standard Building Code*, the *Basic Building Code*, and the *National Building Code*) were used in various regions of the country. This regional code pattern has changed, with development and widespread use of a single model, the *International Building Code*, to provide a more uniform and standardized set of code requirements. Canada has its own *National Building Code*. Knowledge of current code requirements for a project is a critical element of the design process.

Standards are documents that present a set of minimum requirements for some aspect of building design. Such requirements have been developed by a recognized authority (such as Underwriters Laboratories, the National Fire Protection Association, or the American Society of Heating, Refrigerating and Air-Conditioning Engineers). Standards do not carry the weight of government enforcement that codes do, but they are often incorporated into codes via reference. Standards play an important role in building design and are often used by legal authorities to define the level of care expected of design professionals. Standards are typically developed under a consensus process with substantial opportunity for external review and input. *Guidelines* and *handbooks* are less formal than standards, usually with less formal review and/or consensus. *General practice*, the least formalized basis for design, captures the norm for a given locale or discipline. Table 1.2 provides examples of codes, standards, and related design guidance documents.

(b) Costs

Costs are a historic influence on the design process and are just as pervasive as codes. Typically, one of the earliest and strictest limits on design flexibility is the maximum construction budget imposed by the client. First cost (the cost for an owner to acquire the keys to a completed building) is the most commonly used cost factor. First cost is usually expressed as a maximum allowable construction cost or as a cost per unit area. Life-cycle cost (the cost for an owner to acquire and use a building for some defined period of time) is generally as important as, or more important than, first cost, but is often ignored by owners and usually not well understood by designers.

Over the life of a building, operating and maintenance costs can far exceed the cost to

TABLE 1.2 Codes, Standards, and Other Design Guidance Documents

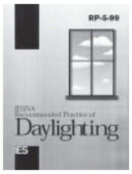
Document Type		Characteristics	Examples
Code		Government-mandated and government-enforced (typically via the building and occupancy permit process); may be a legislatively adopted standard	*Florida Building Code*; *California Title 24*; *Chicago Building Code*; *International Building Code* (when adopted by a jurisdiction)
Standard		Usually a consensus document developed by a professional organization under established procedures with opportunities for public review and input	ASHRAE Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*; ASTM E413–87, *Classification for Rating Sound Insulation*; ASME A17.1, *Safety Code for Elevators and Escalators*
Guideline		Usually a consensus document developed by a professional organization, but within a looser structure and with less stringent public review	ASHRAE Guideline 0, *The Commissioning Process*; *IESNA Advanced Lighting Guidelines*: NEMA LSD 12, *Best Practices for Metal Halide Lighting Systems*
Handbook		Development can vary widely—involving formal committees and peer review or single/multiple authors with no formal external review	*IESNA Lighting Handbook*; *ASHRAE Handbook—Fundamentals*; *NFPA Fire Protection Handbook*
Design guide		Development by experienced practitioners and educators; may offer schematic design process guidance, address architectural implications, links to other resources	Design procedures; general sizing procedures; green design strategies; case studies
General practice		The prevailing norm for design within a given community or discipline; least formal of all modes of guidance	System sizing approximations; generally accepted flashing details

Image Sources: code—used with permission of the International Code Council; standard—used with permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers; guideline and handbook—used with permission of the Illuminating Engineering Society of North America; general practice—used with permission of John Wiley & Sons.

Acronyms: ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers; ASME = American Society of Mechanical Engineers; ASTM = ASTM International (previously American Society for Testing and Materials); IESNA = Illuminating Engineering Society of North America; NEMA = National Electrical Manufacturers Association; NFPA = National Fire Protection Association.

construct or acquire a building. Thus, whenever feasible, design decisions should be based upon life-cycle cost analyses and not simply first cost. The math of life-cycle costing is not difficult. The primary difficulties in implementing life-cycle cost analysis are estimating future expenses and the uncertainty naturally associated with projecting future conditions. These issues are not as difficult as they might seem, however, and a number of well-regarded life-cycle cost methodologies have been developed. Appendix J provides basic information on life-cycle cost factors and procedures. The design team may find life-cycle costing a persuasive ally in the quest to convince an owner to make important, but apparently expensive, decisions.

(c) Passive and Active Approaches

The distinction between passive and active systems may mean little to the average building owner, but it can be critical to the building designer and occupant. Development of passive systems must begin early in the design process, and requires early and continuous attention from the architectural designer. Passive system operation will often require the earnest cooperation and involvement of building occupants and users. Table 1.3 summarizes the identifying characteristics of passive and active systems approaches. These approaches are conceptually opposite in nature. Individual systems that embody both active and passive characteristics are often called hybrid systems. Hybrid systems are commonly employed as a means of tapping into the best aspects of both approaches.

The typical building will usually include both passive and active systems. Passive systems may be used for climate control, fire protection, lighting, acoustics, circulation, and/or sanitation. Active systems may also be used for the same purposes and for electrical distribution and signaling.

(d) Energy Efficiency

Some level of energy efficiency is a societally mandated element of the design process in most developed countries. Code requirements for energy-efficient building solutions were generally instituted as a result of the energy crises of the 1970s and have been updated on a periodic basis since then. As with all code requirements, mandated energy efficiency levels represent the minimum performance level that is considered acceptable—not an optimal performance level. What is considered acceptable minimum performance has evolved over time in response to changes in energy costs and availability, and also in response to changes in the costs and availability of building technology.

In the United States, ANSI/ASHRAE/IESNA Standard 90.1 (published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, cosponsored by the Illuminating Engineering Society of North America, and approved by the American National Standards Institute) is the most commonly encountered energy efficiency benchmark for commercial/institutional buildings. Some states (such as California and Florida) utilize state-specific energy codes. Residential energy efficiency requirements are addressed by several model codes and standards (including the *International Energy Conservation Code*, the *International Green Construction Code*, and ANSI/ASHRAE Standard 90.2). Appendix H provides a sample of energy efficiency requirements from Standard 90.1.

Energy efficiency requirements for residential buildings tend to focus upon minimum envelope (walls, floors, roofs, doors, windows) and mechanical equipment (heating, cooling, domestic hot

TABLE 1.3 Defining the Characteristics of Passive and Active Systems

Characteristic	Passive System	Active System
Energy source	Uses no purchased energy (no electricity, natural gas, fuel oil, etc.); example: daylighting system	Uses primarily purchased (and nonrenewable) energy; example: electric lighting system
System components	Components play multiple roles in system and in the building as a whole; example: concrete floor slab that is structure, walking surface, and solar collector/storage	Components are commonly single-purpose elements; example: gas furnace
System integration	System is usually tightly integrated (often inseparably) with the overall building design; example: natural ventilation system using windows	System is usually not well integrated with the overall building design, often seeming an add-on; example: window air-conditioning unit
Passive and active systems represent opposing philosophical concepts. Design is seldom so straightforward as to permit the exclusive use of one philosophy. Thus, the hybrid system. Hybrid systems are a composite of active and passive approaches, typically leaning more toward the passive. For example, single-purpose, electricity-consuming (active) ceiling fans might be added to a natural ventilation (passive) cooling system to extend the performance of the system and thus reduce energy usage that would otherwise occur if a fully active air-conditioning system were turned on instead of the fans.		

water) performance. Energy efficiency requirements for commercial/institutional buildings address virtually every building system (including lighting and electrical distribution). Most energy codes present a set of prescriptive minimum requirements for individual building elements, with an option for an alternative means of compliance to permit innovation and/or a systems-based design approach.

Efficiency is simply the ratio of system output to system input. The greater the output for any given input, the higher the efficiency. This concept plays a large role in energy efficiency standards through the specification of minimum efficiencies for many items of mechanical and electrical equipment for buildings. *Energy conservation* implies saving energy by using less. This is conceptually different from efficiency but is an integral part of everyday usage of the term. Energy efficiency codes and standards include elements of conservation embodied in equipment control requirements or insulation levels. Because of negative connotations that some associate with "conservation" (doing without), the term *energy efficiency* is generally used to describe both conservation and efficiency efforts in buildings.

The majority of energy efficiency standards deal solely with on-site energy usage. The reason for this approach lies in the controversy surrounding assigning site-source energy adjustment factors that do not disadvantage one fuel over another (there is no such controversy regarding renewable energy sources). Off-site energy consumption (for example, that required to transport fuel oil or natural gas, or the substantial process losses from electrical generation plants) is not typically addressed in energy efficiency regulations. A site-source focus can seriously skew thinking about energy efficiency design strategies, and this should be recognized by the design team. Off-site energy consumption that is directly tied to on-site consumption is real, can be substantial, and contributes to carbon emissions and fossil fuel depletion.

Passive design solutions usually employ renewable energy resources. Several active design solutions, however, also utilize renewable energy forms. Energy conservation and efficiency concerns are typically focused upon minimizing depletion of nonrenewable energy resources—even when not explicitly stated. The use of renewable energy sources (such as solar radiation and wind) changes the passive versus active discussion, should change the perspective of the design team, and may affect the way compliance with energy efficiency codes/standards is evaluated.

(e) Passive House Performance

At the risk of sowing confusion, it is appropriate to discuss *Passive House* performance in conjunction with energy efficiency. Passive House (with caps) is a building performance guideline with stringent energy benchmarks for both site (specifically space conditioning) and source energy. A Passive House (denoting annual energy performance) is not necessarily a house with passive heating/cooling/lighting systems—although a Passive House will have a well-designed enclosure system (which is very much a passive approach). To stir potential confusion a bit more, a Passive House does not need to be a house; it may be an office, school, or other building type. A building certified under PHIUS+2015: Passive Building Standard, will be a highly energy-efficient building that approaches net-zero energy performance levels.

Currently, the benchmark requirements for passive building performance in the United States (PHIUS) meet climate-specific targets for particular locations in North America: Annual Heating Demand, Annual Cooling Demand, Peak Heating Load, and Peak Cooling Load, along with an air-tightness requirement, a source energy limit, and space conditioning criteria.

The general performance of a Passive House home ranks around 30–40 within the HERS rating system (Fig. 1.11), depending on the size of the home, the climate, and if a solar thermal system is installed (without added photovoltaics). Several other performance targets (such as those set by LEED for Homes and Architecture 2030) are also shown in Fig. 1.11.

(f) Net-Zero Energy

Pushing energy efficiency toward its limits will lead to the realm of building performance associated with net-zero energy buildings. High efficiency alone is not sufficient to produce a

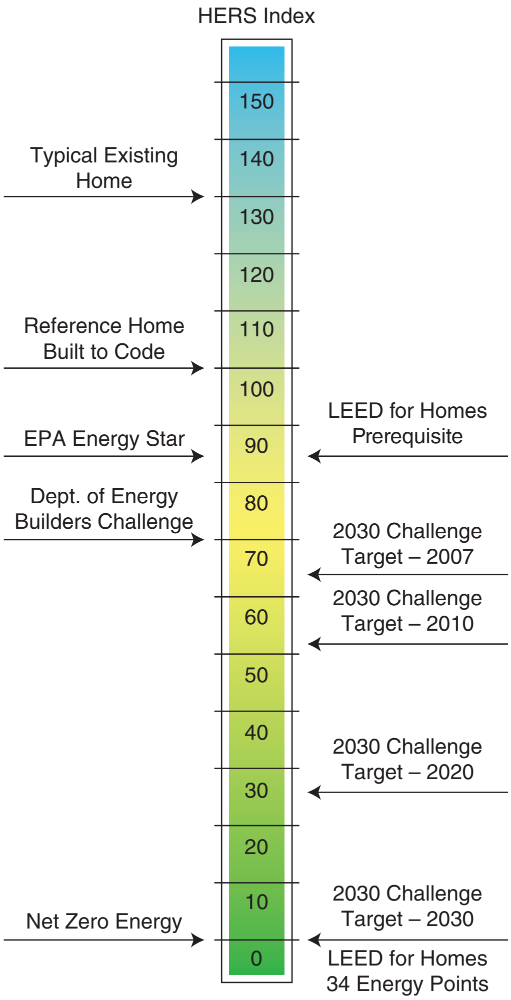


Fig. 1.11 *HERS (the Home Energy Rating System) is a relative comparison scale for residential energy performance. It sets baseline performance as 100 (which is linked to compliance with the 2006* International Energy Conservation Code*) and sets exemplary performance at 0, which is a net-zero energy residence. (Courtesy BuildingGreen, Inc.; used with permission.)*

net-zero building, but it is a practical prerequisite. By definition (National Renewable Energy Laboratory, NREL), a net-zero energy building will—on an annual basis—produce as much energy from renewable resources (solar and wind, for example) as it consumes. Such a building will, despite aggressive energy-efficiency efforts, still use energy (for things such as domestic water heating, electric lighting, space heating/cooling, and appliances). Any such residual energy requirements will, however, be provided by renewable energy resources that match the magnitude of fossil-fuel-based energy consumption, thus the use of the term "net-zero energy," as opposed to "zero energy" (which would essentially mean an unused building). There is currently an effort to use the term zero-energy in lieu of net-zero-energy; purportedly to avoid confusing consumers. We believe this effort to be misguided and ethically-suspect. A zero-energy building would be a perpetual motion machine.

Looking at a net-zero energy building from another perspective—such a building may use energy derived from fossil fuels (such as electricity from a coal-fired power plant) to meets its programmatic and occupancy needs. But every Btu (kWh) of energy from a nonrenewable resource must be matched by a Btu (kWh) of energy from a renewable resource. A net-zero energy building is not a no-energy building, and it is not a no-nonrenewable-energy building. It is, however, a low-energy building that employs at least 50% (annually) renewable energy. This is a big step on the road to sustainability. Sustainability (on the energy front) may lie in what some designers are describing as plus-energy buildings. More on sustainability in a following section.

Architecture 2030 launched the ZERO Code in 2018 as a national and international building energy standard for new building construction that integrates cost-effective energy efficiency standards with on-site and/or off-site renewable energy resulting in zero-net-carbon buildings. It provides prescriptive and performance paths for building energy efficiency compliance based on current standards (e.g., ASHRAE Standard 90.1–2016 or other existing or new prescriptive and performance standards, such as the International Green Construction Code (IgCC), ASHRAE Standard 189.1–2017), or any building energy efficiency standard that exceeds ASHRAE Standard 90.1–2016, and are widely used by municipalities and building professionals worldwide (Architecture 2030 ZERO Code, https://zero-code.org/). Additional tools, software (energy calculator), and technical support documentation provides designers valuable resources to plan and implement the prescriptive or the performance path.

Designers have some flexibility in defining a net-zero energy building within the clear limits of energy balance described above. This flexibility lies in the setting of system boundaries. The system boundaries may be spatial, temporal, and/or organizational. Some examples follow:

- Today, the most common perception of a net-zero energy building is one that is net-zero considering operational energy measured at the site boundary.
- The system boundaries may be expanded back to the proximate source of the building's energy, such that source (versus site) energy is balanced; this is roughly three times more challenging for an all-electric building (as a result of generation and transmission losses that are not included in a site-based analysis).
- One could, in theory, extend the analysis boundary back to the ultimate source of the building's energy (such as a coal mine or gas well); this is rarely done.
- Rather than considering only operational energy, the net-zero analysis boundary might be extended backward in time to include construction process energy (and perhaps design process energy).
- An owner might want to consider not just the building as the system, but also the organizational efforts supported by (or perhaps required by) the building; employee commuting energy might be considered, and/or the energy required to clean and maintain the building.

The source of renewable energy inputs to a net-zero building may also be addressed as a function of site boundary. For example, the renewable energy component might come from a green power purchase agreement (with the energy production occurring remotely), or the energy might be produced from systems located on or adjacent to a building. The authors' philosophical preference is for site-based renewables—such that the design team is directly responsible for necessary energy production. In this case, the design process (relative to energy, and perhaps also water) will be seen as a job of balancing demand with supply.

(g) Green Building Design Strategies

Green design considerations—whether part of a formal building rating or just a matter of better design—are entering the design process for many buildings. Green design goes beyond energy-efficient design in order to address both the local and global impacts of building energy, water, and materials usage. Energy efficiency is a key, but not sole, element of green design. The concept that is broadly called "green design" arose from concerns about the wide-ranging environmental impacts of design decisions. Although there is no generally accepted concise definition of *green*, the term is typically understood to incorporate concern for the health and well-being of building occupants/users and respect for the larger global environment. A green building should maximize beneficial impacts on its direct beneficiaries while minimizing negative impacts on the site, local, regional, national, and global environments.

Several rating systems have found wide acceptance as benchmarks for "greenness." These include the U.S. Green Building Council's LEED system, the Green Building Initiative's Green Globes Environmental Assessment system, and an international evaluation methodology entitled GBTool. Green building rating systems are in active use in the United Kingdom, Canada, and Japan. Most green building ratings systems are voluntary and would be correctly termed guidelines. A code-language set of green building design requirements, however, was developed by a coalition of professional organizations under the auspices of ASHRAE Standard 189, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*.

Typical of green guidelines, the LEED systems (there are a number of rating schemes for a variety of project types) present a palette of design options from which the design team can select strategies appropriate for a particular building (Fig. 1.12) and its context. Amassing points for selected strategies provides a means of attaining green building status—at one of several levels of achievement—via a formal third-party certification procedure. Prerequisite design strategies (such as baseline energy efficiency and acceptable indoor air quality) provide an underpinning for the palette of optional strategies.

The emergence of green building rating systems has greatly rationalized design intent and design criteria in this particular realm of architecture. Prior to the advent of LEED (or GBTool),

(*a*) (*b*)

Fig. 1.12 *(a) The Jean Vollum Natural Capital Center, Portland, Oregon. A warehouse from the industrial era was rehabilitated by Ecotrust to serve as a center for the conservation era. (b) LEED plaque on the front façade of the Vollum Center. The plaque announces the success of the design team (and owner) in achieving a key element of their design intent. (© Alison Kwok; all rights reserved.)*

anyone could claim greenness for his/her designs. Although green design is entered into voluntarily (few codes currently require it, although a number of municipalities require new public buildings to be green), there are now several generally accepted standards against which performance can be measured. Appendix H provides an excerpt from the LEED-NC green building rating system to provide a sense of the scope of green building expectations.

Although not a "green" design strategy per se, the WELL Building Standard is mentioned here. Developed by the International WELL Building Institute, this certification system is intended to assist in the design, construction, and operation of buildings that provide healthy environments for their occupants. The WELL Building Standard is structured somewhat like LEED, but with a different focus and requirements. In addition to familiar concepts such as air, water, and light the WELL Building Standard addresses nourishment, fitness, and mind. Intriguingly for the designer, certifying a building under the standard will require substantial collaboration with the owner/client who will be responsible for a number of credits.

(h) Carbon-Neutral Design

Climate change and global warming are growing concerns in the design community, as evidenced by the positive response of many professional organizations to the 2030 Challenge issued by Architecture 2030 (Architecture 2030). Design to reduce carbon emissions is becoming an issue on many building projects. The term *carbon-neutral design* is generally used to express this concern, and it accurately represents a primary design intent in a number of innovative projects. The Aldo Leopold Legacy Center in Baraboo, Wisconsin, is an exciting example of such a project.

Carbon dioxide (CO_2) is a major greenhouse gas; methane is another. Greenhouse gasses trap heat below the Earth's atmosphere in more or less the same way that glass traps heat from solar radiation in a greenhouse (or in a passive solar heating system). This trapping of heat increases temperatures and leads to climate change (ASES, 2007). Buildings are important contributors to carbon dioxide emissions and are therefore logical targets for mitigation in an attempt to reduce climate change potential. See Fig. 1.13 for an estimate of the role buildings play in producing CO_2 emissions.

At an organizational scale, carbon (and other climate-changing) emissions may be classified in three broad categories (EPA), termed scopes:

Scope 1: All direct GHG (greenhouse gas) emissions (such as from a gas-fired boiler or wood-burning stove)

Scope 2: Indirect GHG emissions from consumption of purchased electricity, heat, or steam

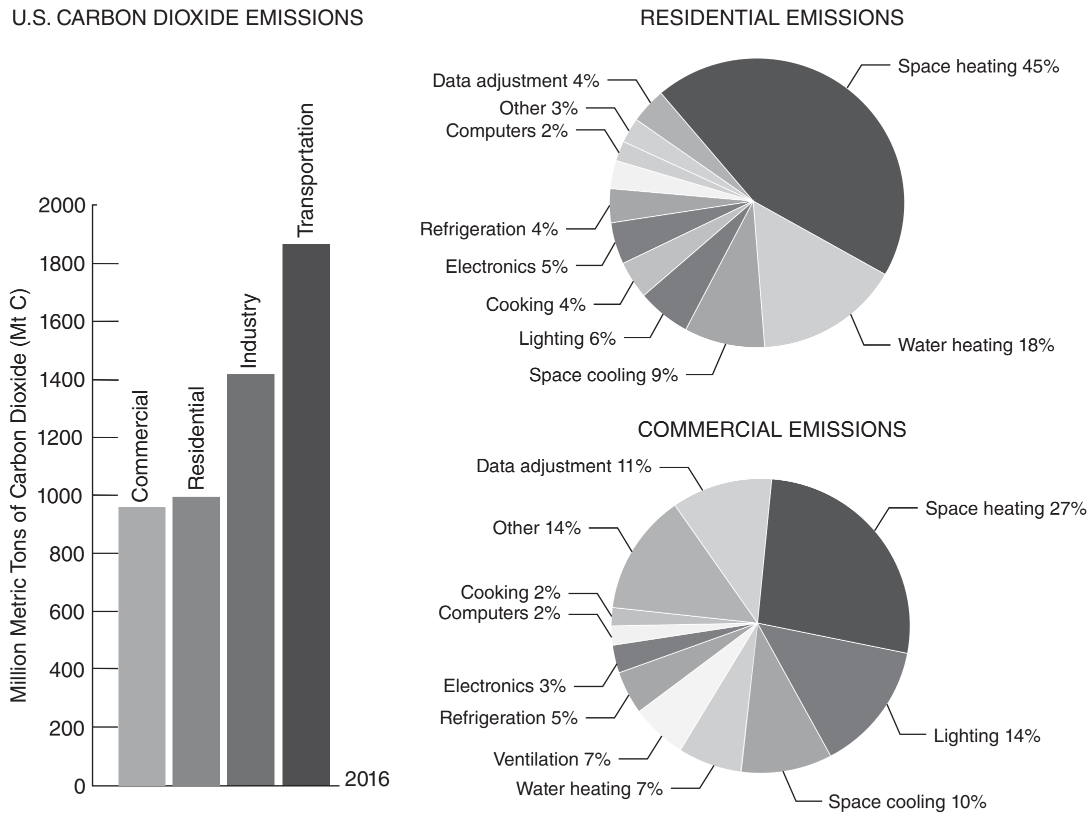


Fig. 1.13 *Contribution of the buildings sector (commercial and residential) to U.S. carbon dioxide emissions (Mt C = million metric tons of carbon dioxide), and the relative impact of various use categories on commercial and residential carbon impacts. (Drawn by Sharon Alitema. Source:* 2017 Buildings Energy Data Book*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.)*

Scope 3: Other indirect emissions, such as from the extraction and production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, electricity-related activities (e.g., transmission and distribution) not covered in Scope 2, outsourced activities, waste disposal, etc.

These scopes apply at the scale of a single project, but as with net-zero energy analyses, it might be useful to consider that buildings produce (or are linked to) carbon dioxide emissions in several distinct ways that may be of concern to an owner:

- As a result of fossil fuel energy consumed during the design process (computer use, printing, site visits, etc.)
- As a result of fossil fuel energy consumed during the construction process (by equipment, worker commutes, site conditioning, etc.)
- Through the disposal of organic construction waste that decomposes
- As a result of ongoing fossil fuel energy consumption for heating, cooling, lighting, and building support operations
- As a result of vehicle use associated with building functions and siting (including fossil fuels used for employee commuting, product deliveries, etc.)
- As a result of waste produced by a building in operation

Of these various carbon release mechanisms, energy consumption for building operation is likely the largest contributor and the most readily available target for reductions. A reminder: Energy use itself is not the carbon culprit, but rather the use of fossil fuels to produce the energy.

Options for reducing carbon emissions from the operation of building systems include improving the efficiency of building envelopes and systems (the ultimate, and unrealistic, goal being a zero-energy project); using renewable energy to meet the energy needs that remain after aggressive efficiency moves (the goal being a net-zero-energy building); and purchasing or obtaining carbon offsets (or credits) to mitigate the effects of residual carbon emissions not stemmed by efficiency and renewables. Carbon credits are somewhat controversial, being akin to buying one's way out of trouble—but they are an appropriate means of reducing carbon impacts beyond what can reasonably be achieved by skillful design solutions.

As cities begin requiring energy benchmarking for buildings, it is important for designers and building owners who need to quantify savings and create energy and carbon reduction goals to have an understanding of energy use and associated emissions metrics. Building plans, occupancy, energy loads, utility data, and areas associated with different uses are needed to calculate energy use intensity (EUI), which is measured in Btu/square foot/year. EUI is defined as the annual on-site intensity estimate for a design that accounts for all energy consumed at the building location (EPA Target Finder).

Another metric used to gauge how well a building performs in terms of greenhouse gas emissions is CO_2e. The term CO_2e is used because it takes into consideration several additional greenhouse gases such as methane and nitrous oxide (Bryan and Trusty, 2008). For example, on a personal scale, if we wanted to calculate the carbon emissions from plug loads in a typical U.S. single-family home, we would first calculate the EUI of all appliances (take kWh used in a year by all appliances, divide by the area of the house, convert kWh to Btu) and multiply by the operational CO_2e conversion for grid-delivered electricity. The EPA's ENERGY STAR program provides an online tool called Target Finder to allow designers who work with more complex projects to compare both the estimated building energy use and the estimated CO_2e emissions for their projects to a national standard.

At this time, there is no code, standard, or guideline that defines "carbon neutral" and only limited formal design guidance to assist in reaching that goal. This situation should change as interest in and demand for carbon-neutral projects grow.

(i) Embodied Energy/Embodied Carbon

Operational energy and operational carbon are the focus, respectively, of net-zero energy and carbon neutral design. In addition to the energy consumed in the day-to-day use of a building, however, energy is consumed to manufacture, transport, and install the materials that constitute a building. This energy is termed *embodied energy*. In addition to the carbon emitted in the day-to-day use of a building, carbon (specifically, carbon dioxide) is emitted as materials are manufactured, transported, and installed in a building. This carbon is termed *embodied carbon*. Neither embodied energy nor embodied carbon is trivial. In typical, code-compliant buildings with a reasonable life span, embodied carbon (and energy) may be 10–15% of the total carbon attributable to a building during its life. In highly energy-efficient buildings, operational energy and carbon magnitudes decrease, while embodied energy and carbon—if not addressed through design—remain the same as in a nonefficient project. The proportion of operational to embodied energy/carbon thus increases as buildings become more efficient.

A client or design team truly interested in environmentally responsive projects will look at the embodied impacts of design decisions. Unfortunately, design resources and tools to assist with reducing embodied carbon and embodied energy are not as well-developed as resources for reducing operational energy. The majority of resources dealing with embodied carbon/energy are found in the life-cycle assessment field. This is an evolving and somewhat complex area of building design—requiring, for example, clear definitions of system analysis boundaries and tracking of environmental inputs across time and space. Several resources, however, can open the door to engagement with this issue. *Life Cycle Assessment* by Simonen (2014) provides an excellent overview of embodied carbon. The Embodied

Carbon Network (2018) is an online repository of information. Appendix L in this book lists several life-cycle assessment tools.

There are at least three rationales for considering the carbon and energy required to place building materials into a project. First, even at say 10% of total energy/carbon, the magnitude of environment effects is worthy of consideration—particularly if no- or low-cost changes to materials specifications can be enacted. Second, at some point in the journey to low-energy buildings, more economical effects can be had by mitigating embodied carbon than by further reducing operational energy—it will be cheaper to save the next unit of carbon emissions by reducing embodied rather than operational carbon. Third, an intriguing argument for better addressing and mitigating embodied carbon lies in efforts to stem atmospheric carbon dioxide concentrations sooner rather than later in order to constrain global temperature rise. This design context suggests that the operational life of a building of concern to society is much shorter than the life as seen by an owner. If a 10- or 20-year life is seen as the window of opportunity for constraining average global temperature, then emitted carbon associated with construction materials becomes critical in designing mitigating buildings. The ratio of embodied to operational carbon increases substantially as the building life assumed for analysis decreases.

(j) Design Strategies for Sustainability

Unlike green design, the meaning of "sustainability" in architecture has not yet been rationalized. The term *sustainable* is used freely—and often mistakenly—to describe a broad range of intents and performances. This is unfortunate, as it tends to make sustainability a meaningless term—and sustainability is far too important to be rendered meaningless by baseless claims. For the purposes of this book, sustainability will be defined as follows (paraphrasing the Brundtland Commission): *Sustainability involves meeting the needs of today's generation without detracting from the ability of future generations to meet their needs.*

Sustainability for most is essentially long-term survival under an assumed standard of living. In architectural terms, sustainability involves ensuring the survival of an existing quality of life for future generations. From the standpoint of energy, water, and materials, it can be argued that sustainability requires zero use of nonrenewable resources. Any long-term removal of nonrenewable resources from the environment will surely impair the ability of future generations to meet their needs (with fewer resources being available, as a result of our actions). Because sustainability is so important a concept and objective, the term should not be used lightly. It is highly unlikely that any single building built in today's economic environment can be sustainable (yielding no net resource depletion). Sustainability at the community scale is more probable; examples, however, are rare.

(k) Regenerative Design Strategies

Energy efficiency is an attempt to use less energy to accomplish a given design objective (such as thermal comfort or adequate lighting). Green design is an attempt to maximize the positive effects of design while minimizing the negative ones—with respect to energy, water, and material resources. Sustainable design is an attempt to solve today's problems while reserving adequate resources to permit future generations to solve their problems. Energy efficiency is a necessary constituent of green design. Green design is a necessary constituent of sustainable design. *Regenerative design* goes beyond sustainability.

The goal of energy efficiency is to reduce net negative energy impacts. The goal of green design is to reduce net negative environmental impacts. The goal of sustainability is to produce no net negative environmental impacts. The goal of regenerative design is to produce a net positive environmental impact—to leave the world better off with respect to energy, water, and materials. If design for sustainability is difficult, then regenerative design is even more difficult. Nevertheless, there are some interesting examples of regenerative design projects, including the Eden Project in the United Kingdom and the Center for Regenerative Studies (Fig. 1.14) in the United States. Both projects involve substantial site remediation and innovative design solutions.

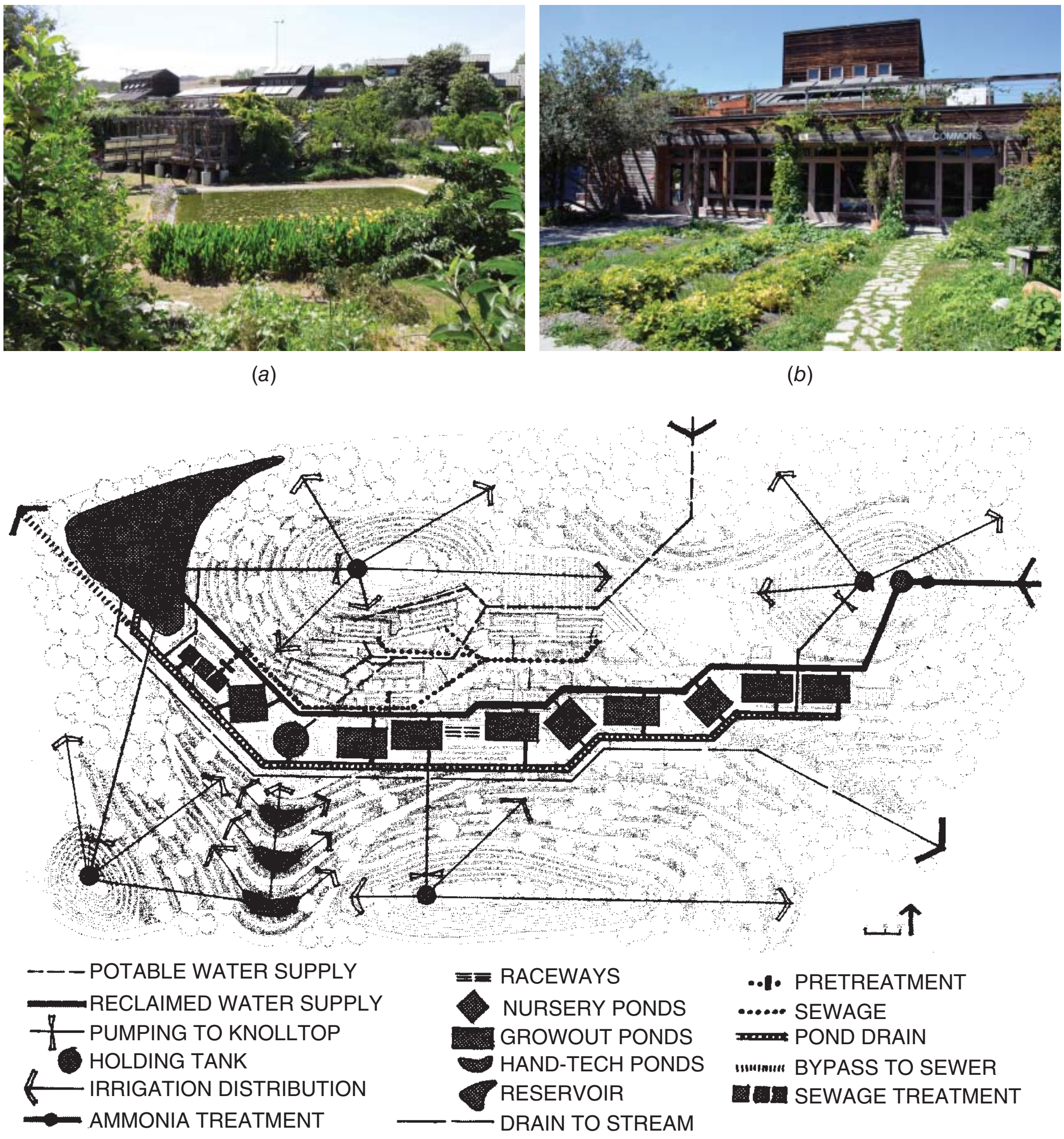


Fig. 1.14 *(a) The Center for Regenerative Studies (CRS), California Polytechnic State University–Pomona. (b) Plants provide water treatment and generate biomass in an aquacultural pond at the Center for Regenerative Studies, Cal Poly–Pomona. (c) Site plan for the CRS. It's not easy being regenerative—the highlighted elements relate only to the water reclamation aspects of the project. (Photos © Terri Meyer Boake; used with permission; drawing from John Tillman Lyle. 1994.* Regenerative Design for Sustainable Development. *Hoboken, NJ: John Wiley & Sons.)*

(l) Extreme Events

A series of notable extreme events, such as Hurricane Harvey's impact on Houston or Extra-tropical Storm Sandy's destruction in the New York area, have raised questions about the role of buildings and building design in buffering owners and occupants from the effects of such events. There are several distinct concepts associated with design for extreme event mitigation.

Resilience. Relative to infrastructure, resilience has been described as "the ability to reduce the magnitude and/or duration of disruptive events" (NIAC, 2009). There is no formal definition of *resilient building* or list of characteristics that would identify such a building. Herein, we define a resilient building (or system or assembly) as one that can take a beating (during a flood, hurricane, ice storm, earthquake) and keep on working. The project-specific limits of "beating" and "working" will be established under the owner's project requirements (OPR).

The essential concept of resilient building design is that a building, system, or assembly can weather an exceptional event without abject failure. The basic design principles are common sense, hardening, and redundancy. There are a range of issues and potential solutions—such as air-conditioning condensers that are not washed away by storm surge; windows that are not blown out in a hurricane; key electrical equipment that is not under water in a flood. In some cases, the answer lies in better placement of equipment (emergency generators above flood stage); in some cases in hardening systems (storm shutters); in some cases redundancy (municipal and PV power systems).

The Resilient Design Institute, headed by Alex Wilson, provides resources to assist designers engaging in design for extreme events (see https://www.resilientdesign.org/category/news-blogs/alex-wilson/). Also, the New York State Energy Research and Development Authority (NYSERDA) and the University of Buffalo have released the report Climate Resilience Strategies for Buildings in New York State, which uses the specific information provided in existing strategy documents and expands the offering to provide general descriptions of climate resilience strategies that are accessible to all audiences. This document aims to give readers an overview of climate resilience strategies, while clickable links within the text allow readers to dig deeper and access more specific information.

Passive Survivability. This concept is different from resiliency. The fundamental precept of passive survivability is that habitable conditions can be maintained in a building (or portion of a building) during an extreme event. This would allow sheltering in place—assuming a resilient project—rather than abandonment or attempting to endure under severe interior conditions. The basic design question for passive survivability is: what can be done to allow occupants to stay in place, without risking their health, in the event of failure of normal utilities (electricity, natural gas, water, sewer)?

The tools to assist a designer in addressing passive survivability exist. They are generally the same tools used for conventional building systems analysis—but assuming that the active systems are shut off.

Adaptability. Adaptability refers to the ability of a building to perform reasonably well under changing (but not extreme) conditions. One example is the design of a building that can perform well without radical renovations under changing climate conditions. Design for adaptability might involve overdesigning for today's conditions in an effort to better align with expected future conditions. This can be expensive but might make sense for an element that would be very difficult to change (such as wall insulation). Another approach is to allow space for future installation of systems or system modules—such as preparing for a rooftop PV system in anticipation of a lower-cost system in the future.

1.7 DESIGN TIPS AND STRATEGIES

From a design process perspective, the operating philosophy of this book is that development of appropriate design intent and criteria is critical to the successful design of buildings and their mechanical and electrical systems. Passive systems should generally be used before active systems (this in no way denigrates active systems, which will be necessary features of almost any large-scale building); life-cycle costs should be considered instead of simply first cost; and green design is a desirable intent that will ensure energy efficiency and provide a pathway toward sustainability. Design validation, commissioning, and post-occupancy evaluation should be aggressively pursued.

John Lyle presented an interesting approach to design (that elaborates upon this general philosophy) in his book *Regenerative Design for Sustainable Development*. The following discussion presents an overview of his approach. The strategies provide design teams with varied opportunities to integrate site and building design with components and processes. Those strategies most applicable to the design of mechanical and electrical systems are presented here. This approach guided the design of the Center for Regenerative Studies at the California Polytechnic State University at Pomona, California (Fig. 1.14).

(a) Let Nature Do the Work

This principle expresses a preference for natural/passive processes over mechanical/active processes. Designers can usually find ways to use natural processes on site (Fig. 1.15), where they occur, in place of dependence upon services from remote/nonrenewable sources. Smaller buildings on larger sites are particularly good candidates for this strategy.

(b) Consider Nature as Both Model and Context

A look at this book reveals a strong reliance upon physical laws as a basis for design. Heat flow, water flow, electricity, light, and sound follow rules described by physics. This design principle, however, suggests looking at nature (Fig. 1.14) for biological, in addition to the classical physical, models for design. The use of a Living Machine to process building wastes, as opposed to a conventional sewage treatment plant, is an example of where this strategy might lead.

Fig. 1.15 *Letting nature do the work—via daylighting. Mt. Angel Abbey Library, St. Benedict (Mt. Angel), Oregon, designed by Alvar Aalto. (© Tyler Mavichien; used with permission.)*

(c) Aggregate Rather Than Isolate

This strategy recommends that designs focus upon systems, and not just upon the parts that make up a system—in essence, seeing the forest through the trees. The components of a system should be highly integrated to ensure workable linkages among the parts and the success of the whole. An example would be optimizing the solar heating performance of a direct-gain system involving glazing, floor slab, insulation, and shading components, even though such optimization might reduce the performance of one or more constituent parts of the system (Fig. 1.16).

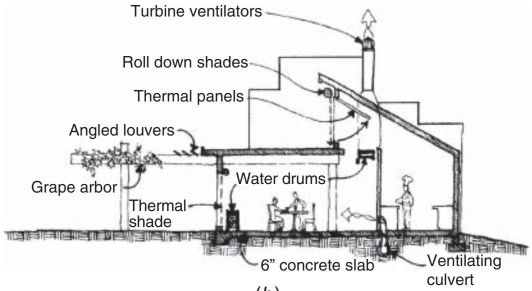
(d) Match Technology to the Need

This strategy seeks to avoid using high-grade resources for low-grade tasks (Fig. 1.17). For example, it is wasteful to flush toilets with purified water, but perhaps less clearly wasteful (but equally a mismatch) to use electricity (a very high-grade energy form) to heat water for bathing. The concept of exergy (discussed in a subsequent chapter) relates to this design strategy.

A new tool offered by Architecture 2030 is the *2030 Palette*, an interactive online platform that gives the designer guiding principles, information, and resources to select appropriate technologies for a variety of scales: building, site, district, city, and region (http://2030palette.org/).

In 2007, the AIA published *50to50*, a resource offering 50 strategies with useful guidance to assist architects and the construction industry toward a 50% reduction in fossil fuels by 2010, and carbon neutrality by 2030. The strategies include a range of broad site and planning objectives to building-specific concepts. Each strategy includes an overview of the subject, typical applications, emerging trends, links to information sources, and important relationships

(a)



(b)

Fig. 1.16 *Aggregating, not isolating. (a) The former Cottage Restaurant, Cottage Grove, Oregon, operated successfully with passive strategies for thirty years. (b) This section through the restaurant illustrates the substantial integration and coordination (aggregation) of elements typical of passive design solutions. (Photo by Lisa Leal; drawing by Michael Cockram; © by John S. Reynolds; all rights reserved.)*

Fig. 1.17 *Match technology to the need. Sometimes it's the simple things that count. Keeping cool with a solar-powered fan cap.*

Fig. 1.18 *Seek common solutions. The "atrium" of the Hood River County Library, Hood River, Oregon, provides a central hub for the library, daylighting, views (spectacular), and stack ventilation. (© Alison Kwok; all rights reserved.)*

to other carbon reduction strategies (American Institute of Architects, 2007).

(e) Seek Common Solutions to Disparate Problems

This approach requires breaking out of the box of categories and classifications. An understanding of systems should lead to an increased awareness of systems capabilities—which will often prove to be multidisciplinary and multifunctional. Making a design feature (Fig. 1.18) serve multiple tasks (perhaps mechanical, electrical, and architectural in nature) is one way to counteract the potential problem of a higher first cost for green design features. Solutions can be as simple and low-tech as using heat from garden composting to help warm a greenhouse.

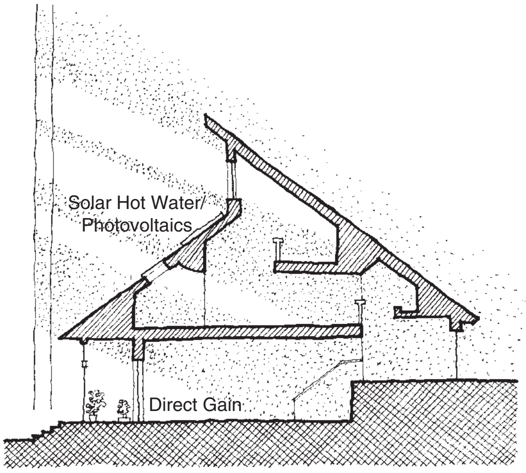


Fig. 1.19 *Shaping the form to the flow. Using a "band of sun" analysis as a solar form giver (see Chapter 3 for further details). (Redrawn by Jonathan Meendering.)*

(f) Shape the Form to Guide the Flow

The best examples of this strategy are solar-heated buildings that are shaped (Fig. 1.19) to gather winter sun, or naturally ventilated buildings shaped to collect and channel prevailing winds. Daylighting is another place to apply the "form follows flow" strategy, which can have a dramatic impact upon building design efforts and outcomes.

(g) Shape the Form to Manifest the Process

This is more than a variation on the adage "If you've got it, flaunt it." This strategy asks that a building inform its users and visitors about how it works both inside and out (Fig. 1.20). In passive solar-heated and passively cooled buildings, much of the thermal performance is evident in the form of the exterior envelope and the interior space, rather than hidden in a closet or mechanical penthouse. Professor David Orr of Oberlin College addresses this issue succinctly by asking, "What can a building teach?"

(h) Use Information to Replace Power

This strategy addresses both the design process and building operations. Knowledge is suggested as a substitute for brute force (and associated energy waste). Designs informed by an understanding

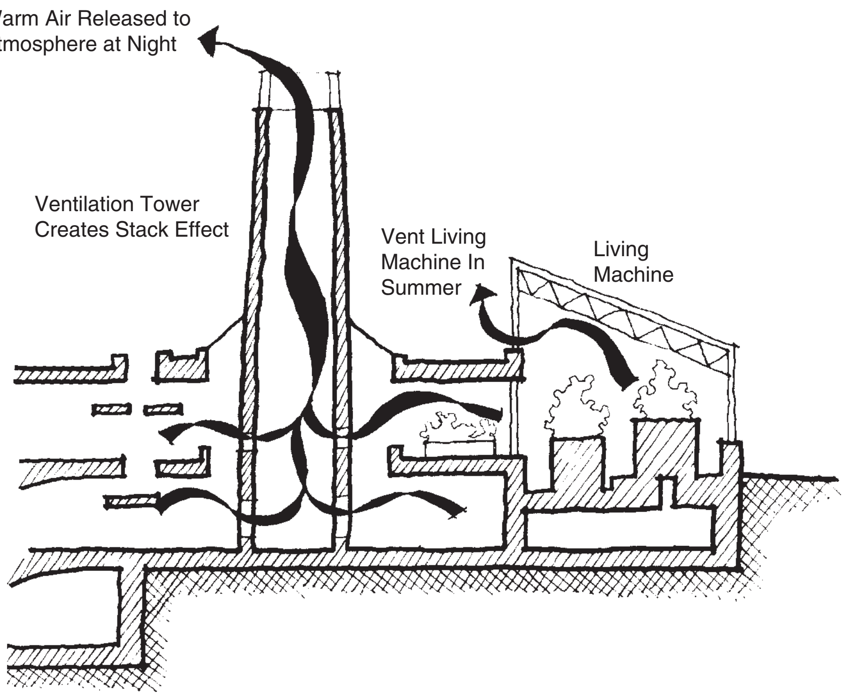


Fig. 1.20 *Shaping the form to the process. Stack effect ventilation is augmented by the building form in this proposal for the EPICenter project, Bozeman, Montana. (Courtesy of Place Architecture LLC, Bozeman, Montana, and Berkebile Nelson Immenschuh McDowell Architects, Kansas City, Missouri. Redrawn by Jonathan Meendering.)*

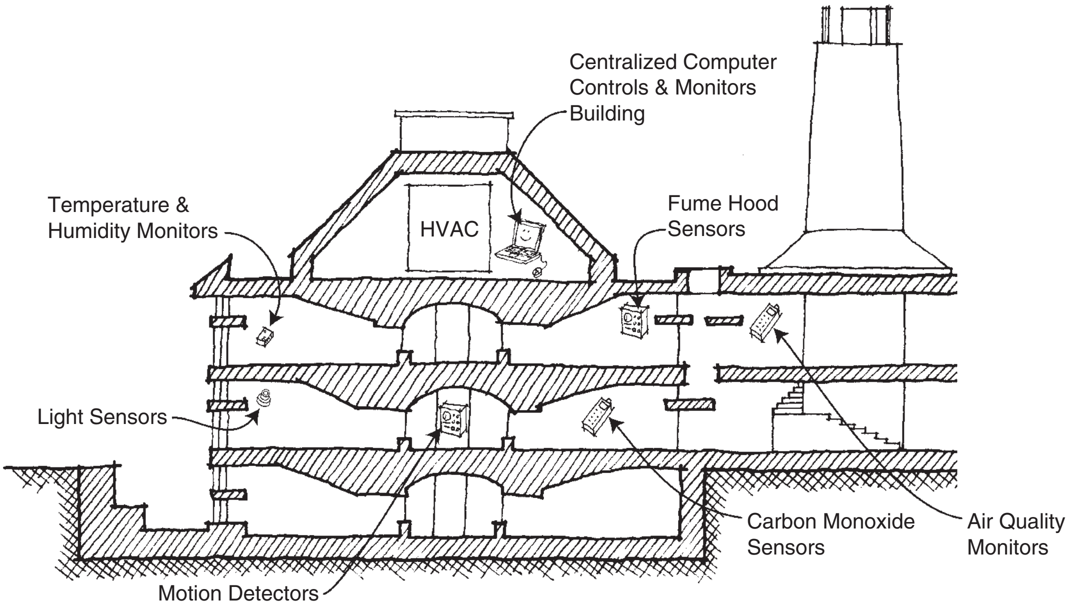


Fig. 1.21 *Use information to replace power. Section showing intelligent control system components for the proposed EPICenter project, Bozeman, Montana. (Courtesy of Place Architecture LLC, Bozeman, Montana, and Berkebile Nelson Immenschuh McDowell Architects, Kansas City, Missouri. Redrawn by Jonathan Meendering.)*

of resources, needs, and systems capabilities will tend to be more effective (successfully meeting intent) and efficient (meeting intent using fewer resources) than uninformed designs. Building operations informed by feedback and learning (Fig. 1.21) will tend to be more effective and efficient than static, unchangeable operating modes. Users of buildings can play a leading role in this approach by being allowed to make decisions about when to do what it takes to maintain desired conditions. Reliance on a building's users is not so much a direct energy saver—most controls use very little power—as it is an education. A user who understands how a building receives and conserves heat in cold weather is likely to respond by lowering the indoor temperature and reducing heat leaks. Furthermore, some studies of worker comfort indicate that with more personal control (such as operable windows), workers express feelings of comfort across a wider range of temperatures than with centrally controlled air conditioning.

(i) Provide Multiple Pathways

This strategy celebrates functional redundancy as a virtue—for example, providing multiple and separate fire stairs for emergency egress. There are many other examples, from backup heating and cooling systems, to multiple water reservoirs and piping pathways for fire sprinklers, to emergency electrical and lighting systems. This strategy also applies to climate-site-building interactions in which one site-based resource may temporarily weaken but can be replaced by another (Fig. 1.22).

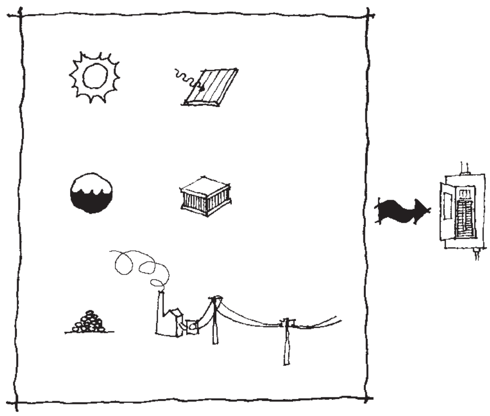


Fig. 1.22 *Providing multiple pathways. Three distinct sources of electricity are projected in this conceptual diagram for the proposed EPICenter project, Bozeman, Montana. (Courtesy of Place Architecture LLC, Bozeman, Montana, and Berkebile Nelson Immenschuh McDowell Architects, Kansas City, Missouri. Redrawn by Jonathan Meendering.)*

(j) Manage Storage

Storage is used to help balance needs and resources across time. Storage appears as an issue throughout this book. The greater the variations in the resource supply cycle, the more critical storage management becomes. Rainwater can be stored in cisterns, balancing normal daily demands for water against variable monthly supplies. The high variability of wind-generated electricity output can be managed with hydrogen storage, providing a combustible fuel that can be drawn on at a rate and time independent of wind speed.

On sunny winter days, excess solar energy reaching a room can be stored in thermally massive surfaces (Fig. 1.23), to be released at night. On cool summer nights, *coolth* (the conceptual opposite of heat) can be stored in these same surfaces and used to condition the room by day. Most storage solutions will strongly impact building architecture.

Fig. 1.23 *Manage storage. The 2007 MIT Solar Decathlon house features a Trombe wall made of translucent tiles to capture and store heat. (© Alison Kwok; all rights reserved.)*

1.8 CASE STUDY—DESIGN PROCESS

Rocky Mountain Institute Innovation Center, Basalt, Colorado

Project Basics

- Location: Basalt, Colorado, US
- Latitude: 39.40°N; longitude: 107.0°W; elevation: 6611 ft (2015 m)
- Heating degree days: 8549 base 65°F (4801 base 18.5°C); cooling degree days: 1716 base 50°F (953 base 10°C) at Aspen Airport; annual precipitation 16 in. (427 mm)
- Building area: 15,610 ft^2 (1450 m^2) conditioned space
- Completed December 2015
- Client: Rocky Mountain Institute (RMI)
- Core team members: ZGF Architects (architect of record), JE Dunn (general contractor), Architectural Applications (high-performance design consultant), PAE Consulting Engineers (mechanical, electrical, plumbing, IT), David Nelson & Associates (lighting); True North Management (owner's representative), Graybeal Architects, TG Malloy (land planner), Sopris Engineering (civil engineer), KPFF Consulting Engineers (structural engineers), DHM Design (landscape architect), Resource Engineering Group (commissioning), Collective Sun (PPA), SunPower (Solar panels)

Background. The RMI Innovation Center, located near Aspen, Colorado, was designed to demonstrate how an "aggressively green" office building should be designed, built, and operated. The project incorporates a wide variety of passive and active design strategies and systems, and it has earned an impressive number of high-performance building citations including LEED Platinum certification, Living Building Challenge Petal status, and Passive House certification The client sees these positive outcomes as a consequence of a deliberate and robust integrated design process that sought exceptional levels of building performance in one of the coldest climates in the United States.

Context. The Rocky Mountain Institute (RMI) was founded in 1982 by Amory and Hunter Lovins to promote sustainability and energy efficiency through research, education, and consultancy.

Fig. 1.24 *South façade showing solar shading devices and daylight apertures. (Courtesy of ZGF Architects LLP; © Tim Griffith.)*

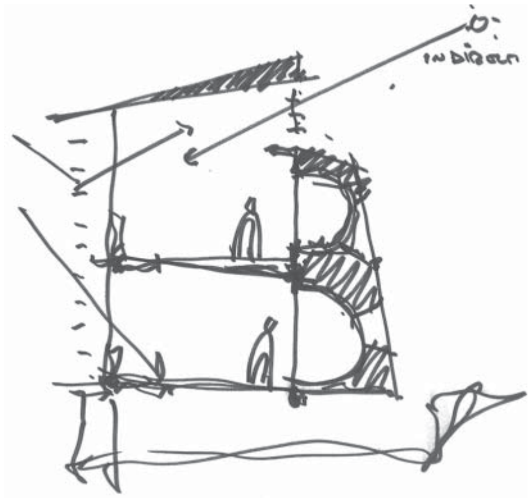


Fig. 1.25 *Early design sketch from a team meeting. (Courtesy of ZGF Architects LLP.)*

The Innovation Center (Figs. 1.24 and 1.28) is a direct extension of RMI's organizational mission that showcases high-performance green building design and provides space for collaboration with communities, thought leaders, and industry. From the onset, RMI had a clear vision for the building that included building performance targets as well as the ways in which the design team would work together to achieve them (Figs. 1.25 and 1.26). Perhaps the most valuable lesson from this project is the value that a client brings to the design process by clearly outlining requirements, expectations, and goals to guide the design team in their efforts to achieve challenging building performance outcomes that will be measured upon completion.

Design Intent. The RMI Innovation Center sought to demonstrate that moderately sized commercial office buildings, a common and energy-intensive building type in the United States, can be designed to achieve very high energy efficiency and outstanding comfort conditions for its users. The design process and strategies employed aimed to provide viable precedent and guidance to assist the building industry to achieve similar results for office buildings going forward.

Design Criteria and Validation. Although RMI is a staunch advocate for energy-efficient building and renewable energy, the design criteria outlined in the initial request for proposals (RFP) emphasized integrated design and the Integrated Project Delivery (IPD) acquisition model as ways to ensure that the design team focused on collaboration and finding design synergies rather than on discrete systems, technologies, or components. The Owner's Project Requirements (OPR) document provided specificity on which systems would be tested and validated using the commissioning process and the performance expectations for those systems. RMI then went a step further and tied fees for the design team to satisfaction of performance goals.

Key Design Features

- Long façades face south and north minimizing solar exposure on the east and west for logical passive heating, solar shading, and glare control
- Heating, ventilating, electrical, and fire protection systems integrated into cross-laminated timber (CLT) floor panels
- 83 kW peak photovoltaic system producing over 114,000 kWh annually, 50% more than the facility uses (Fig. 1.27)
- 30 kW, 45-kWh battery storage system that reduces the building's peak demand
- Dual-pipe plumbing system configured for graywater reuse (sink and shower water for