

ASHRAE GreenGuide

Design, Construction, and Operation
of Sustainable Buildings

Sixth Edition

- Completely revised by experienced industry professionals
- Updated information on building decarbonization and zero energy emissions
- Focused and in-depth GreenTips and Digging Deeper sidebars



ASHRAE GreenGuide

Design, Construction, and Operation of Sustainable Buildings

This publication was developed under the auspices of ASHRAE Technical Committee (TC) 2.8, Building Environmental Impacts and Sustainability. TC 2.8 is concerned with the impacts of buildings on the local, regional, and global environment; means for identifying and reducing these impacts; and enhancing ASHRAE member awareness of the impacts.

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ASHRAE GreenGuide

Design, Construction, and Operation of Sustainable Buildings

Sixth Edition



Peachtree Corners

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PREFACE TO THE SIXTH EDITION

by Tom Lawrence

ASHRAE GreenGuide has become one of ASHRAE's primary contributions toward the sustainable design of the built environment. The industry and the people in it have evolved significantly since the original edition was released in January 2004. By the time this new edition of *ASHRAE GreenGuide* is released, it will be roughly 20 years since work began on the very first edition of the book. When the planning for the first *GreenGuide* was being done, the intent was to provide guidance for the young professional or for a person who was about to begin their first green project. Back then, awareness and knowledge of sustainable design practices were not commonplace nor mainstream. That has changed, which is a good thing. There is still a need for a resource that helps inform the young professional or student about the concepts of green design (more on the terminology of what to call this practice later). ASHRAE addressed this with the publication in late 2019 of *High-Performance Buildings Simplified* (I was the primary author of that book along with Dr. Julia Keen). ASHRAE and the team writing this book agreed that the *GreenGuide* would be evolved to include material and concepts focused more toward the level of understanding of a practicing professional. This helps avoid overlap and serves two distinct needs for the industry and the ASHRAE membership.

A lot has changed in the industry in general, and in green design practices in particular, since the first edition's release. Many of the concepts that seemed "out there" in the period that the first edition was published are now considered mainstream and, in some cases, are now actually required by code. That is the main reason why ASHRAE has adopted an unofficial "continuous maintenance" process for this book, with the goal of having a new edition every three to four years that incorporates new concepts and improves upon the treatment of technologies from prior editions. ASHRAE has a committed goal of global leadership in sustainability and technical education, and continuously updating this book follows the example set by ASHRAE's rebranding for a focus on sustainability in 2012.

Since the fifth edition of *GreenGuide*, several key developments have occurred in the industry related to green building practices. Perhaps the biggest of which has

been the merging of ANSI/ASHRAE/USGBC/IES Standard 189.1 with the *International Green Construction Code* (IgCC). In this arrangement with the International Code Council (ICC), ASHRAE is responsible for the technical content, and ICC is responsible for the administrative provisions. This will hopefully result in further adoption and use of this code, and other organizations and jurisdictions are using these as the basis for their own codes and design standards. Thus, the industry is witnessing the continued evolution of green building programs from strictly voluntary to being both more mainstream within the industry as well as mandatory in jurisdictions that have adopted these standards for their building codes.

This sixth edition was edited to remove material that felt too basic for the practicing professional while including other material that will help guide them in their design and operation of better-performing buildings. One change is that the chapters on Construction and Construction Documents were eliminated. These chapters never were a key part of the *GreenGuide*, and the committee working on this new edition concluded that space would be better allocated to the design features and technologies. Material from the Operations and Maintenance chapter was incorporated into the chapter on Existing Buildings. While no new chapters were added, we decided to focus on the impacts of buildings on the climate in the Emerging Trends and Epilogue chapter. As buildings impact the climate, climate change also impacts the design and operation of buildings. Therefore, new material is included on the topics of designing and operating buildings and their systems in response to current and expected climate change and accompanying extreme weather events; the need to increase resilience in the built environment; and identifying the interrelationship of sustainability, efficiency, and smart technologies with building resilience. Significant edits were performed on a number of the chapters, and we have reached out to others beyond the traditional group that has worked on this chapter to provide updates and modernization of chapters (for example, to the Illuminating Engineering Society [IES] and members of that community with the chapter on Lighting).

No one person, or even a small committee of people, can be expected to have the breadth and depth of expertise to create a book that covers the wide range of issues governing the design, construction, and operation of green buildings. Thus, many people with various backgrounds were recruited to help review and provide edit suggestions for the prior edition's existing chapters. One of the goals of the editorial committee for this revision was to bring in a large number of additional outside reviewers. We truly appreciate those who contributed their time and talents to review, edit, and write this guide. Finally, the current edition could not have been possible without all the hard work and dedication put into it by others who created the previous editions. This book truly represents the collaborative nature of the work done by dedicated volunteers within ASHRAE. All work performed—by the authors, editors, developing subcommittees, other reviewers, and technical committee participants—was strictly voluntary.

WHO SHOULD USE ASHRAE GREENGUIDE

The original stated purpose for the *ASHRAE GreenGuide* was to primarily guide HVAC&R designers and operators in creating and operating green buildings, but time has shown that it is also a useful reference for architects, owners, building managers, operators, contractors, students, and others in the building industry who want to understand the technical issues regarding high-performance design from an integrated building systems perspective. Considerable emphasis is placed on teamwork and close coordination between parties.

The *GreenGuide* was originally intended for use by younger engineers and architects or more experienced professionals about to enter their first green design projects. However, a survey conducted several years ago of those who purchased one of the earlier editions of this publication revealed that more experienced individuals were primarily using it. The survey also indicated a higher percentage of the readership from countries outside North America, perhaps reflecting the growing internationalization of ASHRAE. *High-Performance Building Design Simplified* acts as the reference material for the original target audience of *ASHRAE GreenGuide*, which allowed this edition to evolve its target audience toward more experienced professionals.

HOW TO USE ASHRAE GREENGUIDE

This book is intended to be used more as a reference than as something one would read in sequence from beginning to end. The table of contents is the best place for any reader to get an overview of what this publication covers. Throughout *GreenGuide*, numerous techniques, processes, measures, or special systems are described succinctly in a modified outline or bullet form. These are termed *ASHRAE GreenTips*. Each GreenTip concludes with a listing of other sources that may be referenced for greater detail. (Lists of GreenTips and Digging Deeper sidebars can be found in the table of contents.)

Readers are encouraged to review Chapter 1, Introduction and Background, which provides essential definitions and meanings of key terms (for example, is the correct term a *green building* or maybe a more recently preferred term a *high-performance building*?). Chapter 2 describes green rating systems and the relevant standards and paths to compliance. The project's initial phases are covered, with Chapter 3 providing an overview of project strategies and the early stages of the design process. Chapter 4 addresses this subject from the architectural design and planning perspective, emphasizing how the changing climate informs how building design needs to change. Chapter 5 discusses how commissioning fits into the delivery of a green building.

The bulk of this book covers the design process, starting with the concept design phase in Chapter 6. These chapters are essential reading for all looking for guidance in specific areas of a building design. Other topics in this section include sustainable

sites, indoor environmental quality, energy use, conversion and distribution, energy and water resources, lighting, water efficiency, and smart building systems.

The final portion of the book includes a chapter focusing on the sustainable design and operation of residential buildings and another on how these topics can be applied to existing buildings (which make up the bulk of the structures that will be around by 2030). The last chapter of this book includes a discussion on emerging trends in the industry, focusing on the impacts on climate and other key topics such as resilience in the built environment. The Appendix contains a collection of common building type GreenTips followed by a comprehensive References and Resources section, which compiles all the sources mentioned throughout the guide, and an index for rapid location of a particular subject of interest.

HISTORICAL BACKGROUND ON ASHRAE GREENGUIDE

The idea for the publication of this guide was initiated by 1999–2000 ASHRAE President Jim Wolf and carried forward by then President-Elect (and subsequently President) William J. Coad. Members of that first subcommittee were David L. Grumman, Fellow ASHRAE, chair and editor; Jordan L. Heiman, Fellow ASHRAE; and Sheila Hayter, chair of Technical Committee (TC) 1.10 (a precursor to today's TC 2.8).

As stated earlier, ASHRAE sees this book as one of their key resources for use by Society members and potentially by society as a whole. Therefore, ASHRAE has published several revisions and updates to the books, with TC 2.8 in charge of the development of each revision. Over the years, many people have contributed to the continued evolution and refinement of this publication, and this book truly represents the team effort of ASHRAE to provide leadership to meet ASHRAE's vision statement of providing "a healthy and sustainable built environment for all." Key people who contributed toward the development of this book are mentioned in the Acknowledgments section, but the large number of contributors, reviewers, and the like who helped with portions of this edition and with prior editions make it impossible to include everyone; but their efforts are well appreciated.

Tom Lawrence
Senior Editor of the fourth, fifth, and sixth editions of *ASHRAE GreenGuide*
Athens, Georgia, May 2021

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The following individuals served as coeditors on this edition of *ASHRAE GreenGuide*, provided written materials and editorial content, and formed the Senior Editorial Group of the ASHRAE TC 2.8 *GreenGuide* subcommittee for this new sixth edition:

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The committee, and indeed ASHRAE as a Society, are deeply thankful for all the individuals who helped with or contributed to the first five editions of the *GreenGuide*. This new edition would not be where it is without their help. However, because of space constraints, their names cannot be listed here.

Section 1: Basics

CHAPTER ONE

INTRODUCTION AND BACKGROUND

INTRODUCTION

There is a growing awareness about the impact of the built environment on the environment around us and on the human occupants of buildings. The use of sustainable engineering concepts has evolved quite rapidly in recent years and is now well recognized as mainstream in the HVAC&R and related engineering professions. This in turn is being encouraged by increased client demand for more sustainable buildings, commonly called *green buildings*.

Interest in green buildings has been particularly evident in the concern about energy and water resource consumption, but also includes broader concerns such as indoor environmental air quality, material use, and “smart” development and planning. Many countries in the world now have green-building rating systems (voluntary) and/or codes (mandatory) in some form or other. Organizations devoted to green buildings now also exist in most countries. Even as the concept of green design is reaching mainstream acceptance, these organizations continue to promote these concepts, exhort the industry and society to action, strive to motivate industry practitioners and building owners, warn of consequences from ignoring these concepts, and instruct how to achieve green design.

ASHRAE identified a need for guidance on green building concepts specifically directed toward practicing professionals involved on a day-to-day basis in the mechanical/electrical/plumbing (MEP) building system design process. However, readers may find that this guide may also be useful for professionals in other disciplines related to the design, construction, and operation of buildings. From a survey conducted in 2011, a wider range of people were using the *ASHRAE GreenGuide* than originally anticipated, including students and other professionals in related disciplines. The topics covered in this guide are global and thus there has been an effort to keep this guide applicable internationally. As mentioned in the Preface, the focus of this book has evolved to meet the needs of more experienced practicing professionals (of any discipline) rather than those of

students or people just entering the profession (for whom ASHRAE's parallel publication *High-Performance Buildings Simplified* was developed).

There has even been an evolution in terminology to describe the concepts presented in this book. Originally the term used was *green buildings*, which was the prevailing description when this book and organizations such as the U.S. Green Building Council were first conceived of. Since then, two other terms have come into use: *sustainable design* and *high-performance buildings*. *Green* is one of those words that can have many meanings, depending on the circumstances. One of these is the greenery of nature in the flora around us. This symbolic reference to nature is the meaning this term relates to in this publication. For brand continuity, ASHRAE is continuing to use the term *green* in this book's title. However, some may not recognize the difference the terms green, sustainable, or high-performance and use them interchangeably; this is also the general approach taken in this book. This guide is not intended to cover the full breadth of sustainability, as this would require an extensive series of volumes, but it is a good overview of the main topics and issues involved. For additional key characteristics and detailed discussion of sustainability in buildings and the built environment, refer to the "Sustainability" chapter in *ASHRAE Handbook—Fundamentals* (ASHRAE 2021).

The remaining portions of this Introduction chapter cover a few topics that do not easily fit in one chapter or another but are more pervasive throughout this Guide. These include a brief discussion of the need to maintain a commitment to green/sustainable/high-performance design throughout the project; a reminder of how important achieving high-performance is to addressing climate change; a comparison of how green design issues are being addressed in various parts of the world; and finally the concept of considering the embodied energy and using life-cycle assessments to evaluate the overall impact of the building.

COMMITMENT TO GREEN/SUSTAINABLE HIGH-PERFORMANCE PROJECTS

Green projects require more than a project team with good intentions; they require commitment from the owner and the rest of the project team, early documentation of sustainable/green goals recorded by the Owner's Project Requirement (OPR), and the designer's documented basis of design. The most successful projects incorporating green design are ones with dedicated, proactive owners who are willing to examine (or give the design team the freedom to examine) the entire spectrum of ownership—from design to construction to long-term operation of their facilities. These owners understand that green buildings require more planning, better execution, and better operational procedures, requiring a firm commitment to changing how building projects are designed, constructed, operated, and maintained to achieve a lower total cost of ownership and lower long-term environmental impacts.

Implementing green/sustainable practices could indeed raise the initial design soft costs associated with a project, particularly compared to a code minimum building design. First cost is an important issue and often is a stumbling block in moving building design from the code minimum (“good or adequate design”) to one that is more truly sustainable. Implementing the commissioning process early in the predesign phase of a project adds an initial budget line item but can often actually reduce overall total design/construction costs and the ultimate cost of ownership.

In addition, significant savings and improved productivity of the building occupants can be realized for the life of the building, lowering the total cost of ownership and/or providing better value for tenants. To achieve lifelong benefits also requires operating procedures for monitoring performance, making adjustments (continuing commissioning) when needed, and appropriate maintenance.

THE IMPACT OF CLIMATE CONSIDERATIONS

There is bad news and good news when we look at how buildings are involved with greenhouse gas (GHG) emissions. First, the bad news: buildings (commercial and residential) are directly or indirectly responsible for nearly 40% of the GHG emissions in the United States and most developed countries, and the trend is also holding up in key developing nations. The good news is that buildings have also been identified as the economic sector with the best potential for cost-effective mitigation of GHG emissions, as highlighted in Figure 1-1. In this figure, the carbon dioxide (CO₂) emissions by sector and total non-CO₂ GHG emissions across sectors are shown in the baseline scenario at top while the bottom portion of Figure 1-1 shows the net result from mitigation scenarios that reach an average of about 450 ppm (in a range of 430 to 480 ppm) CO₂ equivalent (CO₂-eq) emissions (likely to limit warming to 3.6°F [2°C] above preindustrial levels) with CO₂ capture and storage (CCS, left) and without CCS (right). The difference between the baseline and mitigation scenarios in this figure represent the net emissions decrease possible for each sector, and the buildings sector represents one of the highest potential options. Therefore, the buildings industry can and should take responsibility for reducing GHG emissions, primarily through a reduction in energy consumption for new construction, in refurbishing existing buildings, and planning for the operation and maintenance to maintain the high level of efficiency.

The Conference of the Parties meeting in Paris in late 2015 (COP21) was, at the time, recognized as a breakthrough event where the first significant changes to a global approach to address climate concerns were made in nearly 25 years. More importantly for the buildings industry, the important role of buildings in addressing this problem was recognized at this conference and a new organization, the Global Alliance for Buildings and Construction, was created. This alliance has a four-step strategic approach to: (1) reduce the energy demand of buildings (in particular,

Sectoral CO₂ and non-CO₂ GHG emissions in baseline and mitigation scenarios with and without CCS

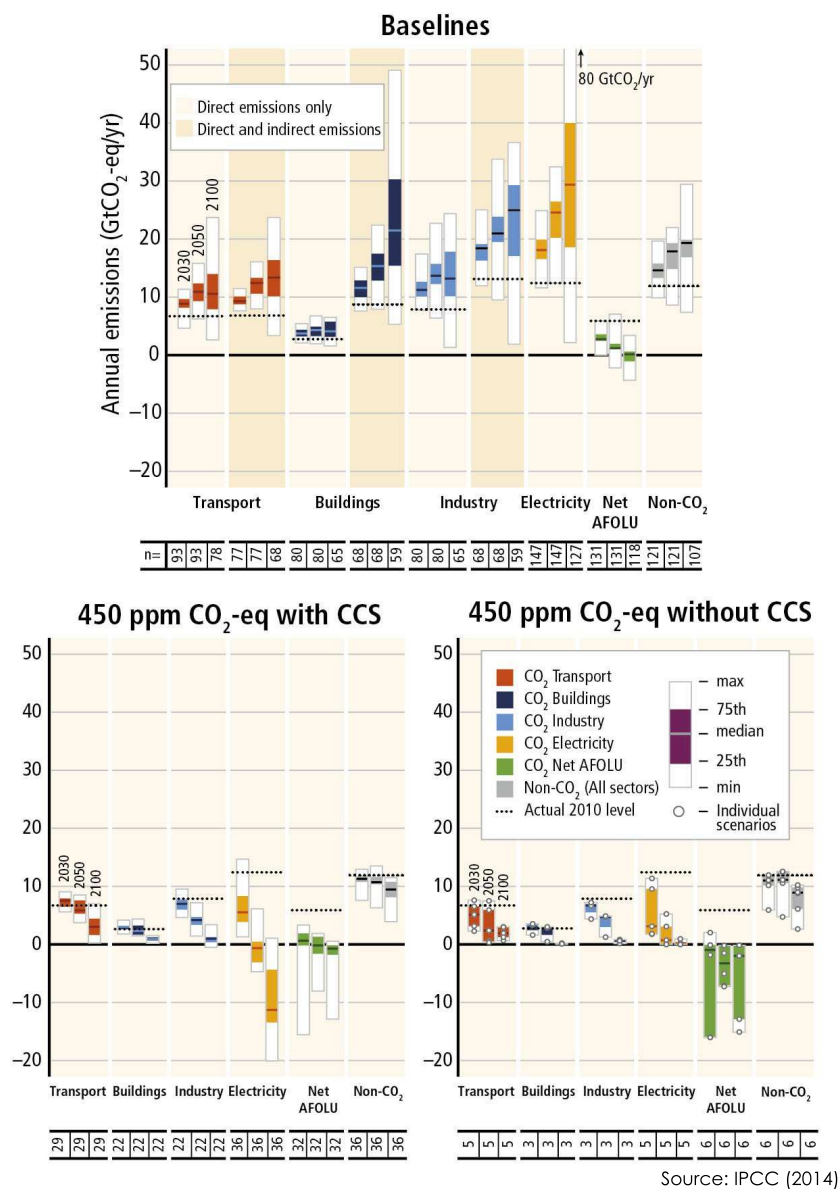


Figure 1-1 Cross-sectoral mitigation strategies.

existing buildings), (2) decarbonize the energy and power supply for buildings, and (3) reduce the embodied greenhouse gases in materials and equipment through life cycle analysis, and increase resiliency by adaptations against climate change and associated other risks.

ASHRAE has been a leader in meeting the challenges to reduce GHG emissions associated with building operations in several ways. Significant effort was put into modifying ANSI/ASHRAE/IES Standard 90.1 to drastically improve energy efficiency. The 2010 version of Standard 90.1, in essence, met an AIA challenge by introducing requirement changes that were developed and introduced during that decade. Subsequent versions of Standard 90.1 continue to increase the minimum energy efficiency requirements, and hence their associated GHG emissions. Although the specific requirements may differ in some cases, the *International Green Construction Code* (IgCC), which has its technical basis in the ANSI/ASHRAE/USGBC/IES Standard 189.1, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings* (ICC 2021), has energy efficiency levels that exceed the minimum code values in Standard 90.1.

Another way this is being accomplished is through the production of the *Advanced Energy Design Guide* (AEDG) series. The series covers prescriptive measures that result in significant energy efficiency improvements, with the initial series of guides dealing with measures that should achieve 30% savings over the 1999 version of Standard 90.1 (ASHRAE 1999) and the 50% guides working to achieve that level of savings over the 2004 version of that Standard. More recently, ASHRAE has started to produce AEDG publications with a goal of achieving net zero energy (on an annualized basis).

All new building projects that wish to comply with green principles should at least estimate the CO₂ equivalent emissions footprint of the building (of which a large part is produced through energy consumption). Using publicized emissions factors, these calculations are not complicated and can provide insight. For existing buildings, the goal is to compute the reduction in emissions associated with proposed energy conservation measures. In both cases, the GHG emissions factor used should be based on source energy and not on energy consumed on site alone. A good initial reference source for emissions factors is a 2007 National Renewable Energy Laboratory (NREL) report (Deru and Torcellini 2007). The emissions factors for site electricity consumption in the United States have been updated by the U.S. Environmental Protection Agency (EPA) to reflect recent trends away from coal-based electricity production to more natural gas and other renewable energy systems such as solar and wind. Along the same lines, the European Commission recently updated the value of the primary energy factor in the context of revising the Energy Efficiency Directive (EED). This coefficient is used for calculating energy savings in primary energy terms using a bottom-up approach based on final energy consumption. Currently, a default coefficient of 2.1 may be used to convert kilowatt-hour electricity (European Commission 2018) to primary energy units,

down from the previous value of 2.5 that was used since 2015. EU member states may define a different coefficient based on the energy mix and other justified national circumstances. By the end of 2022 and every four years thereafter, the European Commission shall revise the default primary energy factor on the basis of observed data. The ongoing efforts underline the need to regularly revise the conversion factor for electricity and that the methodology adequately reflects the strong efforts of the European power sector to decrease the carbon footprint and increase the share of renewables in the power generation mix. European informative default values for various energy carriers are available in ISO 52000-1, *Energy Performance of Buildings—Overarching EPB Assessment*.

Digging Deeper

INTERNATIONAL PERSPECTIVE: REGULATIONS AND COMMENTARY

Society has recognized that previous industrial and developmental actions caused long-term damage to our environment, resulting in loss of food sources and plant and animal species, and changes to the Earth's climate. As a result of learning from past mistakes and studying the environment, the international community identified certain actions that threaten the ecosystem's biodiversity, and, consequently, it developed several governmental regulations designed to protect our environment. Thus, in this sense, the green design initiative began with the implementation of building regulations. An example is the regulated phaseout of fully halogenated chlorofluorocarbons (CFCs) and partially halogenated refrigerant hydrochlorofluorocarbons (HCFCs).

In Europe, the main regulatory instrument for tackling the energy consumption of buildings is the Energy Performance of Buildings Directive (EPBD) recast (European Commission 2018), which took effect in 2020 and replaced the original EPBD Directive (European Commission 2002). EPBD is on continuous maintenance along with the Energy Efficiency Directive (EED) and the Renewables Energy Directive (RED), with amended directives of the trilogy in the final stages of being published (Balaras and Dascalaki 2022). All EU member states introduced national laws, regulations, and administrative provisions for setting minimum requirements on the energy performance of new and existing buildings that are subject to major renovations and for energy performance certification of buildings. Additional requirements include regular inspection of boilers and air conditioning systems in buildings, an assessment of the existing facilities, and provision of advice on possible improvements and alternative solutions. Moreover, the EPBD recast

Digging Deeper

strengthens the energy performance requirements and clarifies and streamlines some of the original EPBD provisions to reduce the large differences between EU member states' practices. In particular, it requires that EU member states lay down the requirements so that new buildings are nearly zero energy by 2020 (2018 for public buildings) and the application of cost-optimal levels for setting minimum energy performance requirements for both the building's thermal envelope and technical systems.

Energy performance certificates (EPC) are issued when buildings are constructed, sold, or rented out. The EPC documents the energy performance of the building and is expressed as a numeric indicator or a letter grade that allows benchmarking of primary energy consumption. The certificate also includes recommendations for cost-effective improvement of the energy performance and is valid for up to ten years. National efforts and examples of EPCs are detailed in the works by Arcipowska et al. (2014) and Maldonado (2016).

The Concerted Action EPBD launched by the European Commission provides updated information on the implementation status in the various European countries (www.epbd-ca.org).

Buildings are at center stage of the ambitious European efforts and energy strategies for secure, competitive, and sustainable energy toward 2020, 2030, and 2050 (<https://ec.europa.eu/energy/en/topics/energy-strategy>). It is not just in developed countries that green-building design and energy efficiency concerns are taking hold. The later part of the past decade has seen an explosion of adopting building energy efficiency standards and green-building design programs. For example, India was the first expansion of the Leadership in Energy and Environmental Design® (LEED®) Green Building Rating System programs outside of the United States, with the establishment of the India Green Building Council in 2003. India also created a nationwide energy efficiency standard, the Energy Conservation Building Code, in 2008. This code was based on ANSI/ASHRAE/IES Standard 90.1 but modified for the local climates and situations. Similarly, ANSI/ASHRAE/IES Standard 90.2 was used as the basis for energy efficiency in residential construction in Kuwait (known as Kuwait 90.2), as modified for Kuwait's local climate and construction practices.

Energy efficiency standards throughout the world generally adopt two approaches. One is to have a set of mandatory requirements and then offer a prescriptive or a performance-based path for compliance (examples include the approaches taken for energy codes in the U.S., Canada, India, and Australia). Another approach is to have a set of mandatory items, then build on this with a point system for other features, with a minimum number of points required. This approach is the one taken by Japan and South Korea, for example.

Embodied Energy and Life-Cycle Assessment

Building materials used in the construction and operation of buildings have energy embodied in them due to the manufacturing, transportation, and installation processes of converting raw materials to final products. The material selection process should consider the environmental impact of demolition and disposal after the service life of the products. Design teams looking to achieve a green building must focus not just on the life-cycle cost of system design and equipment, but also on the environmental impact of products and processes used. This is termed *life-cycle environmental assessment* or simply *life-cycle assessment* (LCA). This is a cradle-to-grave approach that evaluates all stages of a product's life to determine its cumulative environmental impact. In the case of a building, the structure is a product itself, but it also is comprised of a large number of other individual products (e.g., materials, equipment). Thus, the combined impact of the entire building as a system should be quantified, which implies the combined impact of its individual parts as well as how they interact together to operate as a system. Different issues and priorities should be considered. For example, the selection of building materials with a lower embodied energy may be desirable for the construction phase, but it may be more environmentally conscious to consider a more energy-intensive one if it results in higher operational energy savings during the building's life cycle or the product's lifetime, whichever comes first. Similarly, during building refurbishment and the evaluation of different energy conservation measures, one should also consider the embodied energy in the new building materials (e.g., adding thermal insulation) or the replacement of building elements or systems (e.g., replacing windows or boilers), by comparing them against the resulting operational energy savings.

Several international efforts are underway to develop a standard approach, along with professional and easy-to-use tools to overcome cumbersome calculations and facilitate performing an LCA in routine, day-to-day projects. This is critical to ensure that these issues are addressed during the early stages of the decision-making process, when most critical decisions are made, for new building design or refurbishment. For large projects, use of building information modeling (BIM) can support LCA by reducing the time to reenter data (e.g. material quantities) and facilitate calculations, once ontology and semantic issues for the exchange of data and relevant information are properly handled.

A detailed description of the LCA approach has been developed by the EPA, and more detail can be found on their website on LCA, included in the Online Resources section at the end of this chapter. LCA databases and tools are used to calculate and compare the embodied energy of common building materials and products. Designers should give preference to resource-efficient materials and reduce waste by recycling and reusing whenever possible.

The building design team has a variety of options to consider in conducting an LCA analysis. The International Organization for Standardization (ISO) 14000

series of standards on environmental management serves as a method to govern the development of these tools. LCA tools are available from private commercial as well as governmental or public domain sources. The Building for Environmental and Economic Sustainability (BEES) tool was developed by the National Institute for Standards and Technology in the United States, with support from the U.S. Environmental Protection Agency. The Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) from the EPA focuses on chemical releases and raw materials usage in products. In Canada, the Athena life-cycle inventory database contains detailed, high-quality and regional construction data and complies with ISO 14040/14044 standards (Athena 2014). Some commercial firms also offer LCA tools.

The European Commission has long recognized that LCA provides the best framework for assessing the potential environmental impacts of products and underlined the need for more consistent data and consensus LCA methodologies. A European platform from the European Commission Joint Research Centre is available to facilitate the availability of quality-assured life-cycle data. The European reference Life Cycle Database (ELCD) is composed of life-cycle inventory data from front-running European business associations and other sources for key materials, energy carriers, transport, and waste management. Data sets can be used free of charge and also distributed to third parties.

Resilience and Other Emerging Trends

This edition of the *GreenGuide* has added more material and emphasis on other emerging trends, including the concept of resilience. Buildings are an integrated part of the overall built environment and society structure, and events (both human-induced, such as the 9/11 terror attacks, and natural, such as strong hurricanes and heavy flooding) over the past couple of decades have underlined the importance of building resilience. More recently, we have seen the important role of building systems' design in helping with medical resilience during the COVID--19 pandemic that started in 2020.

In summary, tremendous growth has occurred in the development of green building programs and practices over the past few decades. This *GreenGuide* provides insight into the making the design and operation of buildings more sustainable.

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www.architecture2030.org.
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www.ashrae.org/technical-resources/aedgs.
- Building for Environmental and Economic Sustainability (BEES)
www.nist.gov/el/economics/BEESSoftware.cfm.
- BuildingGreen
www.greenbuildingadvisor.com.
- Building Research Establishment Environmental Assessment Method
 (BREEAM[®]) rating program
www.breeam.org.
- European Commission, Concerted Action Energy Performance of Buildings Directive
www.epbd-ca.eu.
- European Commission, Energy
https://energy.ec.europa.eu/topics_en.
- European Commission Joint Research Centre. European Life Cycle Database.
<http://eplca.jrc.ec.europa.eu/ELCD3/>.
- European Commission Joint Research Centre. European Platform on Life Cycle Assessment.
<http://eplca.jrc.ec.europa.eu>.
- Green Globes
www.greenglobes.com.
- GreenSpec[®] Product Guide
www.buildinggreen.com/product-guidance.
- International Initiative for a Sustainable Built Environment.
www.iisbe.org.
- International Living Building Institute, The Living Building Challenge
www.living-future.org/lbc/.
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www.iso.org/iso/home/standards/management-standards/iso14000.htm.
- Intergovernmental Panel on Climate Change
www.ipcc.ch.
- Lawrence Berkeley National Laboratories, Energy Technologies Area
<http://eetd.lbl.gov/>.
- National Renewable Energy Laboratory, Buildings Research
www.nrel.gov/buildings.
- New Buildings Institute
www.newbuildings.org.

Rocky Mountain Institute

www.rmi.org.

Tools for the Reduction and Assessment of Chemical and Other Environmental
Impacts (TRACI)

[www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals
-and-other-environmental-impacts-traci](http://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci).

U.S. Green Building Council, Leadership in Energy and Environmental Design,
Green Building Certification System

www.usgbc.org/leed.

The Whole Building Design Guide

www.wbdg.org.

CHAPTER TWO

GREEN RATING SYSTEMS, STANDARDS, AND OTHER GUIDANCE

As the green building industry continues to expand in depth and breadth, the resources to encourage or require green building continue to grow also. There are three general types of programs or resources that exist to encourage green-building design.

1. Voluntary green building rating systems that provide certification or recognition,
2. Mandated green building codes, or government incentive programs and policies, and
3. General guidelines, standards, or resources, such as this guide, that share knowledge and best practices.

In practice, there is often overlap between these different categories. For example, rating systems often incorporate best practice standards, and local jurisdictions may mandate certification programs.

As all three of these types of green guidance documents gain broader adoption, the scope of what is considered “green” has expanded as well. The scope has grown from an early focus on environmental impacts with an emphasis on traditional metrics such as energy use, air quality, and material resources to a more holistic approach incorporating metrics such as social equity and biodiversity. Most recently, standards and certification related to health and wellness of occupants are gaining traction. These health and wellness standards are often considered under the same umbrella as green building standards since they follow a familiar framework established by green building rating systems.

Within these rating systems there are often separate categories based on building type, such as new versus existing buildings, residential versus nonresidential, and subcategories for different nonresidential building types.

This chapter provides a brief summary of the most common resources for green building design.

VOLUNTARY GREEN BUILDING RATING SYSTEMS AND CERTIFICATION

Voluntary green building rating systems set forth specific criteria then assess and certify the extent to which the criteria are met. Incorporating a rating system into a project is generally mission-driven, market-driven, or both. Mission-driven forces include a desire to demonstrate commitment to issues addressed in the standard. Nonprofit organizations, especially those with environmental goals, often adopt rating systems that align with their mission. Market-driven forces are based on the added economic value and marketability that a certification has to future tenants or buyers of a building.

Various rating systems developed by organizations around the world provide useful tools to identify and prioritize key environmental issues as well as methods to accomplish, validate, and benchmark sustainably designed projects. As with any generalized method, each has its own limitations and may not apply directly to every project's regional, political, and owner-design-intent-specific requirements.

There are a wide variety of labeling and certification programs available to measure the environmental impact and performance of existing buildings. These programs can be divided into two general categories: those narrowly focused on a single metric (such as energy or water) and those more broadly encompassing a variety of sustainability categories.

Key programs in the first category include the U.S. Environmental Protection Agency's (EPA) ENERGY STAR® Portfolio Manager and ASHRAE's Building EQ. These both focus on energy use. Key programs in the second category include U.S. Green Building Council's Leadership in Energy and Environmental Design® (LEED®) rating system, the Building Research Establishment (BRE) Global Environmental Assessment Method (BREEAM®), and the International Living Futures Institute's (ILFI) Living Building Challenge. Each of these have broad scopes covering many aspects of sustainability and occupant health.

All of these rating systems are developed as voluntary certifications to demonstrate a higher-performance building. Thus certification under these programs is often limited to an upper tier of buildings.

This section gives a brief overview of some common green-building rating systems. This summary is not comprehensive of all systems and includes additional resources at the end of the section for overviews of other rating systems.

EPA Energy Star Portfolio Manager

The EPA Portfolio Manager is an online tool that uses utility bills and basic building information to develop building energy performance reports, water performance reports, and greenhouse gas emissions reports. It is intended for use by building owners and managers. The tool assigns a normalized ENERGY STAR score of 1 to 100 to each building, with a score of 50 indicating median energy per-

formance compared to its peers. Buildings receiving a score of 75 or above are eligible for ENERGY STAR certification, which must be obtained from a Professional Engineer or a Registered Architect. This tool also makes high-level recommendations on how to reduce water and energy use.

ASHRAE Building EQ

ASHRAE unveiled a building energy labeling program known as the Building Energy Quotient (Building EQ) program in 2009. The program provides a method to rate a building's energy performance both "As Designed" (Asset Rating) and "As Operated" (Operational Rating).

ASHRAE's Building EQ assessment is performed by either an ASHRAE-certified Building Energy Assessment Professional (BEAP) or a licensed Professional Engineer. This assessment includes both utility bill analysis and an ASHRAE Level 1 Energy Audit. ASHRAE produces an energy rating ranging from A+ to F, with a C representing median energy performance in comparison to the building's peers (Figure 2-1). The building owner also receives a report with recommendations for how to reduce energy and water use while maintaining acceptable IEQ. Note that ASHRAE offers a related "as designed" Building EQ rating, so that owners can compare the actual performance of their building to its potential performance (Figure 2-2).

ASHRAE's Building EQ program provides the general public, building owners and tenants, potential owners and tenants, and building operations and maintenance staff with information on the potential and actual energy use of buildings. This information is useful for the following reasons:

- Building owners and operators can see how their building compares to peer buildings to establish a measure of their potential for energy performance improvement.
- Building owners can use the information provided to differentiate their building from others to secure potential buyers or tenants.
- Potential buyers or tenants can gain insight into the value and potential long-term cost of a building.

Operation and maintenance staff can use the results to inform their decisions regarding maintenance activities, influence building owners and managers to pursue equipment upgrades, and demonstrate the return on investment for energy efficiency projects.

Passive House (Passivhaus) and EnerPHit Standard

The Passive House or Passivhaus Standard was originally developed in Germany in the 1990s but has become an international energy performance standard for resi-



Figure 2-1 Sample Building EQ plaque.

dential and nonresidential buildings, with more than 30,000 buildings certified around the world.

This standard is extremely rigorous in its focus on ultra-low energy consumption with a strong focus on building envelope performance. The standard mandates upper limits on the heating, cooling, and air leakage rates for the building as follows:

- 15 kWh/m² (4,755 Btu/ft²) per year for heating and cooling, or a peak heat load of 10 W/m² (3.17 Btu·h/ft²), based on local climate data.
- 60 kWh/m² (19,020 Btu/ft²) per year primary energy for heating, cooling, hot water, and electricity.
- 0.6 air changes per hour ($n_{50} \leq 0.6/\text{h}$) or up to 0.05 cfm per square foot (0.13 L/min per square meter) of the surface area of the enclosure at 50 Pa (0.0073 psi) as tested by a blower door under both positive and negative pressure.

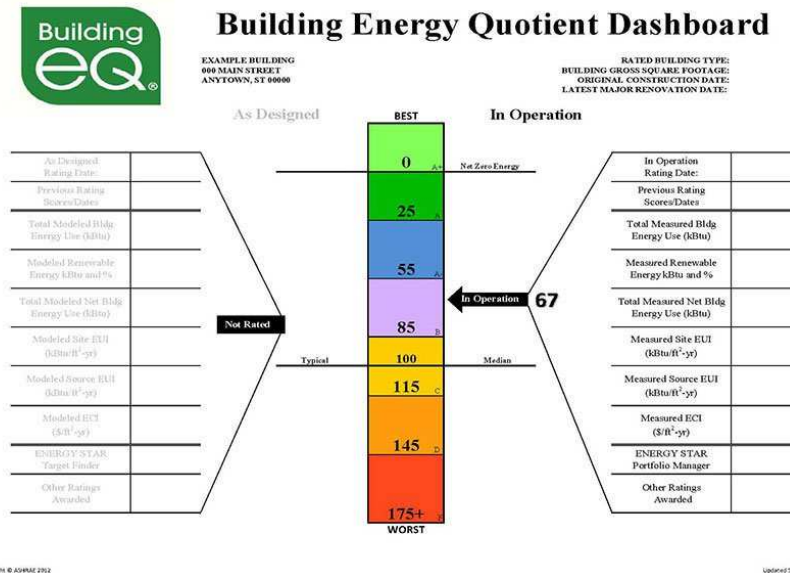


Figure 2-2 Sample Building EQ dashboard.

To achieve these levels of performance, Passive House designs incorporate very high levels of insulation, high performance windows, heat recovery ventilation, construction techniques to eliminate thermal bridging, high levels of airtightness, and very efficient lighting and appliances. The result (and intention) of the strict criteria in this standard is that Passive House buildings often do not require conventional heating systems, with passive solar gain or internal heat sources (occupants, lights, plug loads, etc.) providing sufficient heat for the building. In colder climates, where supplemental heat is still required, heating is often provided as a small supplemental coil in the heat recovery ventilation system, rather than a large conventional boiler or gas-fired furnace. In practice, a Passive House building generally uses 75-95% less energy than similar buildings built to current codes.

While the Passive House Standard can technically be applied to either a new construction or renovation project, it is often not feasible to retrofit to a level that meets the Passive House requirements. To address this, the EnerPHit Standard was developed. The EnerPHit Standard provides either component-based criteria or whole-building energy demand criteria adjusted for climate zone that can be more reasonably achieved by retrofit of older buildings.

Certification for the Passive House Standard is done through the Passive House Institute (PHI) or its affiliates around the world. The PHI and its affiliates are also responsible for the development and distribution of the Passive House Planning Package (PHPP) software used for passive house design and to demonstrate com-

pliance. In the United States, the standard is supported by the North American Passive House Network (NAPHN). It is worth noting that there is a separate organization called Passive House Institute US (PHIUS). PHIUS was originally affiliated with the international Passive House Institute, but the two organizations are now separate and PHIUS has launched an independent standard called “PHIUS+.”

ASHRAE is also working to develop a new passive building design standard. The proposed standard (227P) will provide requirements for the design of buildings that have exceptionally low energy usage and that are durable, resilient, comfortable, and healthy. The standard will be applicable to all new and existing buildings intended for human occupancy. It will provide requirements for the design and construction of the building envelope, heating and cooling equipment and systems, ventilation systems, service hot water systems, interior and exterior lighting systems, and plug and appliance loads.

BREEAM

It could easily be said that the green-building movement really started in earnest with the initial establishment of the BREEAM rating system in 1990. BREEAM is a creation of the Building Research Establishment (BRE) in the UK. This is a voluntary, consensus-based, market-oriented assessment program. With one mandatory and two optional assessment areas, BREEAM encourages and benchmarks sustainably designed office buildings. The mandatory assessment area is the potential environmental impact of the building; the two optional areas are design process and operation/maintenance. Several other countries and regions have developed or are developing related spinoffs inspired by BREEAM, and BREEAM has been adopted in other countries. Although initially focused on specific building types, it has been adapted to include a wider range of different types of buildings. Similar to what has happened with other green rating systems, BREEAM has been adapted to various types of programs (called *schemes*), such as BREEAM for new construction, domestic refurbishment, communities, in-use (existing buildings), and for homes (Eco-Homes).

Finally, BRE Global developed and maintains the BREEAM “in-use” standard. This program encompasses nine sustainability and IEQ categories: energy, water, materials, pollution, land use and ecology, health and well-being, waste, transport, and management. Points may be obtained in each category and are then converted to a weighted score ranging between 0% and 100%. Assessments range upward from “Acceptable” (one star) to “Outstanding” (six stars). Organizations either self-assess or obtain formal certification. Obtaining formal certification requires engaging the services of an assessor licensed by BRE Global.

LEED

The rating method most commonly used in the United States is the Leadership in Energy and Environmental Design (LEED) program, created by the U.S. Green Building Council (USGBC). USGBC started offering this system in the 1990s and it is intended to be a voluntary, consensus-based, market-driven green-building certification system. USGBC's goal has been to raise awareness of the benefits of building green. It has been arguably been successful in that goal as a key factor that has brought sustainability into standard design practice and transformed the marketplace by creating demand for high performance buildings.

LEED evaluates environmental performance from a “whole-building” perspective over a building's life cycle, providing a numerical standard for what constitutes a green building. It has been applied to numerous projects over a range of project certification levels. The LEED rating system started out with a basic program for new commercial construction, but it has evolved through four different versions to LEED v4 and applies to a variety of specific building types. These include building core and shell and commercial interiors for project developers and tenants (respectively), as well as schools, retail, hospitality, data centers, warehouses and health care, and homes. Growing in importance is the role of LEED for Existing Buildings Operations and Maintenance (EBOM). The LEED program and registered building projects have already been, or are being, established in other countries including India, Australia, Canada, and China, and new project registrations in countries outside the United States make up about 40% of the total, according to recent trends. Many other countries have developed their own green building rating systems following the basic criteria in LEED or other rating systems.

LEED uses a point-based rating system. The number of points assigned to different credits provide focus to drive positive environmental and health benefits in specific areas.

The LEED program also includes regional priority credits to put additional emphasis on design features that are particularly important in relation to the local climate and region where the project is to be located. For example, in areas with known stormwater problems, the Sustainable Sites Credit 6.1 for Stormwater Design—Quantity Control may be included in this priority list. A full list of the Regional Priority credits can be found on the USGBC website (see the References and Resources section at the end of the chapter).

The number of LEED points achieved determines the level of certification awarded. Under LEED v4, achieving 40 points will earn LEED Certified status, and the higher levels of silver, gold, and platinum can be achieved with 50, 60, and 80 points, respectively. The percentage distribution of these credits is illustrated in Figure 2-3. “Energy and Atmosphere” is the category with the highest number of points available, and this is in the direct purview of the HVAC&R engineer.

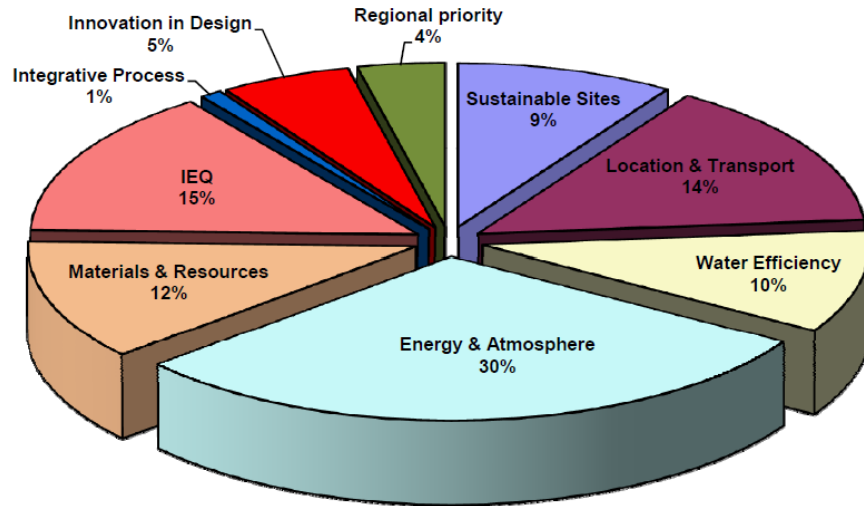


Image courtesy of Brendan Owens, U.S. Green Building Council

Figure 2-3 Credit point distribution for LEED for New Construction, v4.

Further discussion on how LEED may evolve to more closely align with other green-building codes is given in the following section on ANSI/ASHRAE/USGBC/IES Standard 189.1 and the *International Green Construction Code*.

GreenGlobes

Another rating method that was originally developed in Canada and is being used in the United States is the Green Globes program. Green Globes is an online auditing tool that includes many of the same concepts as LEED. While both aim to help a building owner or designer develop a sustainable design, Green Globes is primarily a self-assessment tool (although third-party assessment is an option) and also provides recommendations for the project team to follow for improving the sustainability of the design. In the United Kingdom, Green Globes is known as the Global Environmental Method program.

Living Building Challenge/Zero Energy Building

The Living Building Challenge was launched in 2006 and is administered by the International Living Futures Institute (ILFI) with the intention of pushing sustainable design beyond the goal of being “less bad” and to create regenerative buildings that have a positive impact on their surrounding community and environment. The standard is crafted around the metaphor of a flower, which is adapted to and integrated in its local ecosystem, receives all its water and energy from the sun and

rain, and is a source of beauty. Using this metaphor as a framework, the Living Building Challenge has seven “petals” or categories of focus: place, water, energy, health & happiness, materials, equity, and beauty. Within each petal are a number of criteria or “imperatives” that must be met.

Among other criteria, Living Buildings must operate at a balance of net positive energy and water. Net positive energy requires that the project generate more electricity than it consumes in a year and prohibits the use of combustion energy. To meet the water requirement, all water must be harvested from on-site sources (rain or groundwater). Beyond the energy and water “petals,” the materials petal is notoriously difficult to meet since it includes a “Red List” of materials that cannot be used in the building. Red List materials have damaging health or environmental impacts either to occupants or as a result of their manufacturing process.

Unlike other points-based rating systems that allow projects to pick or choose different measures to achieve different levels of certification, the Living Building Challenge requires all imperatives be met to achieve certification. Additionally, certification is not based on the design documentation and modeling. Living Building Challenge certification is obtained only after a “performance period” of one year post-occupancy in which performance is verified in practice.

In some cases, if an imperative cannot be met due to local building codes (e.g. on-site treatment of potable water is not allowed) the Living Future Institute may allow for an alternate means of meeting the imperative. These alternative approaches generally require implanting the means to achieve the imperative (e.g. installing the on-site treatment system but not activating it) and demonstrating that the team has engaged with the local authority to advocate for change to the codes.

The Living Building Challenge maintains an intentionally high bar and is not easily achieved. To encourage more projects to pursue regenerative goals, the ILFI offers a number of other certification targets. Petal Certification can be achieved for projects that meet the imperatives in either the Energy, Water or Materials petal (plus a few select additional imperatives). ILFI’s Core Green Building Certification requires that 10 specific imperatives from across the petals be met. Finally, ILFI offers their own Zero Energy and Zero Carbon certifications focusing specifically at the project’s net energy or carbon use.

Architecture 2030 Challenge/AIA 2030 commitment

The Architecture 2030 Challenge was launched in 2006 with the goal of achieving carbon neutrality in buildings by 2030. It was set up as a phase approach, initially calling for buildings to meet greenhouse gas emissions and energy consumption targets of 70% below the regional average/median for that building type. This target increased to 80% in 2020, it will be 90% in 2025 and finally targeting carbon neutrality in 2030.

Rather than being a challenge or certification for a specific project, the Architecture 2030 Challenge is for architects and design professionals to have all their new

projects and major renovations meet the specified targets. Additionally, the Challenge states that an equal amount of existing building area shall be upgraded to meet the target threshold.

To demonstrate building performance relative to the Architecture 2030 Challenge, the designer must establish a baseline EUI and target using the “Zero Tool” provided by Architecture 2030. They must then incorporate design strategies to hit the target performance threshold in place at the time. In conjunction with on-site strategies, projects may purchase off-site renewable energy to meet up to 20% of their energy demand.

The Challenge was launched and is managed by the organization Architecture 2030. To support the Challenge the American Institute of Architects created the 2030 Commitment, encouraging their members to sign on to meet the 2030 Challenge. The AIA 2030 Commitment gives design professionals access to the Design Data Exchange, which is a national database managed by the AIA for reporting and measuring progress of projects and to anonymously compare to other projects.

WELL Building Standard

Created in 2013, the WELL Building Standard is a performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and wellbeing. It is managed and administered by the International WELL Building Institute (IWBI) and third-party certified by the Green Business Certification Incorporation (GBCI).

WELL Building Standard version 2 (WELL v2) is the latest version of the certification program and was formally launched in 2020. WELL v2 considers ten aspects of a space, including air, water, nourishment, light, movement, thermal comfort, sound, materials, mind, and community. There are four levels of certification, including Bronze, Silver, Gold, and Platinum, and certification is valid for three years. For a building to maintain its WELL certification, there are annual reporting requirements, including occupancy surveys, proof of maintenance, and ongoing monitoring of environmental parameters (i.e., air and water quality).

Fitwel

Fitwel is a certification system that provides guidelines for designing, constructing, and operating healthier buildings. It was created by the Center for Disease Control (CDC) and the US General Services Administration in 2017. The Center for Active Design is the operator of Fitwel and is responsible for third-party verification.

Fitwel measures health based on twelve categories: location, building access, outdoor spaces, entrances and ground floor, indoor environment, vending machines and snack bars, workspaces, shared spaces, water supply, stairwells, cafeterias and prepared food retail, and emergency procedures. The Fitwel Scorecards include over fifty strategies that enhance buildings by addressing a range of health behav-

iors and risks. Each strategy is allocated points based on its impact on occupant health, which means that strategies with stronger impacts receive more points. There are three tiers of certification, including One, Two, or Three Stars, and recertification is required every three years.

SITES

The Sustainable SITES Initiative (SITES) is a program that encourages the design, development, and maintenance of sustainable landscapes. It was jointly developed by the American Society of Landscape Architects (ASLA), the Lady Bird Johnson Wildflower Center at The University of Texas, and the US Botanic Garden. SITES was acquired by Green Business Certification Inc. (GBCI) in 2015.

SITES certification can be applied to a variety of project types (with or without buildings), including open spaces; streetscapes and plazas; and commercial, residential and educational or institutional spaces. The four goals of the rating system are to create regenerative systems and foster resiliency; ensure future resource supply and mitigate climate change; transform the market through design, development, and maintenance practices; and enhance human well-being and strengthen the community. There are four levels of certification, including SITES Certified, SITES Silver, SITES Gold, and SITES Platinum.

Envision

Envision is a sustainability rating system aiming to improve the sustainability aspects of infrastructure projects during planning, design, construction, and operation. The rating system covers roads, bridges, pipelines, railways, airports, dams, levees, landfills, water treatment systems, and other civil infrastructure, primarily in the US and Canada. Envision was developed in a joint collaboration between the Zofnass Program for Sustainable Infrastructure at the Harvard University Graduate School of Design and the Institute for Sustainable Infrastructure (a nonprofit education and research organization founded by the American Public Works Association, the American Council of Engineering Companies, and the American Society of Civil Engineers).

Envision has 60 sustainability criteria arranged in five categories: quality of life, leadership, resource allocation, natural world, and climate and risk. Envision has four award levels: Bronze, Silver, Gold, and Platinum. There is no cost to download or use Envision for project planning and self-assessment. The Institute for Sustainable Infrastructure offers optional independent third-party review and verification.

Other Programs

The previous discussion was by no means an exhaustive list of available certification programs. Other green-building rating programs exist in countries throughout the world, for example, Australia's Green Star and National Australian Built Environment Rating System (NABERS), Japan's Comprehensive Assessment Sys-

tem for Built Environment Efficiency (CASBEE), Hong Kong's Building Environmental Assessment Method (BEAM), and the Estidama program in the United Arab Emirates. Bernardi et al. (2017) provide a more extensive overview comparing some of the most commonly used rating systems around the world.

The procedures used by those organizations and governments providing building rating systems vary. Many building rating programs use static building labels—that is, the building's energy (or other green attributes) is evaluated once, the label is applied, and the providing organization does no reassessment to determine if the building continues to actually meet the original specifications. The application of dynamic labeling is preferred. A few building rating programs include a reassessment (e.g., every two years), and buildings not continuing to perform lose their building label (Means and Walters 2010).

GREEN BUILDING CODES, POLICIES, AND PUBLIC INITIATIVES

Since the middle part of the past decade, there has been a movement to make green building practices a more mandatory part of the normal building code process. Several cities in the United States now require LEED certification for building projects above a certain size or classification (such as a government building). In addition, ASHRAE has initiated a process to create a series of new standards for high-performance green buildings, which has been continuously evolving since 2010 and is elaborated on in the following section.

ANSI/ASHRAE/USGBC/IES Standard 189.1 and The International Green Construction Code (IgCC)

In 2006, ASHRAE (in conjunction with USGBC and IES) began a process to create a standard that would address a growing need within the industry for a code-language document for green buildings suitable for adoption as part of building codes. ANSI/ASHRAE/USGBC/IES Standard 189.1, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*, was initially developed over a more than three-year process with extensive public review and was initially published in early 2010.

The Standard differs from LEED or other products in that it is not a rating system, nor is it a design guideline *per se*. The purpose of Standard 189.1 is to provide minimum requirements for the siting, design, construction, and plans for the operation of high-performance green buildings while attempting to balance environmental responsibility, resource efficiency, occupant comfort and well-being, and community sensitivity. One key point of this is that Standard 189.1 is not targeted for any building project but rather specifically for high-performance building projects. This document is intended to help fill a perceived gap in the evolving building codes in this area as localities begin to adopt green-building designs as a requirement.

While many of the topics and criteria may overlap or seem similar to LEED for new construction, Standard 189.1 differs in that it establishes mandatory, minimal requirements across all topical areas. Besides the obvious intent of providing a vehicle for adoption into building codes, this standard may also be used by developers, corporations, universities, or governmental agencies to set requirements for their own building projects.

Standard 189.1 is not intended to do away with other ASHRAE standards. Rather, it builds upon key ASHRAE standards and adopts these with modifications when considered necessary to develop a document dealing with high-performance green buildings, as illustrated in Figure 2-4.

This standard includes mandatory criteria in all topical areas (for example, water or energy) and provides for two compliance paths. The prescriptive path includes simple compliance criteria—simple in the sense that they are more like a checklist of technologies or system requirements. The performance path is more complicated in that it requires more analysis to verify that compliance is indeed achieved.

Soon after the initial release of Standard 189.1, ASHRAE and the International Code Council (ICC) reached an agreement whereby the standard would be included as an appendix to the *International Green Construction Code* (IgCC). The IgCC was first released in March 2012 and initially specified Standard 189.1 as a compliance option. By that it was meant that the project team had a choice for compliance: they can comply with the IgCC or with Standard 189.1.

After several years of a dual set of standards, ASHRAE and ICC agreed that the two standards should be merged. Since the 2018 code cycle, ASHRAE has been the subject matter expert for technical content while ICC is responsible for the administrative provisions in the IgCC. This “IgCC powered by 189.1” will hopefully lead to more widespread adoption of green building codes.

European Energy Performance of Buildings Directive (EPBD)

The Energy Performance of Buildings Directive (EPBD) aims to promote the improvement of building energy performance in the European Union. First published in 2002, the EPBD requires member states to develop methodologies for calculating the energy performance of buildings, establish minimum energy performance requirements for both new buildings and existing buildings subject to “major” renovation, and develop energy performance certification programs. An energy performance certificate (EPC) must be issued when any building (commercial or residential) is constructed, sold, or rented to a new tenant. The EPC documents the building’s energy performance, expressed as a letter score from A to G, based on primary energy consumption, carbon dioxide emissions, or energy cost per unit floor area to facilitate comparisons between similar buildings. The EPC also includes cost-effective recommendations for improving the building’s energy performance, which specify the initial cost, estimated annual energy and carbon dioxide emissions savings, and the simple payback period.



Image courtesy of Tom Lawrence and ASHRAE

Figure 2-4 Relation of Standard 189.1 to other ASHRAE standards.

As of 2021, all new buildings in the European Union are nearly zero energy buildings (nZEB), i.e., a building that has a very high energy performance. The nearly zero or very low amount of energy required is covered by a very significant extent from renewable sources, including sources produced on-site or nearby. Existing buildings or building units undergoing a major renovation should meet minimum energy performance requirements (i.e., energy class B) where technically and economically feasible. Progressively, the focus is placed on building energy renovation activities and the uptake of nZEBs in the European Union toward a decarbonized building stock by 2050.

For building certification, most national schemes have implemented an asset rating system based on calculated energy use for new and small existing nonpublic buildings; some have chosen an operational rating system based on billed energy for large and complex nonresidential buildings. The majority of the national schemes require a certified energy inspector to perform a building energy audit to collect all relevant data, which are then used to perform the calculations for issuing a certificate. Implementation and oversight of the certification process are typically the responsibility of the national government. Additional information concerning European EPCs is provided in Arcipowska et al. (2014).

The latest EPBD recast (as of this writing) was published in 2018 as part of the Clean Energy for all Europeans policy package (EPBD 2018). A key component of this revision was the establishment of the Smart Readiness Indicator

(SRI), a voluntary European rating scheme for buildings. The indicator will allow for rating the smart readiness of buildings to meet the needs of occupants, while also optimizing energy efficiency and overall performance. The SRI aims to raise awareness of smarter building technologies and make their value more tangible for building owners and occupants. The three key functionalities of smart-ready buildings include the ability to respond to the needs of the occupant, the ability to facilitate maintenance and efficient operation, and the ability to adapt in response to the situation of the energy grid.

The total SRI score is based on the average scores for seven impact criteria, including energy savings on-site, maintenance and fault protection, comfort, convenience, health and wellbeing, information to occupants, and grid flexibility and storage. One impact criterion score is the weighted average of scores in nine domains: heating, cooling, domestic hot water, ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control. The impact criterion score is expressed as a percentage of the maximum score achievable for the building type being evaluated.

There are currently two SRI assessment methods. Method A is a simplified method for residential and small-scale buildings and it includes an online assessment tool that can be performed by the user and a third-party assessor. Method B is a more detailed assessment for non-residential buildings and can be performed by third-party qualified experts.

Member states are responsible for developing a smart-ready catalogue that can be used as the basis for identifying and assessing smart-ready services. The catalogue includes a list of smart-ready services, including functionality levels and individual scores for the impact criteria. Examples can be found in Annex C (simplified service catalogue) and Annex D (detailed service catalogue) of the SRI Study's Final report (EC 2020).

An overview of international building energy-efficiency policies (e.g., codes, incentives, and labels for all types of buildings including mandatory, model code, and voluntary programs) is maintained by the IEA in a publicly available database at www.iea.org/beeip/.

US STATEWIDE BUILDING CODES

A compilation showing where in the United States states and jurisdictions have surpassed minimum energy code requirements and an outline of several green rating systems is available online by the Building Codes Assistance Project (<http://bcapcodes.org>). Major cities such as Chicago, New York, San Francisco, and Washington, DC, have taken exceptional steps toward increasing the energy efficiency of their buildings. At a statewide level, California's energy code (often referred to as Title 24) and the CalGreen green building code have positioned the state as a leader in mandating green design for new construction and renovation projects in the state and can serve as a guide for other states across the country.

CALGREEN CODE: AMERICA'S FIRST STATEWIDE GREEN-BUILDING CODE

In 2010, the California Green Building Standards Code (CALGreen) was developed to promote the design of efficient and environmentally responsible residential and nonresidential buildings in California. The CALGreen code is part of the overall California Building Standards Code and is the first statewide green code established in the United States. It was developed, in part, in an effort to meet the provisions of Assembly Bill (AB) 32, which requires a cap on greenhouse gas (GHG) emissions by 2020, with mandatory reporting. The 2010 CALGreen Code became effective on January 1, 2011, and a modified 2016 version took effect in January 2017. CalGreen is now on the same triennial code cycle as all California building codes, with the current 2019 CalGreen having taken effect on January 1, 2020.

To reduce the overall environmental impact of new buildings constructed in California and meet their maximum environmental efficiency targets, the CALGreen Code adopts many green-building practices as mandatory building code requirements. The CALGreen Code includes requirements (divisions) for planning and design, energy efficiency, water efficiency and conservation, material conservation and resource efficiency, and environmental quality. The code also requires building commissioning to verify and ensure that all building systems operate as designed to meet their maximum energy-efficiency targets.

Some similarities to LEED programs include standards for stormwater pollution prevention, light pollution reduction, indoor and site water savings, construction waste management, energy performance, outdoor air delivery, carbon monoxide monitoring, and materials selection. In some cases, CALGreen has stricter targets than LEED, in others, LEED is stricter, and in many others, the requirements are identical. There are several CALGreen requirements not found in LEED, such as installing water meters on buildings with an area greater than 50,000 ft² (4600 m²), providing weather-resistant exterior walls and foundation envelopes, defining the type of fireplace that can be installed, and employing acoustical control (interior and exterior).

In addition to the mandatory statewide CALGreen requirements, a city or county may adopt local ordinances to require more restrictive standards that go above and beyond the mandatory measures. These packages of voluntary measures, called Tier 1 and Tier 2, include a set of provisions from each code division. These provisions are additional measures that are stricter than the mandatory codes. For instance, building energy performance must exceed the California Energy Code (Title 24) by 15% and 30% for Tier 1 and Tier 2, respectively. Additionally, Tier 1 includes one additional elective from the water efficiency division, whereas Tier 2 includes 3. Some cities that have adopted Tier 1 include Burlingame, Napa, and Santa Rosa. As of the writing of this edition, only Palo Alto has adopted Tier 2.

GREEN BUILDING GUIDELINES, RESOURCES, AND STANDARDS

Besides the rating systems and codes discussed above, other types of guidance documents and resources are available to measure and improve the environmental performance of buildings (existing or new construction).

This section outlines just some of those additional resources that the green building designer can access. ASHRAE has publications that can help inexperienced and experienced industry professionals alike. These include the following:

- ASHRAE User's Manuals for many of its most widely used standards, such as Standards 62.1, 62.2, 90.1 and 189.1.
- ANSI/ASHRAE/IES Standard 202, *Commissioning Process for Buildings and Systems* (ASHRAE 2018).
- *Advanced Energy Design Guide* (AEDG) series. The AEDGs are a series of books that provide a set of prescriptive technical approaches to achieve significant energy savings. The documents focus on specific building types, typically smaller building projects that may not have resources available for much engineering study and analysis of energy-saving technologies (e.g., small retail stores). Recommendations are provided based on the climate zone in which the project is located. The initial series of guides was targeted toward achieving 30% energy savings compared to Standard 90.1-1999, and the intent is to repeat the series with increasing efficiency levels leading to net-zero designs. The follow-up 50% Guides are designed for 50% savings compared to the 2004 version of Standard 90.1. Most recently, the series is being enhanced with the addition of AEDGs for Achieving Zero Energy, which provides a cost-effective approach to achieve advanced levels of energy savings. These Guides offer contractors and designers the tools, including recommendations for practical products and off-the-shelf technology, needed for achieving a *zero energy building*, which is defined as *a building that, on an annual basis, draws from outside resources equal to or less energy than it provides using on-site renewable energy sources*. These energy guides were produced in collaboration with the American Institute of Architects (AIA), the Illuminating Engineering Society of North America (IES), and USGBC, with assistance provided by the US Department of Energy (DOE). These guides are available for free from the ASHRAE website (<https://www.ashrae.org/technical-resources/aedgs>) and have been widely distributed since their release.
- *Indoor Air Quality Guide: Best Practices for Design, Construction and Commissioning* (ASHRAE 2009a). The *Indoor Air Quality Guide* was released in January 2010 and was developed in conjunction with AIA, the Building Owners and Managers Association (BOMA), the Sheet Metal and Air Conditioning Contractors National Association (SMACNA), the US EPA, and USGBC. A summary of the guidance offered is available for free download from the ASHRAE website, while the detailed document is available for purchase.

- *The ASHRAE Guide for Buildings in Hot and Humid Climates*, Second Edition (ASHRAE 2009b).
- *Cold-Climate Buildings Design Guide*, Second Edition (ASHRAE 2021).
- *High Performing Buildings* magazine. This publication was created by ASHRAE to provide real-world, case study examples for reference.
 - The Whole Building Design Guide
 - *The Living Building Challenge* V2.0 (An updated version 2.1 of this program was released in May 2012)
 - Green Building Advisor
 - California Collaborative for High Performance Schools
 - Minnesota Sustainable Design Guide
 - New York High Performance Building Guidelines (Released in 1999 by the non-profit Design Trust for Public Space, but still has relevant information for today)

Work referred to by architects includes:

- *The Hannover Principles* (William McDonough Architects 1992)
- GreenSpec® Product Guide
- Information from The Natural Step (a nonprofit organization)
- International Organization for Standardization (ISO 14000 family of standards)
- Building for Environmental and Economic Sustainability (BEES). (This software tool to analyze the impact of a building uses a life-cycle assessment approach as specified in ISO 14040. An online version was released in 2010.)
- Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)

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Online

The American Institute of Architects
www.aia.org

Architecture 2030
www.architecture2030.org

ASHRAE Building Energy Quotient
www.ashrae.org/technical-resources/building-eq

ASHRAE Advanced Energy Design Guides
www.ashrae.org/standards-research--technology/advanced-energy-design-guides

BuildingGreen
www.greenbuildingadvisor.com

Building Codes Assistance Project
<http://bcapcodes.org>

Building Research Establishment Environmental Assessment Method
(BREEAM®) Rating Program
www.breeam.org

Center of Excellence for Sustainable Development, Smart Communities Network
www.smartcommunities.ncat.org

Collaborative for High Performance Schools
www.chps.net

Estidama (United Arab Emirates)
www.upc.gov.ae/en/estidama/estidama-program.

Envision
www.asce.org/envision/

European Commission—Nearly Zero Energy Buildings (nZEB)
https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

Fitwel
<https://fitwel.org/>

Green Building Advisor
www.greenbuildingadvisor.com

Green Globes
www.greenglobes.com

GreenSpec® Product Guide
www.buildinggreen.com/product-guidance

Green Star (Australia)
www.gbca.org.au/green-star/

International Code Council (ICC).
www.iccsafe.org/

International Energy Agency, Building Energy Efficiency Policies Database
www.iea.org/beep/

International Initiative for a Sustainable Built Environment
<https://www.iisbe.org/>

International Living Future Institute, The Living Building Challenge
<http://living-future.org/lbc>

International Organization for Standardization: Family of 14000 Standards,
www.iso.org/iso-14001-environmental-management.html

Intergovernmental Panel on Climate Change
www.ipcc.ch

International Performance Measurement and Verification Protocol
www.evo-world.org

Lawrence Berkeley National Laboratories, Environmental Energy Technologies
 Division
<http://eetd.lbl.gov>

Minnesota Sustainable Design Guide
www.sustainabledesignguide.umn.edu

National Australian Built Environment Rating System (NABERS)
<https://nabers.gov.au/public/webpages/home.aspx>

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 Economic Sustainability (BEES)
www.nist.gov/el/economics/BEESSoftware.cfm

National Renewable Energy Laboratory, Buildings Research
www.nrel.gov/buildings

Natural Resources Canada, Evaluation of the Built Environment Portfolio.
www.nrcan.gc.ca/evaluation/reports/2014/16317

The Natural Step
www.naturalstep.org

New Buildings Institute
www.newbuildings.org

Rocky Mountain Institute
www.rmi.org

SITES
www.sustainablesites.org/

www.usgbc.org/resources/sites-rating-system-and-scorecard
Tools for the Reduction and Assessment of Chemical and Other Environmental
Impacts (TRACI)
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other-environmental-impacts-traci](http://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci).
The 2030 Commitment
www.aia.org/resources/202041-the-2030-commitment
US Green Building Council, Leadership in Energy and Environmental Design,
Green Building Certification System
www.usgbc.org/leed
US Green Building Council, Regional Priority Credit Listing
www.usgbc.org/rpc
WELL Building Standard
www.wellcertified.com/
The Whole Building Design Guide
www.wbdg.org

Section 2: The Design Process

CHAPTER THREE

PROJECT STRATEGIES AND EARLY DESIGN

INGREDIENTS OF A SUCCESSFUL GREEN PROJECT ENDEAVOR

The following ingredients are essential in delivering a successful green design:

- Commitment from the entire project team, starting with the owner.
- Establishing Owner's Project Requirements (OPR), including green design goals, early in the design process.
- Integration of team ideas.

The Owner's Role

Of all participants, the owner is the most crucial when it comes to making a green building happen. With the owner's commitment, the design, construction, and operating teams will receive the motivation and empowerment needed to create a green design.

Key design team members can—and should—attempt to educate the owner on the long-term benefits of a sustainable/green design, particularly if the owner is unfamiliar with the concept. After all, experienced design team members are in the best position to sell the merits of green design. However, to be effective, such the owner must make a commitment early in the design process.

Specific roles that an owner can fill in making a sustainable/green design effort successful include the following:

- Expressing commitment and enthusiasm for the green endeavor
- Establishing a basic value system (i.e., what is important, what is not)
- Selecting a commissioning authority (CxA) or the commissioning team (Cx Team)
- Participating in the selection of design team members
- Setting schedules and budgets
- Participating in the design process, especially the early stages
- Maintaining interest, commitment, and enthusiasm throughout the project

The owner on a project could be a corporation or small business, hospital, university or college, office building developer, nonprofit organization, or an individual. In any case, that owner will have a designated representative on the building project team, presumably one who is very familiar with the owner's views and philosophy and can speak for that owner with authority.

Equally important is the role of O&M (Operation and Maintenance) personnel, whether part of the owner's organization or subcontracted. After the project is commissioned and delivered, it is the O&M personnel that will ensure the systems in the building continue operating efficiently as per the design sequences of operation to ensure the green goals of the project are achieved. If the O&M personnel are unfamiliar or inexperienced with the systems being proposed, the system will not be optimally maintained and operated, leading to the building drifting over time from its green goals.

Establishing Green Design Goals Early

Establishing goals early in the project planning stages is a key to developing a successful green design and minimizing costs. It is easy to say that goals need to be established, but many designers and owners struggle with what green design is and what green/sustainable goals should be established. The following are typical questions to ask:

- What does it cost to design and construct a green project?
- Where do you get the best return for the investment?
- How far should the team go to accomplish a green design?

Today there are many guides a team can use with ideas on which green/sustainable principles should be considered. Chapter 2 of this guide presents several rating systems and references on environmental performance improvement. The essence of these documents is to provide guidance on how to reduce the impact the building will have on the environment. While the approaches and goals contained in each differ, all suggest common principles that designers may find helpful to apply to their projects.

Integration of Team Ideas

No green project will be successful if the various project stakeholders are not included in the process. These stakeholders include the owner, the owner's operations staff, the commissioning authority, design disciplines, contractors, and users. These stakeholders, if known, should work in close coordination, beginning in the earliest stages. Use the commissioning process, as discussed in Chapter 4, to obtain input from the various stakeholders and define the owner's objectives and criteria based on which the integrated team must work together with a clear direction and focus to deliver the project. It is becoming less frequent that the mechanical, electri-

cal, and plumbing engineers and landscape architects become involved only after the building's form and space arrangements are set (i.e., end of schematic design). That is far too late for the necessary interplay of ideas between engineering and architectural disciplines that must occur for green design to be effective.

INCENTIVES FOR GREEN DESIGN

For both individuals and firms in the design and construction profession, many incentives exist to develop green/sustainable projects. As with any aspect of business practice that adds value to a project, fees and client expectations must be carefully managed. While some clients may balk at added fees charged for the commissioning, additional coordination, and studies necessary to meet green/sustainable goals for systems that are part of a traditional project scope, others welcome these services. First, the appetite of the project client and full project team for a green/sustainable project must be gaged. Then, the commensurate level of commissioning, design, construction, and operational services can be provided.

Individuals and firms are finding that green project capabilities can positively impact building professionals' careers and the firms that employ them. Firms can enhance these capabilities by providing leadership on green issues, building individual competencies, providing ongoing support for professional development in relevant areas, rewarding accomplishments, marketing or promoting green success stories, and building their clientele's interest in green/sustainable design.

When properly delivered, green design/construction/operation capabilities can lead to enhanced service to clients, repeat business, increased public relations and marketing value, and increased demand for these green design services, especially among the architects or owners that represent a substantial proportion of many firms' billings. In addition, green capabilities can also improve employee retention and employee satisfaction. Finally, green/sustainable project competency can reduce risks in practice, meaning that knowledge of green issues is necessary to manage risk when participating in aggressively green projects.

Human Productivity. While difficult to measure, the benefits of improving the learning, living, and workplace environment (all aspects of indoor environmental quality [IEQ]) and feelings of well-being can yield big gains in human productivity. Figure 3-1 shows the typical relationship among the various categories of the costs of operating a business with human costs outstripping all other costs several times over.

Below are some examples of some data generated by private commercial organizations that support the concept that green design increases productivity:

Lockheed

- 15% rise in production
- 15% drop in absenteeism

West Bend Mutual Insurance

- 16% increase in claims processes

NG Bank

- 15% drop in absenteeism

Verifone

- 5% increase in productivity
- 40% drop in absenteeism

Similar results have been shown in learning and living environments. Some projects may lend themselves to the incorporation of green concepts without incurring additional costs beyond the business's own investment in the knowledge of, and experience with, green projects. Other sustainable design projects may require additional services for a greater number of design considerations not customarily included in ordinary design fees, such as extended energy analysis, daylighting penetration, and solar load analysis, or extended review (of materials and components, environmental impacts such as embodied energy, transportation, construction, composition, and indoor air quality [IAQ] performance).

Financial Incentives. The economic benefits of green design strategies as discussed earlier in this chapter are enhanced by identifying funding sources for the high-performance design concepts that are being considered for a building design project. Having the knowledge of where the opportunities can be found and assisting the team in obtaining the funding enhances the engineer's role and importance in the green design process and significantly improves the owner's return on investment

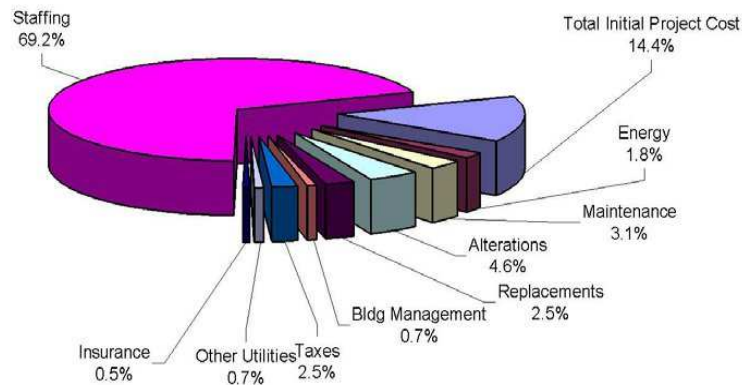


Image courtesy of Michael Dell'Isola, Faithful + Gould

Figure 3-1 People cost versus other costs in business operation.

(ROI). Funding sources include utility company rebates, state and federal grant programs for energy efficiency and renewable energy measures, and private foundation grants for design enhancements and green rating system implementation.

Two broad categories of incentives, external and internal, can each encompass both direct and indirect financial benefits and nonfinancial advantages.

The familiar range of energy incentives offered by many utility-administered, state-mandated, demand-side management programs represents one obvious form of external financial incentive—the rebate check available to owners or utility rate-payers who pursue energy conservation measures in buildings and mechanical/electrical systems. Of course, the availability of these and other financial incentives varies from place to place and project to project. But many other external financial incentives can reduce project costs where applicable, such as the following:

- Sustainable design tax credits
- Marketable emissions credits
- Tax rebates
- Brownfield funds
- Historic preservation funds
- Community redevelopment funds
- Economic development funds
- Charitable foundation funds

In addition, future public policy initiatives associated with climate concerns may direct attention toward low-carbon or net zero carbon designs, as discussed later in this guide.

Incentives that are internal to a project can be created through contractual arrangements. The simplest example is an added fee for added scope in doing the work needed to evaluate green design alternatives. At the other end of the spectrum, some proactive firms offer design review and commissioning services on a performance basis. Construction project insurance offerings have included rebates if no IAQ claims are made a predetermined number of years after construction is completed. If both client and firm are willing, there are many ways to create internal incentives for green engineering design on a project-specific basis.

US Examples. For example, a 26-story, 960-bed residence hall project completed in 2009 at Boston University (BU) used the NSTAR Comprehensive Design Rebate Program (NSTAR is a Massachusetts-based electric and gas utility). The program provides incentives for purchasing and installing high-efficiency equipment for use in commercial and industrial operations. NSTAR offers incentives of 90% of the incremental cost differential for comprehensive design or up to 75% of the incremental cost differential between standard base line and high-efficiency equipment. In addition, customers are eligible to receive cost sharing for engineering services and design and commissioning services.

On the BU housing project, NSTAR and the design team held an energy conservation measure charrette during the schematic design phase. Measures incorporated into the design included energy recovery for the 100% outdoor air ventilation units, chilled-water system energy enhancements, energy conservation measure motors and variable-speed control logic for the fan-coil units, upgraded glazing performance, and variable-speed drives on all pump motors (with integrated system control logic) on the project. The net result was that for an investment of just over \$500,000 on a \$130 million project, BU received a rebate from NSTAR for \$240,000. In addition, the estimated energy savings from incorporation of these measures is estimated to be \$210,000 annually. The result is an annual ROI of greater than 70%. The Database of State Incentives for Renewables and Efficiency provides information on incentive programs for all 50 states: www.dsireusa.org/.

International. The European Union (EU) has made an ambitious commitment toward climate neutrality by 2050 that implies net-zero GHG emissions according to the long-term strategy submitted to the United Nations Framework Convention on Climate Change (EU 2020). The European energy policies are supported by various initiatives and legislative acts (<https://energy.ec.europa.eu/>), including, among others,

- the Clean Energy for All Europeans package that introduced a set of eight revised and new legislative acts on the energy performance of buildings, renewable energy, energy efficiency, governance, and electricity market design;
- the European Green Deal that supports the new European growth strategy and sets a road map for a sustainable EU economy and achieving climate neutrality by 2050; and
- the Renovation Wave, which targets the building sector and promotes the renovation of existing buildings.

The 2030 EU climate and energy framework includes binding targets and policy objectives for reducing greenhouse gas (GHG) emissions by at least 55% from 1990 levels (according to the EU Climate Law [EU 2021]), increasing the share of renewables by at least 32% of final energy consumption, and improving energy efficiency by at least 32.5% (<https://energy.ec.europa.eu/>). Targets are adjusted depending on progress in meeting the 2050 EU climate neutrality objective. Already, recent proposals aim for more ambitious energy efficiency targets for 2030 at 36% for final and 39% for primary energy consumption and at least 40% for the share of renewables. The European Commission has proposed several measures to increase efficiency at all stages of the energy chain, targeting final consumption and the building sector, where the potential for savings is greatest. Over the past two decades, the European Directive 2002/91/EC on the energy performance of buildings (EPBD) and the most recent EPBD recast (Directive 2018/244/EC) constitute the main legislative instruments for improving the energy efficiency

of European building stock. EU member states are strengthening the energy performance requirements and setting more stringent goals for reducing the energy performance of buildings. Accordingly, as of 2021, all new buildings are “nearly zero energy buildings” (nZEBs), and building renovations are encouraged to be energy efficient and cost-effective, with the vision of a decarbonized building stock by 2050. All existing buildings that undergo major refurbishment (25% of building surface or value) should meet minimum energy performance standards, while national policies and specific measures should stimulate the transformation of refurbished buildings into nZEBs.

In 2009, the European Commission launched its BUILD UP initiative to increase the awareness of untapped savings potential for all parties in the building chain. The web portal for energy efficiency in buildings (www.buildup.eu) promotes better and smarter buildings across Europe by connecting building professionals, local authorities, and citizens. It shares and promotes existing knowledge, guidelines, tools, and best practices for energy-saving measures. It also informs and updates the market about the legislative framework in terms of goals, practical implications, and future revisions. EU member states have different schemes with national and regional funding mechanisms that promote energy efficiency and renewable energy in residential and commercial buildings and facilities.

Under the European Green Deal for a sustainable EU economy and achieving climate neutrality by 2050, the “renovation wave” initiative aims to increase the rate and quality of existing buildings’ renovations to reduce energy consumption, lower operational costs, cut emissions, and address energy poverty to lead to safer and healthier buildings and improve occupants’ quality of life. EU member states are developing long-term building renovation strategies, targeted financial instruments, and new mechanisms to create a comprehensive framework by engaging all stakeholders in the buildings sector, removing regulatory barriers, and scaling up innovative mechanisms (Economidou et al. 2020). These efforts are expected to spark innovation and reveal new opportunities to improve the energy performance of European buildings, ensuring resilience to climate change risks and improving living and working conditions.

THE DESIGN PROCESS—EARLY STAGES

The design process is the first crucial element in producing a green building. For design efficiency, it is necessary to define the owner's objectives and criteria, including sustainable/green goals, before beginning the design so as to minimize potential increased design costs. Once designed, the building must be constructed, its performance verified, and it must be operated in a way that supports the green concept. If it is not designed with the intent to make it green, the desired results will never be achieved.

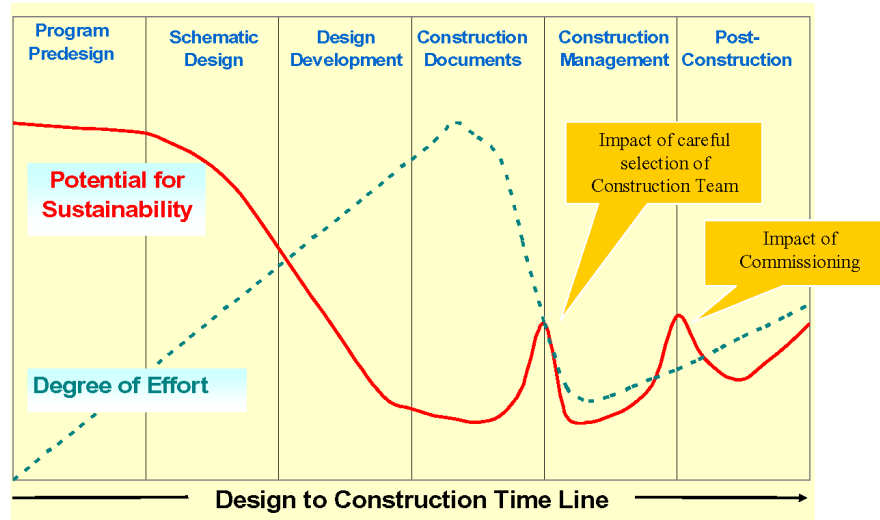


Image courtesy of Malcolm Lewis, CTG Energetics, Inc.

Figure 3-2 The changing potential for sustainability over a project timeline and the impact of commissioning.

Figure 3-2 conceptually shows the impact of providing design input at succeeding stages of a project, relative to the cost and effort required. The solid curve shows it is much easier to have a major impact on the performance (potential energy savings, water efficiency, maintenance costs, etc.) of a building if one starts at the very earliest stages of the design process. The available impacts diminish thereafter as one proceeds through the subsequent design and construction phases. A corollary to this is the cost of implementing changes to improve building performance rises at each successive stage of the project (cost is shown as the dotted curve of the graph).

Designers are often challenged and sometimes affronted by the idea of green design, as many feel they have been producing good designs for years. The experience of many is that they have been forced to design with low construction costs in mind, and when they offer opportunities to improve a building's design, they are often blocked by the owner because of budget constraints. The typical experience is that owners will not accept cost increases that do not show a return in potential savings in five years or less, and many demand 18 months or less. Many owners, especially owners who own the project for life, allow longer return on investments and use life-cycle cost parameters to lower the total cost of ownership.

Both first cost and operating costs can be reduced by applying sustainable/green principles. Correct orientation and correct selection of glazing can reduce HVAC

equipment size and cost, as can the use of recycled materials such as crushed concrete (in place of virgin stone) for soil stabilization and structural fill.

Starting in predesign and carrying through to postoccupancy is essential for the success of a sustainable/green design. It starts with examining every aspect of the process (e.g., the owner's site selection, building configuration, architectural elements, and efficient construction and operation) and can only occur with an integrated approach. Defining the OPR document containing the project goals, even before site selection if possible, is the suggested starting point.

At the very start of the project, green design goals have to be discussed, correlated to the owner's objectives and criteria, agreed to, and in fact embraced by the extended project team. This is often done in a charrette format or simply a session spent discussing the issues. As these goals are defined, they are included in the OPR document.

Goals for a project traditionally include the functional program, leaseable or usable area, capital cost, schedule, project image, and similar issues. The charrette simply puts environmental goals on a plane with the capital cost and other traditional goals.

One of the goals may be to achieve the environmental goals at the same or similar capital cost. (As with any goal, the environmental goals should be measurable and verifiable.) Another one of the goals may be a specific green-building rating system target and an energy target, or perhaps an energy target alone.

A typical set of goals for a green design project might be as follows:

1. Achieve a level of energy use at least 50% lower than the DOE-compiled average levels for the same building type and region, both projected and in actual operation. (Actual energy numbers may be adjusted for actual versus assumed climatic conditions and hours of usage.)
2. Achieve an actual peak aggregate electrical demand level not exceeding 4.5 kW/ft² (50 kW/m²) of building gross area.
3. Provide at least 15% of the building's annual energy use (in operation) from renewable energy sources. (Such energy usage may be discounted from the aggregate energy use determined under the abovementioned Goal 1.)
4. Taking into account the determinations of Goals 1, 2, and 3, assess the impact of the lesser net energy use on raw energy resource use (including off-site energy use) compared to that of a comparable but conventional building, including the changed environmental impacts from that resource use, and verify that the aggregate energy and environmental impacts are no greater.
5. Achieve per capita (city) water usage that is 40% lower than the documented average for this building type and region.
6. Achieve an aggregate up-front capital cost for the project that does not exceed x dollars/ft² (m²) of building gross area, which has been deemed by the project team to be no higher than 102% of what a conventional building would cost.

7. Recycle (or arrange for the recycling of) at least 60% of the aggregate waste materials generated by the building.
8. By means of postoccupancy surveys of building users conducted periodically over a five-year period, achieve an aggregate satisfaction level of 85% or better. Surveys solicit occupant satisfaction with the indoor environment as to the following dimensions: thermal comfort, air quality, acoustical quality, and visual/general comfort.
9. Obtain gold-level USGBC LEED certification for the building.

THE DESIGN TEAM

Setting It Up

One of the first tasks in a sustainable/green design project is forming the design team and the commissioning team. This team should include the design team leader (often the architect), the owner, the CxA, the design engineers, and operations staff. Much of the design team's successful functioning depends not only on having ideas about what should go into the project but on the ability to analyze the impact of the ideas quickly and accurately. It is likely that a large part of this analysis will be completed by one of the engineers on the project.

In addition to the traditional design team members, an expanded project team for a sustainable/green design with commissioning would also include the following members:

- Energy analyst
- Daylighting consultant
- Sustainability consultant
- CxA
- Envelope CxA
- Construction manager/contractor
- Cost estimator
- Building operator
- Building users/occupants
- Acoustical consultant

There are a few roles that are particularly important in green design, including energy analyst, environmental design consultant, and CxA, which are discussed as follows.

Energy Analyst. Although this role has existed for some time, it assumes a much more intense and timely function in sustainable/green design, as there is a need to quickly evaluate various ideas (and interactions between them) in terms of impact on energy. These can range from different building forms and architectural features to

different mechanical and electrical systems. The person in this role must be intimately familiar with energy and daylight analysis modeling tools and able to provide feedback on ideas expressed reasonably quickly. In short, he or she is a much more integral part of a sustainable/green design team than in a traditional design effort. In this respect, for a sizable project, it might be difficult for a single person to fill this role if they are also serving in another role.

Sustainability Consultant. As owners begin to request sustainable/green buildings from the design professions, a new discipline has emerged: the sustainability consultant. The role of this person is to help teams recognize design synergies and opportunities to implement sustainable and green features without increasing construction costs. When the CxA is also the sustainability consultant, the owner and designers benefit from improved integration of the design process across disciplines, with the intent of creating an outcome with much lower environmental impact and higher user satisfaction. Leading projects show that this can often be accomplished without adding cost. The sustainability consultant has input in areas such as site, water, waste, materials, IEQ, energy, durability, envelope design, renewable energy, and transportation. Although this guide focuses primarily on those areas pertinent to the HVAC&R design professional, it is becoming evident that this profession must broaden its sphere of concern in order to contribute meaningfully to the creation of sustainable/green buildings.

The sustainability consultant already has a collaborative relationship with the designers and, as a sustainability consultant, works with the HVAC&R team and others throughout the process to meet the owner's objectives and criteria. For example, a design reviewer may raise the following questions for the team to consider:

- Is the building orientation optimized for minimum energy use?
- Is the combined system of building envelope, including glazing choices and the HVAC system, optimized for minimum energy use and lowest life-cycle cost?
- Have passive, active, and renewable strategies for building energy usage been optimized?
- Are the loads, occupancy, and design conditions properly described?
- Are the proposed analytical tools adequate for the task of computing life-cycle costs and guiding design decisions?
- Is the proposed integrated design approach going to deliver excellent air quality to occupants under all conditions?
- Is the proposed integrated design approach going to deliver thermal comfort to occupants under all conditions?
- Is the proposed integrated design approach going to be easy to maintain? Is there enough space for mechanical equipment and adequate access to service and perhaps to eventually replace it?

- Is the proposed mechanical approach going to give appropriate control of the system to users?
- Is the proposed integrated design approach going to consume a minimum amount of parasitic energy to run pumps and fans?
- Are there site or other conditions likely to impact the mechanical system in unusual ways?
- Has the impact of the building on the site and surroundings been identified and taken into account?
- Are the proposed systems properly sized for the loads?

While it may seem that the role of the sustainability consultant is very similar to that of the energy analyst, the roles differ in that the sustainability consultant is more of a question-asker or issue-raiser, similar to the CxA asking questions and suggesting strategies or solutions for the team to consider. The sustainability consultant's brief is broader and more comprehensive in scope; their role is to take a step back from the project and ask the broader questions regarding the environmental impact of the project.

CxA. Refer to Chapter 4 for more information.

THE ARCHITECT'S ROLE

The architect is always the first to conceptualize the building and thus plays an important role in the success of achieving a project's green goals. Refer to Chapter 4 for an in-depth discussion of the architect's role.

THE ENGINEER'S ROLE

The HVAC&R engineer is a crucial player in the design of a green building. In fact, it is virtually impossible (and certainly not cost-effective) to design a green building without major involvement from that discipline. The HVAC&R engineer must escape the normal box in which they think and become more involved in the *why* of a design, as well as the *how*. This means moving beyond responding to questions asked by others and actively participating in the decision-making regarding how project goals will be achieved.

Engineers help analyze the various options to be considered, create mathematical computer models that are used to judge alternatives, provide creative input, and assist with development of new techniques and solutions. The HVAC&R engineer can be invaluable in helping the architect with building orientation considerations, floor plate form and dimension, and deciding which type of glazing will provide the maximum quantity of natural light, while at the same time analyzing the heat transfer characteristics of the glazing options. The HVAC&R engineer can also help the architect select structural systems and exterior walls to use thermal mass features to reduce equipment needs. Working with the electrical engineer and architect, the HVAC&R

engineer can offer ideas and various options, such as incorporating daylighting and lighting controls to reduce artificial light when natural light is available, which, in turn, can result in lower cooling requirements and lowered HVAC requirements to meet peak load. Smaller equipment size translates into reduced structural and electrical requirements, lower operating and maintenance costs, and lower construction costs, all of which lower the total cost of ownership.

The plumbing engineer, working with the structural and civil engineers, and the landscape architect can reduce the facility's potable water, sewer, and stormwater conveyance requirements. Some examples are waterless urinals or use of stormwater or gray water for irrigation of vegetation or for flushing toilets. Depending on the type of building, water from condensate can be used for gray water applications or for cooling tower makeup. The design engineer must weigh the benefits of water-cooled versus air-cooled condensers and the water versus electrical energy consumed by each. The engineer must examine the site climate, determine what alternatives and strategies can best be applied, and develop life-cycle analyses to guide the owner through the decision process posed by the maze of complex issues surrounding green design.

What Does Integrated Design Mean?

One of the key attributes of a well-designed, cost-effective green building is that it is designed in an integrated fashion, wherein all systems and components work together to produce overall functionality and environmental performance. This has a major impact on the design process for HVAC-related systems, as conceptual development must begin with HVAC system integration into the building form and into the approaches being taken to meet other green-building aspects. For example, consider the following:

- HVAC systems that use natural ventilation and underfloor air distribution, often used in green buildings, can have major impacts on building form.
- Other building energy innovations, such as daylighting, passive solar, exterior shading devices, and active double wall systems, often have significant impacts on the design of the HVAC system.
- On-site energy systems that produce waste heat, such as fuel cells, engine-driven generators, or microturbines, affect the design of HVAC systems so waste heat can be used most effectively.

Beyond these form-giving elements, there are many other specific features of a green building that affect (or are affected by) HVAC systems to achieve the best overall performance. Some of these strongly impact HVAC system conceptual design, and some require only minor adjustments to HVAC specifications. Such features might include the following:

- Using the commissioning process to document the owner's defined sustainable/green objectives and criteria and assist the project team to deliver
- Effective use of ventilation (and indoor air quality [IAQ] sensors linked to the ventilation system) to improve IAQ
- Provision of user controls for temperature and humidity control
- Reduced system capacities to reflect lower internal loads and building envelope loads
- Use of thermal energy storage systems to reduce the overall size of the chiller plant equipment, such as chillers, cooling towers, and pumps (to save capital costs, ongoing energy, and operational costs, and reduce outdoor noise levels during the daytime)
- Selection of non-ozone-depleting refrigerants
- Reduction and optimization of building energy usage below the levels of ANSI/ASHRAE/IES Standard 90.1-2019, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2019) based codes or other applicable state and local energy codes (a reduction in overall energy consumption below that specified by the minimum energy code is becoming more common, either as local regulation or at least by strong encouragement)
- Use of reclaimed water for cooling tower makeup, and minimization of cooling tower blowdown discharge to the sanitary sewer system
- Testing of key systems, especially HVAC systems

Iterative Design Refinement

The design process requires the development of design alternatives. To come up with the most effective combination, these alternatives must be evaluated, refined, evolved, and finally optimized. This is the concept of *iterative design*, wherein the design is progressively refined over time, as shown in Figure 3-3.

Fee and schedule pressures often lead the designer to want to lock in a single design concept at the beginning of the project and stick with it throughout. But this precludes the opportunity to come up with a better system that reflects the unique combination of loads and design integration opportunities for this specific building. This better design usually evolves during schematics and early design development in the iterative process.

THE DIGITAL LANDSCAPE

In his presidential address in the August 2020 *ASHRAE Journal* titled “The ASHRAE Digital Lighthouse and Industry 4.0,” then-ASHRAE president Charles Gulledge describes how landscape and tools are changing the way we design and construct buildings and moving us to the digital, automated world. The tools described can also be leveraged to deliver green buildings. These tools include the following.

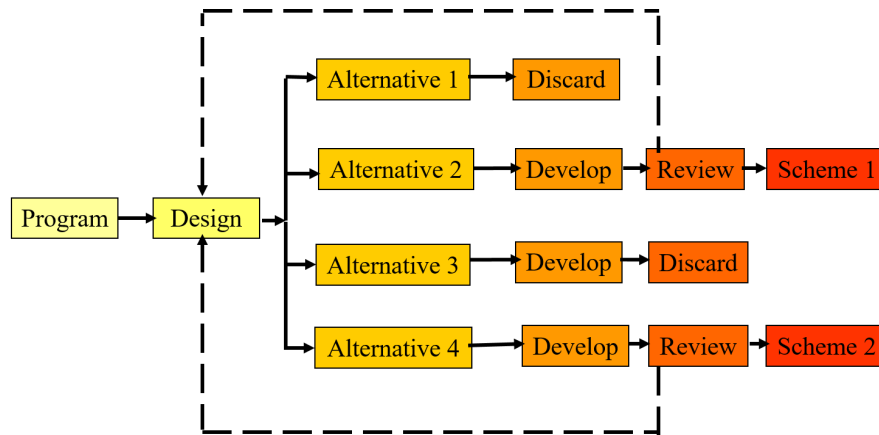


Image courtesy of Malcolm Lewis, CTG Energetics, Inc.

Figure 3-3 The iterative design process.

Virtual Design and Construction

Virtual design and construction or VDC is a process that elevates traditional static drawings to 7-D BIM, which includes the following dimensions:

- 2-D: 2-Dimensional view
- 3-D: 3-Dimensional Model
- 4-D: + Time Schedule
- 5-D: + Budget (Cost)
- 6-D: + Facilities management (Maintenance)
- 7-D: + Sustainability (Life Cycle)

Intelligent objects will not just be a graphical representation but also will contain knowledge. Our use of a 7-D platform will help verify constructability, reveal time and phasing, capture economy, integrate performance modeling, and connect O&M.

Generative Design

Generative design is a computer-driven design exploration process; in other words, let the computer find the optimal solution. Algorithms can test hundreds of variables in thousands of iterations at a speed that can identify optimal solutions within reasonable project design time frames. Humans still define the boundaries and goals, but software handles the rest and the comparison.

Computational Fluid Dynamics

Computational fluid dynamics (CFD) is vital to many projects, especially advanced green projects that require a deeper understanding of airflow patterns in a building and bypass some of the prescriptive measures that could use more energy. CFD allow us to visualize thermal impact, understand the path of air, compare ventilation strategies, simulate thermal comfort, and demonstrate ventilation effectiveness.

Digital Twins

Digital twins can be considered an enhanced version of Building Information Modeling (BIM). By connecting sensors to a digital platform, a virtual mirror of the building can be created to allow designers, users and operators to take a “journey” through the building without visiting it and be able to

- Collect real-time performance data
- Provide an evolving profile of past and current behavior
- Employ analytics to mine data, searching for trends and patterns
- Identify actionable intelligence

This will allow commissioning agents and building operators to have a connected tool for tuning performance and to transition from a reactive mode to a predictive mode.

A digital twin has been created for the new ASHRAE Headquarters in Peachtree Corners, Georgia. For more information on the ASHRAE HQ digital twin, please refer to <https://www.ashrae.org/news/esociety/ashrae-s-digital-twin-evolves-to-serve-renovation-future-projects>.

Drones

The rapid evolution of drone technology has allowed their use in building projects to optimize performance. In addition to other activities on the construction sites, one task that drones can perform that is important to green buildings is thermal mapping, especially for existing buildings. Drone technology was used to evaluate the as-built integrity of ASHRAE’s new headquarters. Thermography provided the insight needed to modify the existing envelope for high performance.

Light Detection and Ranging

Scanning via light detection and ranging (LIDAR) delivers precise point cloud maps of surfaces and complex geometries. This will allow accurate modeling of existing conditions to better optimize buildings.

Augmented Reality (AR)

Augmented reality (AR) technology has been used in video games for years. However, this augmented experience is being used more frequently in construction and architecture, offering immense opportunities to improve the project life cycle. Augmented reality in construction and architecture projects involves placing a 3-D model of a proposed design onto an existing space using mobile devices and 3-D models. For example, wearable goggles can allow us to visualize the complete placement of MEP services inside an existing mechanical room. It will also allow us to locate exactly where penetration and attachments will happen.

Modeling Tools

Modeling of alternate designs is made easier by the plethora of modeling tools available today. The chosen model should meet specific requirements depending on the level of accuracy needed. Error can be introduced into modeling if users forget the “garbage in/garbage out” rule. To reduce the chance of inappropriate or misunderstood input, modeling programs can use input and output formats that allow the user quick reality checks.

Various stages of design, requirements, and associated tools are shown in Table 3-1. While this is not a complete list of tools, it covers the general simulation tools and phases commonly used by the industry.

The following sections describe other approaches to the green-building design process that have been successful.

Zero Energy Design

A net zero building can be a net zero energy building (NZEB), a net zero water building, and/or a net zero wastewater building. Although there are various definitions and classifications for NZE in the literature, the best definition is provided in the 2006 NREL report *Zero Energy Buildings: A Critical Look at the Definition*, which defines four types of NZE buildings:

1. A site NZEB produces at least as much energy as it uses in a year, when accounted for at the site.

For example, if a building consumes

- 3000 kWh of electricity, and
- 100 therms of natural gas (= 2930 kWh),

then the building’s renewable energy system has to produce 5930 kWh for the building to be site NZE.

2. A source NZEB produces at least as much energy as it uses in a year, when accounted for at the source.

For example, if a building consumes

- 3000 kWh of electricity (site) = 10,020 kWh source (3000×3.34), and
- 100 therms of natural gas site (or 2930 kWh site) = 3076 kWh source (2930×1.05),

then the building's renewable energy system has to produce 13,096 kWh at source for the building to be source NZE. Assuming PV (electricity), $13,096 \text{ kWh} / 3.34 = 3920 \text{ kWh}$ will need to be produced at site or 33% less than site NZEB. The site-to-source conversion factors used (3.34 for electricity and 1.05 for gas) are US averages as reported by US EPA. These factors vary throughout the United States and the world.

Table 3-1: Summary of Available Analysis/Modeling Tools

Stage	Requirements	Tools	Reality Checks
Scoping	• Quick analysis • Comparative results • Reduce alternatives to consider • Control strategy • modeling	• System analyzer • Modified bin analysis (where load is not entirely dependent on ambient conditions) • eQUEST • IES VE	• Operation cost/ft² (m²) • Payback or other financial measure
System design	• Accurate output • Industry-accepted methods	• HAP • TRACE 700 • Elite Design • IES VE	• cfm/ft² (L/s/m²) • cfm/ton (L/s/kW_R)
Energy/cost analysis	• Accurate • Complies with energy cost budget method requirements of Standard 90.1 • Industry-accepted methods • Flexible • Allows modeling of complex control strategies	• EnergyPlus • DOE • HAP • TRACE 700 • SUNREL • IES VE • eQUEST	• Btu/h ft² (kWh/m²)/yr • Operation cost/ft² (m²) • Payback or other financial measure
Monitoring	• Simplicity • Intuitive interface • Systemwide • Interoperable	• BACnet-compatible automation systems	• Trended operating characteristics • Benchmark comparisons (such as system kW/ton [kW/kW_R])

3. A net zero energy cost building is one where the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy used over the year. For example, if the building utility bill is

- 3000 kWh of electricity at \$0.12/kWh = \$360, and
- 100 therms of natural gas at \$1/therm = \$100,

then the building's renewable energy system has to export energy in the cost of \$460. Assuming PV (electricity) and the utility company buying at same rate of \$0.12/kWh, the PV system needs to produce 3833 kWh.

4. A net zero emission building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

To perform the calculations, the emission factors need to be determined, which may be difficult to obtain in some regions (e.g., in the state of California, the emission factors are 0.524 lb CO₂/kWh [0.238 kg CO₂/kWh] electricity and 13.446 lb CO₂/therm [0.21 kg/kWh] of gas). In addition, although emissions encompass a variety of pollutants, this definition is still limited primarily to carbon dioxide.

An example of a NZEB is the Aldo Leopold Legacy Center in Baraboo, WI. The building is a carbon-neutral NZEB that uses 39.6 kW rooftop photovoltaic (PV) array to produce about 10% more electricity than that needed annually to operate the building. Specifically, the Legacy Center qualifies as a site NZEB, source NZEB, and emissions NZEB. Another recent example is the National Renewable Energy Laboratory Research Support Facility (NREL RSF) that has demonstrated the production of a net zero energy building that includes plug loads and their data center while still maintaining a high degree of indoor air and environmental quality.

For additional information on the classification of net zero energy buildings, see the online resource listing for the net zero energy buildings database by the U.S. Department of Energy at the end of this chapter.

The following link provides information on incentive programs for all 50 states: www.dsireusa.org/.

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ONE DESIGN FIRM'S TEN STEPS TO A NET ZERO ENERGY BUILDING

1. Define the zero you are seeking (site, source, carbon, or cost)
 2. Establish the design criteria for system performance.
 3. Understand the microclimate the of the project site (local climate surrounding the project site).
 4. Design the siting, form, and thermal mass of the building to maximize the use of natural energy flows and reduce external loads to the absolute practical minimum.
 5. Minimize lighting energy use through effective daylighting.
 6. Reduce plug loads as far as possible
 7. Employ extremely efficient HVAC systems to handle the remaining loads (including natural ventilation and mixed mode where feasible).
 8. Develop accurate predictions of annual building energy consumption.
 9. Provide renewable energy systems to offset resulting energy use
- Commission your systems and ensure proper handover to O&M staff.

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MANAGING RISK IN GREEN PROJECTS

Green Design Documentation Issues

Reviewing green design work done by others allows engineers to see how built projects have created new opportunities and can guide efforts to sell and provide green engineering services. Performing sustainable design can yield important benefits to design engineers individually and to their firms. Improved client service, more repeat work, improved market position, enhanced public relations, and better employee satisfaction and retention are among the many benefits that numerous architectural firms and several pioneering engineering firms have derived from informing their practices with sustainable design expertise.

On the other hand, failure to address client concerns about green design can harm reputation. Disproportionate start-up costs, risk, or other perceived obstacles (e.g., the educational investment and commitment required to change engineering thinking and culture) may be perceived as being associated with undertaking sustainable design. Managing each of these issues, communicating frankly, and crafting creative solutions, as required, can reduce exposure to these potentially negative issues.

However, when documenting the project requirements for bidding by contractors and subcontractors, it is important that the engineer not guarantee that the results predicted by building simulation modeling will actually be achieved. It is important that the engineer not take a disproportionate share of the risk in incorporating newer technologies into a building design project. Sustaining fair and practical business practices is critical to being a successful green engineer.

Contract Provisions

The following is an excerpt from the online essay, “Green Buildings and Risk,” by Tim Corbett (https://aepronet.org/wp-content/uploads/2014/03/GE-2008_01-Green-Buildings-and-Risk.pdf):

A good contract is the best line of defense when it comes to mitigating your risk. The contract is an excellent method for defining your scope of services (e.g., what will be provided, when, and what will not). Contracts are also an excellent method for qualifying clients and managing and establishing expectations. Contracts should address the following:

- *New and innovative products and technology may be used; they may lack proven history of successful application. Owner understands and agrees that project objectives may not be realized. A caveat is that the decision to try new, unproved products or technologies needs to be a decision by the*

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owner and the design team together to make sure the owner is informed of the risks and opportunities.

- *Ordinary skill and care will be used to achieve project objectives; however, there is no warranty or guarantee the project will achieve LEED certification.*
- *Verify the level of investigation and analysis that will be performed for new material and technologies, with no expressed or implied warranty or guarantees of results.*
- *Client agrees to measure the potential risks related to incorporating the innovation product and/or systems and accepts the risks.*
- *Limit your exposure to consequential damages by including appropriate language in your contract.*

NATIONAL RENEWABLE ENERGY LABORATORY'S NINE-STEP PROCESS FOR LOW-ENERGY BUILDING DESIGN

1. Create a base-case building model to quantify base-case energy use and costs. The base-case building is solar neutral (equal glazing areas on all wall orientations) and meets the requirements of applicable energy efficiency codes such as Standard 90.1 (ASHRAE 2016) and ANSI/ASHRAE Standard 90.2-2007, *Energy Efficient Design of Low-Rise Residential Buildings* (ASHRAE 2007).
2. Complete a parametric analysis to determine sensitivities to specific load components. Sequentially eliminate loads from the base-case building, such as conductive losses, lighting loads, solar gains, and plug loads.
3. Develop preliminary design solutions. The design team brainstorms possible solutions that may include strategies to reduce lighting and cooling loads by incorporating daylighting or to meet heating loads with passive solar heating.
4. Incorporate preliminary design solutions into a computer model of the proposed building design. Energy impact and cost effectiveness of each variant are determined by comparing the energy with the original base-case building and with the other variants. Those variants having the most favorable results should be incorporated into the building design.
5. Prepare preliminary set of construction drawings. These drawings are based on the decisions made in Step 3.
6. Identify an HVAC system that will meet the predicted loads. The HVAC system should work with the building envelope and exploit the specific climatic characteristics of the site for maximum efficiency. Often, the HVAC system is much smaller than in a typical building.
7. Finalize plans and specifications. Ensure that building plans are properly detailed and that specifications are accurate. The final design simulation should incorporate all cost-effective features. Savings exceeding 50% from a base-case building are often possible with this approach.
8. Rerun simulations before design changes are made during construction. Verify that changes will not adversely affect the building's energy performance.

Commission all equipment and controls. Educate building operators. A building that is not properly commissioned will not meet energy-efficiency design goals. Building operators must understand how to properly operate the building to maximize its performance.

CHAPTER FOUR

ARCHITECTURAL DESIGN AND PLANNING IMPACTS

OVERVIEW

The architect's role in the design process has evolved over the last few centuries from the "master builder" who took full responsibility for the building's design and construction to the lead of an integrated design team. However, the architect still has a major impact on the systems that will be installed in a building and, consequently, the amount of energy it will use and pollution it may emit.

Today, the emphasis for building design is on sustainability and resiliency through an *integrated* team design approach. The architect plays a critical role within the design team in meeting a project's sustainable design intent. Careful consideration of site selection, building orientation and form, the structure's envelope, spatial zoning, and incorporation of daylight harvesting, passive heating, and cooling and ventilating systems directly affects the building's performance for energy and comfort.

To meet sustainable and resiliency design goals, the architect must take the changing climate into consideration and contemplate how climate change may impact design and material selection. Refer to Chapter 36, Climate Change, in the 2021 *ASHRAE Handbook—Fundamentals* for information on the changing climate, its mitigation, and methods of adaptation.

Architectural design decisions directly affect the well-being and comfort of the occupants, energy-related construction costs, embodied energy in construction materials, carbon footprint, and operational energy cost for the end user. A sustainable designer looks beyond the building boundaries and considers the impact on and by the greater community (refer to Chapter 7, Sustainable Sites, for information on urban heat islands [UHI]). It is important to emphasize the impact of early site and architectural decisions on the ability of the rest of the team to optimize their role in producing a high-performing building. Working as an integrated team with all design stakeholders throughout the entire design and construction phase is crucial. Particularly when using BIM, this integrated team approach carries on into the operation and maintenance during the building's life

cycle and afterward. Architects also have some responsibility for O&M (e.g., they need to provide enough room for a maintenance person to easily change filters, thus affecting future IAQ). Today's ideal of the integrated design team from the initiation of a project and emerging interoperability using new design technologies (BIM, AR, VR, other environmental and energy simulation tools, etc.) encourages the design and operation of sustainable green buildings.

DESIGN PROCESS FOR SUSTAINABLE, ENERGY-EFFICIENT ARCHITECTURE WITH EXCELLENT INDOOR ENVIRONMENTAL QUALITY

Experienced architects should be familiar with the basic approaches for designing sustainable buildings, as detailed in the Architecture chapter in the fifth edition of the *ASHRAE GreenGuide* (2018). Today, it is important to acknowledge that the context of architectural design has transformed with the increasing complexity of digital technologies and rapidly changing climatic conditions with the increased frequency of catastrophic weather events. There is a greater concern with reducing or eliminating carbon emissions and increasing the resiliency of buildings while protecting occupants during catastrophic weather events. The demands for building performance during the entire life cycle have also changed, with considerations for improved indoor environmental quality (IEQ), better energy efficiency, whole-life carbon assessment (WLCA), decreased water consumption, use of nontoxic and low embodied energy materials, and circular economy. Considerations for the standard of care and professional liability must also be incorporated in building designs. It is emphasized that the most successful projects will be those in which all of the design partners work interoperably in a collaborative way to meet the sustainability goals. These considerations are summarized below with emphasis on climate change concerns:

- Work with the owner and design team to set goals for building performance and resilience early in the design process.
- Analyze climatic conditions at the macro- and micro-site levels with anticipation of how the outdoor environment will potentially change over the projected life of the building.
- Identify and stress the use of passive strategies (such as natural ventilation and daylight harvesting) and then apply active strategies for the current and changing climate (refer to Chapter 8, Indoor Environmental Quality, and Chapter 11, Lighting).
- If the building is in an urban setting, work with planning professionals to develop how the building will contribute to an overall sustainable urban design (refer to Chapter 7, Sustainable Sites).

- Design the building envelope, shape, and orientation to reduce energy loads while providing comfort, and design for resilience in anticipation of predicted extreme weather events (refer to Chapter 3, Project Strategies and Early Design).
- Determine room placement and grouping of areas into HVAC zones to meet the following needs
 - reducing energy loads while providing for desired comfort levels and generally good IEQ;
 - providing areas of refuge for occupant protection during projected extreme weather events; and
 - designing with adaptability for future use and climate changes.
- Research case studies and building energy load data for similar building types in the same climate zone to identify typical resource-consuming systems and benchmarked energy demands. Additionally, look at similar buildings in an adjacent climate zone to anticipate potential site environmental condition changes to that zone.
- Select optimal strategies for current and potential future climatic conditions (refer to Chapter 3, Project Strategies and Early Design).
- Apply computer-based simulation studies, using related data sources to evaluate comfort and energy consumption against accepted metrics and benchmarks, as well as for projected climate changes to demonstrate the performance-based sustainable outcomes for alternative designs. Potentially use augmented reality (AR) and/or virtual reality (VR) tools to better understand the effects on occupants of employing varying designs. Refer to Chapter 6, Conceptual Engineering Design—Load Determination, for discussions of AR, VR, and other computer-based simulation programs.
- Incorporate continuous commissioning in the construction documents and recommend future intervals of retrocommissioning to the owner (refer to Chapter 5, Commissioning) in view of traditional building and operational changes, as well as those resulting from the changing climate.
- Employ sustainable building labeling, ensuring that the program chosen includes *dynamic labeling* (i.e., re-evaluation and relabeling over time rather than labeling once without acknowledging changes in climate, building condition, and operation) rather than *static labeling*.
- Design with consideration for building operation and maintenance by analyzing the cost-benefit ratio of using more durable materials and systems with longer life cycles and providing extra space for future additional equipment anticipated to be needed as the building's climate heats up and changes in its humidity, and adequate space around equipment for maintenance (e.g., for ease of access to change filters).
- Design and specify materials that will not jeopardize IEQ (e.g., by specifying non-VOC releasing paint, carpeting, and other interior materials and furnish-

ings), carefully making selections to promote a circular economy, and specifying materials having lower carbon emissions.

The subsequent sections specifically address major steps unique for the architect designing for sustainability.

Climate Studies and the Determination of Most Applicable Passive Strategies and Active Systems

The most important initial considerations for sustainable design in this time of rapid climate change are anticipating how the outdoor environment will potentially change over the projected life of the building and what type of catastrophic weather events it may experience. The starting point is to gather historical data ranges (normally 30-year averages) of design dry-bulb and wet-bulb temperatures, solar exposure, and wind velocity (predominant direction and intensity), followed by an analysis of the potential climatic changes over the projected life of the building. Expected global changes are increased temperatures, with most areas experiencing higher precipitation rates and some areas becoming drier. The most recent climate zone designations are available in ANSI/ASHRAE Standard 169-2021 or Chapter 14, Climatic Design Information, of the 2021 *ASHRAE Handbook—Fundamentals*. The designation of climate zone boundaries has been changing in the last decade due to rapid climate change. For instance, in the 2013 edition of *ASHRAE Handbook—Fundamentals*, climate zone boundaries moved roughly 100 miles toward the poles in each hemisphere, and Zone 1 was divided into two, with a new Zone 0 added to account for the new hottest areas. In the most recent edition, many boundaries in the Northern Hemisphere moved further north (and some south) due to the data gathering from a greater number of weather stations. As with historical design, it is recommended to analyze climate both at the macro- and micro-site level.

Climate dictates whether a building will be heating-dominated or cooling-dominated. With climate change, the level of heating will generally decrease while that of cooling will increase, but some areas will become more humid while others will skew drier. The dominant heating or cooling designation will generally remain the same and, as such, prescribes the relative importance of both envelope and HVAC strategies. In the interest of sustainability, comfort, and future operational costs, passive strategies become more important for the architect to consider. Specific passive and active strategies can be identified once temperature and humidity data are collected by plotting their average minimum and maximum ranges on a psychrometric chart. Alternatively, a computer program can be used to plot these data with their frequency of occurrence. Projected variances due to climate change can then be added to the plot for further analysis.

Overall strategies and means to extend the comfort zone for both passive and active systems have historically been identified and plotted on psychrometric charts

by several researchers as bioclimatic charts. This was originally done by Victor Olgyay in 1963, modified by Baruch Givoni in 1969, then further developed in collaboration by Baruch Givoni and Murray Milne in 1979.

The strategies identified on the bioclimatic charts include sun shading, thermal high mass with or without night flushing, direct evaporative cooling, natural ventilation cooling, passive solar direct gain with low or high mass, humidification, wind protection, conventional cooling, and conventional heating. Free university-developed software is also available to plot a year's set of points and then evaluate these strategies by the percentages of time they can most effectively be applied. See Figure 4-1 for an example using this software for the city of Detroit, Michigan. Once identified, key strategies can then be prioritized based on their percentage contribution to retaining comfort zone conditions. If an active system is the highest-rated strategy for restoring the comfort zone, then reducing the energy load for such equipment is a high priority. Decisions on design strategies should also include occupancy and seasonal use conditions (e.g., a summer camp project in a heating-dominated climate should not be designed for heating loads, as a climate study might initially suggest.) Refer to the Green Tips found throughout this volume.

Strictly speaking, bioclimatic analysis does not consider the building type, the building's intended use, or projected internal load conditions. However some soft-

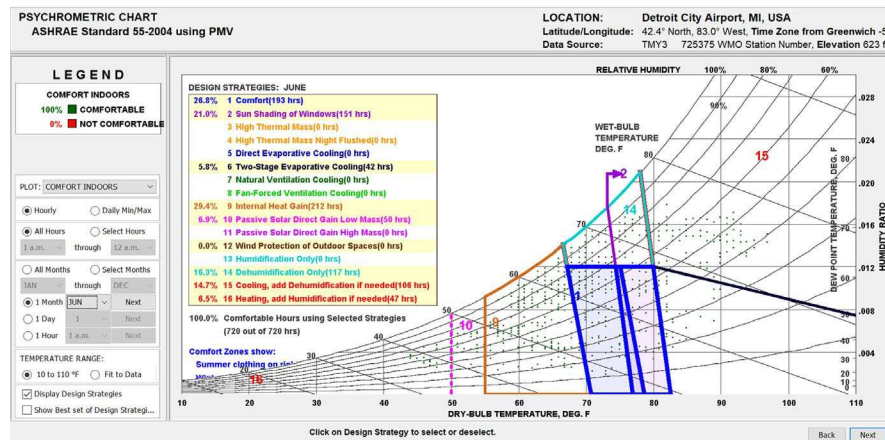


Image courtesy of Murray Milne, UCLA.

Figure 4-1 Climate Consultant Software (UCLA 2020) file report demonstrating the correlation of the June ambient air state points with applicable HVAC strategies for Detroit, Michigan.

ware developers are now making efforts in this area, (e.g., the UCLA-developed Climate Consultant Software includes internal heat gain as a design strategy.)

The free application Climate Consultant displays several pages of useful information for design, including solar path charts and shading recommendations. A complete climate analysis includes studies of solar exposure, the seasonal effects of wind, and the availability of rainwater, which are briefly discussed in the next section and in more detail in Chapter 7, Sustainable Sites, and Chapter 12, Water Efficiency.

Building Form, Orientation, and Envelope Considerations

For sustainable design, architecture studies must be initiated with the knowledge of preferred shape/envelope/footprint ratios and orientation for optimization of energy use while providing comfort.

Decisions for designing a sustainable building's form, orientation, and envelope construction are informed by climate data, the building site's existing landscape details, and potential optimization of on-site natural resources.

In predominately cold climates, a compact cube shape with a tight, well-insulated envelope is optimal for reducing heat loss. However, elongation in an east-west axis will increase exposure to the winter sun, thus increasing winter heat gain. Reducing the overall glazing area, specifying high-performing windows, and placing the bulk of windows on the equator facing exposure while minimizing glazing on other orientations is also recommended.

For a predominately hot climate, consider elevating the structure (for under air-flow) and otherwise creating large, shaded surface areas in contact with the outdoors. Create open courtyards, deep wraparound porches, and/or multiple building wings with several openings for ventilation paths aligned with prevailing wind patterns. For climates that contribute to overheating, architects also need to reduce direct solar gain on the equator-facing and west-facing surfaces. Pole- and east-facing surfaces rarely contribute to overheating from solar radiation. This concern becomes increasingly important with global warming.

The design of thermal mass and weight of building materials is a function of both climate and building use. "Elephant" buildings, those with high mass and heat absorbing materials, are suitable for structures with high internal gains and in climates with large diurnal temperature swings. "Butterfly" buildings, those constructed with lightweight materials, work well for structures with low internal gains and in moderate climates that benefit from natural ventilation.

Charting the apparent sun paths for the year (e.g., on the 21st day of each month) and adjusting the irradiation values using the clear-sky radiation method described in the 2021 *ASHRAE Handbook—Fundamentals* is useful for determining the potential for passive building design and active solar energy collection. Sun angle data can be used to design light shelves and other architectural strategies for daylighting to augment artificial light and also to design shading to reduce unwanted

solar heat gain. Refer to Chapter 10, Energy Sources, for more information on using solar energy and to Chapter 11, Lighting, for information on daylight harvesting.

Wind rose charts can be consulted to find the seasonal direction and speed of the wind for a particular site. They are used to determine the feasibility of collecting wind energy, to analyze a site's ability to protect a building from unwanted wind exposure during the heating season, and to determine options for channeling wind for increased ventilation during the cooling season. If wind rose charts are not directly available for a location, they can be developed with software or manually drawn using data from a local airport wind velocity-recording station. Refer to Chapter 10, Energy Sources, for more information on using wind energy. The designer should remember to consider catastrophic weather events enhanced by climate change that involve high wind velocities (hurricanes, tornadoes, sudden fast-moving storms). These are not likely to be indicated on current wind rose charts.

Optionally, earth berms can be created, or banks of trees or shrubs can be planted to help block wind to protect a building from wind-induced convective heat losses. Earth berms and shrubbery can also be used to redirect or focus wind for use in cooling or enhancing ventilation. Earth sheltering in contact with the building's envelope also diminishes both high- and low-temperature extremes. Sinking the building into the ground or designing the building to extend into a hill can provide cooling when outdoor temperatures are hot. Earth sheltering also acts as a buffer to the cold when berming is located on the windward side of the building and particularly when the berms or hills are situated such that they allow the equator-facing side of the building to still be exposed (maximizing winter solar exposure). Using a green roof provides multiple benefits for all climates: a tempering effect for cold or hot conditions, an offset for stormwater that otherwise would be headed for a storm drain, and a reduced heat island effect. Refer to Chapter 7, Sustainable Sites, for more discussion on further optimizing site conditions.

Tight construction with high levels of insulation and careful placement of fenestration is central to energy conservation in cold climates. Glazing and daylighting should be considered in view of total building energy utilization. Based on studies with whole-building energy-analysis software in cold climates, providing an overuse of daylighting by increasing windows and skylights will result in an overall increase in the total energy use caused by the low thermal performance of glazing systems. The decisions regarding envelope design are central to reducing energy loads and take precedence over alternative energy-related power generation as a priority. Therefore, costly photovoltaic (PV) energy sources should not be used to power artificial lighting when daylighting can be provided to reduce electrical lighting loads.

Rainfall data can be used to determine rainwater collection potential for irrigating plants, toilet flushing, or for other applications. This is an opportunity for saving both energy and conserving water. Rainfall data is also used for planning site

water retention design schemes such as for rain gardens and bioswales. The collection, use, and maintaining of water on a site reduces or eliminates the need for storm water drain systems infrastructure. Again, the design must consider future changes in expected precipitation with climate change.

For structures over three stories, design using the 2021 *International Green Construction Code* powered by ANSI/ASHRAE/USGBC/IES Standard 189.1, *Standard for the Design of High Performance Green Buildings* (hereafter referred to as IgCC/189.1). This code specifies whole-building design, including building-envelope minimum R-values, maximum U-factors, and F-factors based on climate zone and exceeds specifications in ANSI/ASHRAE/IES Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.

Placement and Zoning of Building Spaces

Before placing and zoning internal spaces, consider minimizing the building size by designing flexible or dual-purposed spaces (e.g., a lecture room also serving as a dining room). Considering future flexibility is also sustainable by extending a building's useful life and allows for future climate change adaptation. Room placement and zoning for heating and cooling go hand-in-hand to provide a big impact on energy use and occupant comfort. Where extreme weather events are expected due to climate change, remember to provide refuge rooms or areas. Also, plan to locate sensitive equipment in areas where it will not be damaged by potential flooding, which will be more likely in some areas due to both intermittent events and overall climate change.

Zoning of the spaces is most effective when room placement and their relative positions are optimized so zoning can proceed based on exterior wall orientations, then on function, and finally on occupancy and equipment diversity.

Optimize room placement by considering thermal energy needs and applying the “thermal buffering” principle. Locate high thermal energy need areas (laboratories, natatoriums, etc.) in interior spaces surrounded by areas requiring less thermal energy (corridors, closets, etc.). This action reduces thermal losses from the more sensitive conditioned occupied spaces. Place rooms where people are sedentary on the equator-facing side of buildings. Place corridors, closets, storage rooms, data-com, and utility rooms on non-equator-facing sides of buildings.

Constructing a double-skin façade (DSF) system can also provide a formal thermal buffer zone. A DSF system, also called a *dual-skin wall system* or *envelope system*, is constructed by providing a glazed wall a short distance from a conditioned-space-enclosing wall. This is usually constructed on the equator-facing side of a building but may also be installed on the opposite facing outside wall. Air movement due to natural convection and stack effect between the dual wall skins can contribute to reducing both the cooling and heating load. For example, in summer operation at the Yazaki World Headquarters in Canton, MI, the air between the outer and inner walls rises by natural convection, pulling stale air from conditioned areas (through open windows in the inner wall) up and out of the building. In win-

ter, the air is introduced at a low level, is solar heated and rises between the walls (with inner windows closed), providing a thermal blanket. In some cases, tempered air is ducted into a conventional air handler or heat pump to eventually supply the conditioned space with heat.

There are many variations in DSF design. The interstitial space varies in dimension and design. Some DSFs have a solar tower at the top to increase the convective action. Movable blinds or PV panels may be added. Functioning similarly, a perforated, black-painted metal panel can be mounted on a sunny wall to provide tempered ventilation air. Many retrofitted commercial buildings in Europe and elsewhere have successfully used DSF principles.

Use of Case Studies, Data Collection, and Benchmarking

Referenced buildings can be used as benchmarks to predict typical energy consumption for a building's various purposes (e.g., energy used for heating, cooling, lighting, domestic hot water, and specialized equipment). Case studies are readily available from professional organizations such as ASHRAE, AIA, and USGBC. When choosing benchmarks, the buildings selected should be similar in function, size, expected occupancy, and climate zone. Also, consider future projected climate changes when selecting buildings to use as benchmarks.

Using benchmarks along with microclimatic data should narrow and define the priorities and lead the designer to identify the most viable design strategies for resource conservation. Benchmarking with high-performing reference buildings will provide the designer with exemplary targets. Once energy use targets are defined, the designer can examine alternative energy generation to meet them.

Selecting Optional Strategies Using Alternative-Energy Potential for Buildings and Neighborhoods

Developing alternative-energy strategies begins with examining the magnitude and availability of solar and/or wind energy to the site. The use or application of alternative-energy technologies should be paired with high-load demand conditions, as well as cost considerations. When determining that a building type has a high domestic hot-water demand load and is also located in a climate with strong solar radiation conditions, it is prudent to recommend heating the water using solar energy. However, note that it is more economical to use solar PV electricity to heat the water rather than heating with thermal solar collectors. This is a relatively recent change. If a building needs to be shaded from excessive solar radiation and high electrical loads, using PV panels as part of a shading system on a southern wall would be a possible solution. Alternative-energy costs can be made affordable for clients when tax incentives, rebates, or low-interest loans are available and should be part of initial feasibility studies. Refer to Chapter 10, Energy Sources, for more on alternative-energy sources.

Although not an alternative-energy source, using geothermal heat pump systems is another way to reduce fossil fuel use.

For guidance on working within an urban setting to develop a sustainable neighborhood, refer to publications by Chicago architect Douglas Farr, who has developed processes for and coined the term “sustainable urbanism.”

Prioritizing Design Strategies Using Environmental Simulations Tools

Design strategies need prioritization based on analysis. Evidence-based design or performance-based outcomes require definable problems based on data. The increasing levels of adoption of performance-based metrics by municipalities, states, and corporations (e.g., those used for building labeling) will eventually place the responsibility on designers to validate design proposals with appropriate data and whole-building energy simulation. Refer to Chapter 2, Green Rating Systems, Standards, and Other Guidance.

Several computer programs called environmental simulation tools (ESTs) are available to simulate alternatives to assist in determining an optimal building form, alternative footprints, orientations, shading, insulation levels, glazing distributions, and air circulation for minimizing energy use (e.g., CFD, AR, and VR). Building energy simulations are now possible with interoperable databases linking BIM three-dimensional (3-D) models with object-oriented software and embedded information where building data is exported directly into the simulation software. Unfortunately, not all building system types, use conditions, and environmental characteristics can be modeled using such software; for example, computer programs simulating the effects of mass are more difficult to find. Refer to Chapter 3, Project Strategies and Early Design, and Chapter 6, Conceptual Engineering Design—Load Determination, for discussions of CFD, AR, and VR.

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CHAPTER FIVE

COMMISSIONING

Commissioning (Cx) is defined by ASHRAE Guideline 0-2019 as *a quality-focused process for enhancing the delivery of a project by achieving, validating, and documenting the performance of facility elements in meeting the objectives and criteria of the Owner* (ASHRAE 2019a). The commissioning process also provides an essential foundation for integrated design, delivery, and operation and facilitates adapting to changing needs over the facility's lifetime. Commissioning establishes benchmarks for evaluating the achievement of the owner's defined goals and objectives as they change over time. Commissioning is applied to new building projects and existing facilities to verify that a facility meets the occupants' needs and to effectively and efficiently deliver the owner's purpose for that building and their organization's goals. The true measure of a high-performance building is how it performs over its lifetime; proper commissioning of the building and facilities helps deliver high performance. ASHRAE Guideline 0 defines the specific details needed to establish and conduct a well-organized commissioning process for a project, and this chapter provides additional background and insight as it relates to green building design and long-term building performance on a high level.

Commissioning benefits everyone: the owner, the design and construction teams, building occupants, and building operators. As a part of an owner's quality control process, commissioning provides tools and techniques to help the project team improve quality and avoid rework. It helps to reduce risk and change orders, improve energy efficiency, and lower operating costs. It also results in increased satisfaction of tenants and occupants. The commissioning process should begin early in the predesign phase to provide maximum benefits. Starting early improves designer and contractor quality processes, makes the Cx team part of the process, and identifies and helps resolve problems during design (when corrective action is the least expensive). During construction, commissioning can also benefit the contractor by avoiding costly delays and rework (minimizing final punchlists and postoccupancy repairs).

How and to what extent an owner incorporates commissioning into their project generally depends on the owner's understanding of the process and results of commissioning. Commonly, an owner might start with construction phase commissioning but may soon see how much more they would have benefited by starting in the predesign phase. Other factors that determine the extent of commissioning incorporated in any given project are how long the owner holds the property, the owner's staff capabilities and funding mechanisms for design, construction, and operation, the project schedule, and ownership experience.

Commissioning is not only an important part of successful project delivery but is an essential and, in many cases, required part of green-building design and construction. The commissioning process focuses on verifying and documenting that the building and all of the systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the owner's goals and objectives for the project. Commissioning is also now required in various energy codes and standards. Commissioning is not an exercise in blame. It is, rather, a collaborative effort to identify and reduce potential design, construction, and operational problems by resolving them early in the process, at the least cost to everyone. This chapter will include the selection and role of the commissioning provider, a discussion of various commissioning models, the choice of building systems for commissioning, and the long-term benefits afforded by implementing the commissioning process.

THE EVOLUTION OF THE COMMISSIONING CONCEPT

In 2005, ASHRAE produced initial guidance on the commissioning process with ASHRAE Guideline 0, *The Commissioning Process*, which describes the overall process and provides guidance on implementation for commissioning, and ASHRAE Guideline 1.1, *HVAC&R Technical Requirements for the Commissioning Process* (2007), which contains additional information specifically focused on HVAC&R applications. As of publication, the most recent version of Guideline 0 was published in 2019. ASHRAE also recognized the need for a "code language" standard that specifies the commissioning process. Thus, ASHRAE created ANSI/ASHRAE/IES Standard 202, *Commissioning Process for Buildings and Systems*. Standard 202 defines the minimum acceptable Cx for a project, while ASHRAE Guideline 0 outlines best practices and establishes the order of phases in which the components of Cx are best implemented. Guideline 0 provides a template for Cx plans for specific facility elements or assemblies and establishes common content that serves as a uniform method for achieving different levels of commissioning and meeting varying owner's requirements. The Guideline also serves as the foundation for authoring technical commissioning guidelines that are more narrowly targeted and focused on specific applications, such as Guideline 1.1.

Project commissioning has been increasingly important during the past decade and is being adopted into building construction and energy codes. This is partly due to the LEED-mandatory requirement for commissioning and partly due to the

growing awareness of the benefits commissioning brings to a project. In addition, IgCC/189.1 (ICC 2021) includes a requirement for commissioning for all buildings with a floor area greater than 10,000 ft² (1000 m²), although changes to this threshold are being considered. There is debate on whether all high-performance green buildings should be required to undergo a full commissioning process. Certainly, any building that includes complex systems or a larger number of energy and water-consuming devices should be considered for commissioning.

COMMISSIONING'S ROLE IN ACHIEVING SUSTAINABILITY GOALS

Because of the nature of the delivery process, the further along the team is in the design and construction process, the more difficult and expensive changes become (see Figure 3-1). Waiting until after predesign to define project end goals, occupant requirements, and team roles and responsibilities can lead to increased project cost. The easiest time to evaluate goals, objectives, and criteria (and make changes) is during the schematic design phase, and this is also the best time to reduce or control the cost of any changes. A steep decline in the feasibility to implement sustainability features occurs after the schematic design phase. The ability to make significant cost-efficient changes ends when the project moves into design development. The earlier a design team addresses and implements sustainable features into a design, the more likely these will be included without significant cost. This is a foundation of integrated design and critical to cost-effective green buildings. Historically, owners and contractors set up a contingency fund intended to cover the unpredictable cost of changes in a project. If the design does not meet the owner's needs, the owner may be forced to accept the project as is, because changes needed to meet his or her requirements would be too costly at that point. If the CxP team is engaged as late as the construction phase, there is some, but very limited, opportunity to address potential design problems and missed sustainability goals. The longer an owner waits to engage in the commissioning process, the less influence the CxP team has on resolving problems cost effectively.

THE CxP TEAM'S ROLE

ASHRAE Guideline 0 defines two terms for the entities that lead the commissioning effort on a project. The *Cx Provider* is defined as *an entity, identified by the owner, who leads, plans, schedules, and coordinates the CxP Team to implement the commissioning* (ASHRAE 2019). Previously, the commonly used term for this role was CxA (commissioning authority or commissioning agent), but there was additional terminology for this role used worldwide. Guideline 0 also defines a *CxP Team* as *the team of specialists and related support staff who are responsible for the management of actions and the generation of deliverables by the Cx Provider as outlined in the contract between the owner and the Cx Provider and in the Cx Plan*. The CxP Team may consist of several companies, including subcontractors to the Cx Provider, who acts as the contact to the owner. The role of the CxP Team

varies according to the phase of the project. It is the Cx Provider's role to lead the collaborative team effort required to balance competing interests so that the owner's needs and mission are not lost. To accomplish this task, a benchmark is needed. This benchmark is the Owner's Project Requirements (OPR), and the CxP Team should be involved with the OPR development.

Ideally, before engaging the design team, the owner would engage a CxP Team to develop draft commissioning specifications and a commissioning plan in the pre-design phase of a project. The draft commissioning plan defines the team's roles and responsibilities, suggested communication protocols, commissioning activities, and the schedule of the activities. Additional information on selecting the Cx Provider and CxP Team is provided in later sections. Appendix F of ASHRAE Guideline 0 also provides more details on project team roles (ASHRAE 2019).

It is important to reiterate that the commissioning process is an owner's process, and the members of the CxP Team should serve the owner's needs without actual or perceived conflict of interest. Ideally, the Cx Provider and CxP Team members should consist of the owner's employees. However, while this is the ideal scenario, many owners do not have the expertise "in-house" to accomplish the necessary commissioning tasks. Therefore, the roles of the Cx Provider and CxP Team are commonly filled by a third-party firm or team that is contracted directly to the owner. Other contracting arrangements are not recommended and should be undertaken only with extreme caution. Appendix E of ASHRAE Guideline 0 provides guidance on selecting qualified Cx Providers (ASHRAE 2019).

COMMISSIONING DOCUMENTS

Thorough and useful project documentation is a defining feature of the commissioning process. The following sections describe a selection of several notable documents created during a typical commissioning process. Additional guidance on commissioning process documentation is available in Appendix D of ASHRAE Guideline 0.

The Owner's Project Requirements

The OPR is a written document that details the requirements of a project and the expectations of how it will be used and operated, including project goals, measurable performance criteria, cost considerations, benchmarks, success criteria, training requirements, documentation requirements, and supporting information. Specific information that should be included can be found in ASHRAE Guideline 0 (ASHRAE 2019) and ASHRAE Standard 202 (ASHRAE 2018). It also includes information necessary for all disciplines to properly plan, design, construct, operate, and maintain systems and assemblies.

Many confuse the OPR with an architectural program. The OPR is different from the typical architectural program, which focuses on project floor area needs, adjacencies, circulation, cost, and structural predesign test results. The OPR documents

how the owner intends for this building to function and fulfill the needs of the owner and the occupants. For instance, an architectural program does not contain requirements for how the building will be operated. It also does not contain operation and maintenance (O&M) and training requirements or post-construction documentation requirements for the building, whereas the OPR does. Developing the OPR in conjunction with the architectural program reduces programming effort and provides valuable information to the designers that they typically do not have. In combination with the architectural program, the OPR provides a strong foundation for a successfully integrated design and delivery process and the building's operational criteria. The OPR, however, should not duplicate information contained in the architectural program. The OPR forms the basis from which the commissioning provider verifies that the developed project meets the needs and requirements of the owner. An effective commissioning process depends on a clear, concise, and comprehensive OPR with benchmarks for each of the objectives and criteria. This written document details the owner's goals and requirements for the building and the expectations of how it will be used and operated.

If no formal program exists, the OPR document can be used to assist with identifying the criteria the design team is tasked with meeting. However, the main purpose of the OPR is to document the owner's objectives and criteria. The designer's basis of design (BoD) documents, the decisions and assumptions the designers made to meet the OPR, and a summary of this information is provided to the operators of the project long after the design and construction team have left the project. As such, the OPR document provides the benchmark against which the design, construction, and project operating performance can be measured.

The OPR includes sustainable development goals that are in harmony with the owner's mission. Many teams focus on green rating system credits without knowing how these credit selections will affect the owner's needs. For example, on one military project, the design team selected use of native and adaptive plants to achieve a green rating system credit but neglected to understand that this conflicted with the facility's mission and requirements for no vegetation that was 4 in. (100 mm) in height above the ground.

Additional information on development and recommended format of an OPR is given in Appendix D of ASHRAE Guideline 0.

The Basis of Design (BoD)

This document should be created by the design team and outlines how they have designed the project to meet the goals of the OPR. It should be updated and reviewed as part of each design submission. Detailed examples of what information should be contained in the BoD are given in Appendix F of ASHRAE Guideline 0.

The Commissioning Plan

The draft commissioning plan defines the team's roles and responsibilities, suggested communication protocols, commissioning activities, and the schedule of the activities. Project success is dependent on each team member's understanding of what is expected of them and obtaining their buy-in. The commissioning plan provides the owner with clearly defined roles and responsibilities for each team member for inclusion in contractual agreements and improved team efficiency. It is more economical to define these requirements early, before selecting and contracting the various project team members. Further discussion on the commissioning plan is included in the construction phase paragraphs below. Detailed examples of what information should be contained in the commissioning plan are given in Appendix G of ASHRAE Guideline 0.

Commissioning Specifications

It is important that the contract documents include the commissioning requirements for the construction contractors so they know of their commissioning duties and opportunities during the time of both bidding and construction. The design phase discussion below includes further information on specifications. Good commissioning specifications will increase project efficiency and reduce conflicts. Detailed examples for what information should be contained in the commissioning specifications are given in Section 6.2.4 and Appendix L of ASHRAE Guideline 0.

Systems Manual

One of the most critical documents created by the commissioning process is the Systems Manual. This resource represents a significant improvement over traditional operation and maintenance manuals and is central to the building's long-term performance. According to ASHRAE Guideline 0, developing the Systems Manual encompasses gathering all the information related to the systems, assemblies, and the Cx and incorporating it into a usable information resource with indices and cross-references. It must include the final OPR, BoD, Cx Plan, Cx Report, manufacturer installation manuals, manufacturer O&M manuals, system schematics, verified record drawings, and test results. This information is edited and organized to focus on the building's key systems (roofing, walls, fire alarm, chilled water, hot water, and so on). Coordinating with O&M personnel to develop standard formats and divisions (shops) is accomplished to simplify future Systems Manual development. Also included in the Systems Manual is the development of periodic maintenance and information for insertion into a computerized maintenance management system (CMMS), including equipment make and model information, checking requirements, maintenance requirements, and troubleshooting items.

To make the Systems Manual a reality, the CxP Team should coordinate efforts beginning in the design phase with the development of related specifications. While

others could handle the actual creation of the Manual, Guideline 0 recommends that the CxP Team take the lead in its development and delivery to the owner. Additional guidance on preparing Systems Manuals can be found in ASHRAE Guideline 1.4, *Procedures for Preparing Facility Systems Manuals*.

COMMISSIONING PHASES AND ACTIVITIES

Commissioning for new construction projects can be broken down into four phases: predesign, design, construction, and occupancy and operations. Commissioning for existing buildings also has four phases: investigation, analysis, recommendations, and implementation. Detailed information on the existing building commissioning process can be found in ASHRAE Guideline 0.2 (ASHRAE 2015). For new construction, distinct commissioning activities occur during each of the phases described below.

Predesign Phase

Commissioning is a team effort performed within a collaborative framework. Achieving desired building performance starts with clearly defining the Owner's Project Requirements (OPR) at predesign before developing the architectural program or design. One of the greatest values of involving a CxP Team in the predesign phase is developing a comprehensive OPR document that serves as the project benchmark, guiding all project team members. The CxP Team will also develop the initial commissioning plan for the project during this phase.

The commissioning plan defines the project team's roles and responsibilities and the execution of the commissioning process. It is essential that the owner clearly defines (contractually) the project team's commissioning roles and responsibilities as well as prepare the OPR. With these documents created, the project quality effort is on track to move into the design phase.

Design Phase

During the design phase, the CxP Team's goal is to verify that the design meets the owner's requirement and that the documents produced are high quality. Design phase commissioning promotes communication, identifies disconnects, questions design elements that appear incorrect, and shares experience to produce a better set of contract documents and a better high-performance building.

This effort will reduce the need for rework and the likelihood of delays during the construction phase. This is accomplished by providing designers with tools to assist them in their design quality process and through commissioning-focused reviews of the design documents. Commissioning specifications should also be developed during the design phase for incorporation into the overall project specifications. The specifications identify the roles and responsibilities of the construction phase project team, the systems that will be commissioned, and the criteria for acceptance of the commissioned systems. They will also include requirements for

construction phase verification processes (such as construction checklists), requirements for training and systems manuals, and contractor responsibilities for commissioning tests. Chapter 3 of this guide provides further information on commissioning activities in the design phase.

One of the tools used by the CxP Team during the design phase is design checklists. The design checklists reflect objectives and criteria that designers should check during their quality control process, the amount and type of information provided at each stage of the commissioning design review, and the designer's assertion that items in the commissioning checklists are complete. Typically, two or three reviews occur in most design phases.

Commissioning design reviews focus on assessing whether the design meets the OPR. Typically, the OPR provides:

- the project vision;
- expected service life;
- energy and water efficiency goals;
- maintainability;
- training of operational and maintenance personnel;
- infrastructure for monitoring-based, ongoing commissioning;
- expectations of the building envelope's ability to resist weather, air, and water intrusion; and
- other functional requirements needed for occupants to effectively and efficiently deliver their daily mission.

Commissioning design reviews can also randomly check the designer's quality control process by identifying systemic design issues that lead to potential change orders, including missing or misleading information and insufficient detail needed for accurate pricing and competitive bids. Commissioning design reviews can reduce owner and project team risk, allow corrections to be made at the lowest possible cost, and reduce requests for information, supplemental instructions, and schedule impacts.

Several engineering trade magazines and long-term owners, along with insurance companies that provide errors and omissions (E&O) coverage to the design community, have all voiced their concerns about the quality of construction documents and have charted how E&O premiums are affected as a result of judgments or settlements. Design phase commissioning reduces the risks of change orders, accompanying construction delays, and E&O claims and helps clarify construction documents.

One role of the CxP Team is to assemble a review team experienced in the type of building being designed. Generally, the CxP Team has a team of reviewers with specific backgrounds and experience to review the disciplines selected for design phase commissioning. This process often requires the most senior individuals as

part of the design phase commissioning provider team. (See the Selection of the CxP Team section later in this chapter.) A typical design review process is as follows:

- Written comments from the reviewers are provided to the design team and owner.
- Comments are reviewed, and the design team returns written responses.
- Meetings are scheduled with the review team and the designers to resolve comments, allowing the owner to understand the issues and have an opportunity to provide direction as needed.
- Design concerns, comments, and actions taken are recorded in the design review document. Changes are made as agreed, and the commissioning review team verifies the change and closes the issue as appropriate.

Using a best-practices approach, the commissioning design review could occur four different times during the design: at 100% of schematic design, at 100% of design development, at 50% of complete construction documents, and at approximately 95% of construction documents. (Combining the review of the first two phases can be done on smaller projects.) An advantage of four reviews, however, is that the design is evaluated based on the OPR document goals before the next phase starts.

Although four reviews are ideal, particularly for complicated projects, having at least two (as required for commissioning by Standard 189.1) provides at least some level of checks and balances.

Changes to optimize building performance, daylighting considerations, system selection, and stacking/massing synergies can best be addressed during schematic design review. Review during design development allows the team to identify potential problems and constructability perspectives early enough to resolve many issues before the construction documents phase starts.

The quantity of design concerns typically increases during the 95% construction document phase because more detail is provided about each building system and component. The concerns identified at that point typically revolve around details—finishes, coordination conflicts, and so on. Resolving these concerns provides clearer direction to the contractors, resulting in better cost and schedule predictions.

It is not uncommon for concerns identified at the 50% construction documents phase to go unaddressed by a design team. This is especially true in fast-track projects when designers, responding to owner and contractor demands for documents, struggle to finish and deliver their work product. This is why the later 95% review is so important.

Construction Phase

During construction, the CxP Team's goal is to verify that the installed systems meet the owner's requirements while providing tools to help contractors avoid rework and delays. The CxP Team conducts site visits, verifies construction checklists, confirms progress on redline drawings, and other tasks to assist contractors in their quality control process and documentation. These efforts significantly improve the chances that the systems being commissioned will only need minor modifications during performance testing and will reduce the delivery team's efforts and costs. At the end of the construction phase, the CxP Team verifies through testing that the systems perform as intended and helps resolve issues prior to occupancy.

A more detailed list of the CxP Team's activities during the construction phase will likely include reviewing the construction documents and submittals; developing and integrating contractor construction checklists; identifying and tracking issues to resolution; developing, directing, and verifying functional and performance tests; observing the construction of commissioned systems; reviewing the O&M manuals provided under the contract; and overseeing the development of a Systems Manual and training agenda. The purpose of these activities is to verify that the requirements of the OPR document have been met, commissioned systems are serviceable, commissioned systems perform as intended, and operational personnel receive the training and documentation necessary for operating and maintaining building performance.

Review of Final Construction Documents. The review of final construction documents is used to verify that the concerns and issues raised during the design reviews have been resolved, reducing the risk of contractors building flaws into the project. Sometimes, an agreement between the designers and the commissioning design review team is not reached during the design phase. An example of this would be a disagreement over building pressurization control: the designer may feel that the design provides adequate control, and the CxP Team may disagree. The CxP Team must verify whether or not the building is correctly pressurized through performance tests. If the designer is correct, the CxP Team closes the issue after verification. If pressurization is an issue, the team then has the opportunity to correct the concern before more serious and costly ramifications can occur. Systems failing to perform are identified, and the project team works to resolve the issue while the entire team is still engaged in the project.

Review of Product Submittals. The CxP Team reviews product submittals to look for potential performance problems and verify that what was proposed is in fact delivered. An example would be the contractor's ductwork shop drawings showing high-pressure loss fittings that would increase energy consumption. The CxP Team review activity does not take the place of the designer's review, nor is it meant to. The CxP Team review should reveal whether the contractors are follow-

ing the OPR and BoD. Several purposes can be combined by the CxP Team in their review of the submittals, depending on the role the owner defines for the CxP Team. For instance, if the CxP Team is also assisting the team with LEED certification, the CxP Team can verify that the sustainable development goals identified in the OPR document are being met.

Participation in Prebid Meetings. At the start of construction, a CxP Team may choose to be part of prebid conference meetings with the general contractor or construction manager to describe commissioning activities, describe the general roles and responsibilities the contractor will be asked to fulfill in the commissioning process, and answer questions. Clear communication with the contractors during prebid has proven important in preventing high bids that reflect a fear factor from contractors unfamiliar with the commissioning process.

During Construction. In the early stages of construction, the CxP Team updates the commissioning plan defining the commissioning process, the roles and responsibilities of the project team, lines of communication, systems being commissioned, and a schedule of commissioning activities. The CxP Team conducts an initial commissioning scoping meeting where the project team reviews the commissioning plan, and, based on this information, a final commissioning plan is developed and implemented.

Throughout construction, the CxP Team verifies that the construction is meeting the requirements in the OPR. The CxP Team observes the work to identify conditions that would hinder preventive maintenance or repair, jeopardize operation of the system as intended and/or compromise useful service life, and verifies other sustainability goals (such as IAQ management) during construction. Prior to testing systems and equipment, the CxP Team will verify that the necessary construction checklists and observations have been completed. Construction checklists are used to confirm that the equipment installation is complete and ready to receive power. This includes checks such as correct phasing of electrical connections, correctly installed mounting fasteners, accessible valve operators, and secure pipe and duct connections. All completed and verified construction checklists should be retained and made part of the Systems Manual.

The CxP Team will verify that the contractor's quality control process is working through verification of construction checklists, start-up procedures, and verification of testing and balancing. When contractors have completed their construction checklist for a specific system being commissioned, they are stating that their systems will perform as intended. The CxP Team verifies this by directing and witnessing commissioning tests.

Commissioning Tests. The final activities during the construction phase of the commissioning process involve testing the installed system. With designer and contractor input, the CxP Team develops system tests (previously called functional tests) to ensure that the systems perform as intended under a variety of conditions. Contractors under the CxP Team's direction execute the test procedures while the

CxP Team records results to verify performance. The tests should verify performance at the component level through intersystem and intrasystem levels. Another practice is to have the contractors simulate failure conditions to verify alerts and alarms, as well as system reaction and interaction with associated systems. To the extent possible, problems identified are resolved while contractors and materials are still on site and the designers are engaged.

The commissioning tests are preestablished by the CxP Team and submitted to the contractor early in the construction phase. The contractor is aware at an early stage of all the tests that must be observed. An independent third-party firm (not the CxP Team or the mechanical contractor) typically provides testing and balancing (TAB). The test and balance subcontractor and/or the installing contractor should perform a dry run of the commissioning tests before the formal CxP Team test to verify that the systems are performing as intended. If the systems are not checked in advance of the formal CxP-Team-witnessed test and the systems fail, time delays and additional expenses will be incurred for all parties involved. The contractor must correct the issues, and the CxP Team must return for a rewitness. The CxP Team must have clear contractual contingencies in place to be adequately compensated for retests.

Occupancy and Operations Phase

During the occupancy and operations phase, the CxP Team stays actively engaged with the building operations and maintenance (O&M) staff to monitor system performance and verify that training provided was understood. The CxP Team assists operators in better understanding their systems and maintaining maximum performance, which helps prevent inappropriate modifications by the operators (due to lack of understanding). The first year of operations is critical to finding and resolving issues that arise, and the CxP Team plays an important role in helping a building perform at its optimum. The warranty period during the first year of operation is also the period when the contractors and manufacturers are responsible for the materials and systems installed, and is the only time the owner has to identify warranty repairs without additional construction costs. As such, the CxP Team takes on a vital role to assist the owner and operational staff in identifying and resolving problems and assisting with resolution that gives the least interruption to the occupants during this critical period. This phase may also be coordinated with a postoccupancy evaluation, particularly if one is being performed as part of the LEED green-building rating program.

During the first several months, the CxP Team verifies that systems are performing as intended through monitoring of system operation. Many systems cannot be fully tested until the building is occupied. Some systems, such as the heating and cooling equipment, can only be fully tested when the season allows testing under design load conditions. There might be a small percentage of system components that pass initial testing but, under actual load, fail to perform as intended. These

components must be identified in the warranty period and replaced or repaired as necessary. The CxP Team's role in conjunction with the operational staff is to search out problems that only become evident under actual load. To accomplish this, the commissioning provider performs several specific tasks.

The commissioning provider may also help identify system points to trend, verifying efficient system operation; installs independent data loggers to measure parameters beyond the capabilities of the building automation system (BAS); and monitors utility consumption. Using the trend system data from the selected BAS input points, the CxP Team can help in the analysis of the information, looking for operational sequences that consume resources unnecessarily and conditions that could compromise occupant satisfaction within the working environment. In addition, the CxP Team also looks for conditions that could result in building failure, such as high humidity in interstitial spaces in the building's interior, hot spots in the electrical distribution system, or analysis of electrical system harmonics where power quality is essential to the owner. These functions can only be tested after occupancy.

The CxP Team works closely with the operational staff to identify and help resolve issues that become apparent in the warranty period and verifies that the operational staff fully understands and meets their warranty responsibilities. In addition, the CxP Team should provide operational staff with the specific test procedures developed for their use in maintaining performance for the life of the building. By having the CxP Team work with the operational staff during the warranty period, the operators gain valuable insight into how the building should operate and what to look for to ensure continued performance. This helps to overcome a typical industry problem: the bypassing of system components and controls because of a lack of understanding of how the systems are intended to operate.

Ongoing Commissioning

An important part of green design is verification that the goals defined by the owner are integrated by the design and construction team to achieve the owner's objectives for the lifetime of the building, as defined in the OPR. The OPR is a living document that changes over time as the owner requirements change. Once the building is occupied, changes in the owner/occupant mission can occur that impact and modify the original project requirements. The original OPR is maintained for its historical value in marking the original project requirements. However, for long-term operations, the owner should maintain a document known as the current facility requirements (CFR), which documents the requirements of the owner for their current daily mission (independent of past requirements). The CFR provides the foundation to guide the future project teams in modifications needed to meet the changing needs of the owner/occupant.

Ongoing commissioning in both new and existing projects provides the owner and operators with the tools necessary to efficiently manage financial and human

resources to achieve desired returns on their investment, building performance, and reduction of environmental impact. Owners and operators cannot manage what is not measured. During occupancy, the CxP Team monitors the building's performance and identifies deterioration of performance. This deterioration typically falls into one of two categories: operator error or system malfunction or deterioration. Monitoring-based, ongoing commissioning identifies the cause of the deterioration and recommendations can be made for correction. Operator errors resulting in deterioration of building performance provide training opportunities to improve O&M staff understanding of correct building operation, which helps prevent future operational mistakes. Monitoring-based, ongoing commissioning identification of degradation of building performance due to system malfunction provides in-depth failure information, which lessens the O&M staff's troubleshooting efforts and can verify that the repairs performed resolve the problem. Monitoring-based commissioning is most easily implemented by the CxP Team when integrated into the OPR or CFR. Implementation in existing buildings does require more effort and some additional cost, but it provides significant financial benefits immediately and over the lifetime of the building. Commissioning providers can also help integrate measurement and verification (M&V) plans and procedures that can be used to identify when a building begins operating outside of allowable tolerances, signaling the owner that corrective action is needed to maintain performance.

The operational staff's knowledge and understanding of how the building should be operated and their methods of operation in practice typically determine the actual building system's performance. The most common reason facilities fail to meet performance expectations or experience deterioration of performance is tied directly to how the building is operated and maintained. Changes in operational personnel often result in loss of the institutional knowledge needed to maintain the building's performance and meet occupants' needs. The System Manual is the repository for essential information needed by the operator to maximize occupant satisfaction and building performance. Without this information, the operator is running blind, without reference points for correct system operation. The result is that it may be difficult to meet the owner's goals and objectives and operation costs may increase. Monitoring-based, ongoing commissioning provides regular monitoring and analysis of utility usage, system interaction, and operator performance. Performed on a regular basis, monitoring-based commissioning improves financial and operator performance by changing the culture from constantly responding to problems and replacing it with routine maintenance. It establishes processes to retain institutional knowledge despite changes in personnel, occupant mission, and building modifications. For owners to get maximum performance from their facilities, they must know when systems fall outside of allowable performance tolerances or be aware of when operational personnel makes changes that could negatively impact the facilities' performance. This is best done through monitoring-based, ongoing commissioning.

For ongoing commissioning activities, it is not necessarily required that a third-party CxP Team be retained to oversee the day-to-day activities. Ideally, the facility's staff can perform this function and integrate ongoing Cx into the management of the facility.

ASHRAE Guideline 14, *Measurement of Energy, Demand and Water Savings* (ASHRAE 2014), provides several methods to establish operational benchmarks for energy consumption. Sustainable, healthy, high-performing facilities often measure other parameters, including water consumption, waste generation, recycling, pesticide use, etc. The operational tracking of these parameters reduces the total cost of ownership, lessens the environmental impact, improves building occupants' quality of life, and can increase building value. An owner can obtain guidance on integrating sustainable operation practices by adopting USGBC's LEED for Operation and Maintenance program at this stage of the building's life.

Additional information and insight into the application of these concepts in the operation of existing buildings can be found in Chapter 15, Existing Buildings.

DECISIONS TO MAKE DURING THE COMMISSIONING PROCESS

A good description of how to initiate a commissioning project is provided in Appendix C of ASHRAE Standard 202. This section outlines the series of decisions that must be made to get started.

Selection of the CxP Team

As with finding a doctor, lawyer, contractor, or other professional, the key element is that the commissioning provider should have experience in the types of systems an owner wants commissioned. In other words, an owner must match the experience with the job. A good CxP Team generally has a broad range of knowledge, including hands-on experience in O&M, design, construction, and investigation of building/system failures. CxP Teams must also be detail-oriented, good communicators, and able to provide a collaborative approach that engages the other members of the project team.

ASHRAE offers the Building Commissioning Professional Certification for individuals implementing commissioning and engaging commissioning providers. People who pass this certification understand how to lead, plan, coordinate, and manage a commissioning team to implement commissioning processes in new and existing buildings.

In the US, there is no single national commissioning certification or requirement to use a "certified" commissioning provider for projects other than what an owner may require as qualifications for their own projects. Other countries worldwide have differing requirements. For example, in Malaysia, commissioning is mandatory on projects and must be performed by an entity called a "commissioning specialist" (CxS).

Selection of Systems to Commission

Commissioning was originally developed in areas where energy efficiency was a prime driver. The commissioning process has expanded beyond the original commissioning of HVAC systems to include building envelope, electrical, plumbing, lighting, security, etc. This expansion from HVAC is often referred to as *whole-building commissioning* or *total-building commissioning*.

Although numerous commissioning service models exist, commissioning should be performed by the owner's own commissioning team or a third-party provider whenever possible. Commissioning of all systems using the whole-building approach has proven to be beneficial. However, because of budget constraints, owners may want to look at commissioning systems that will yield the greatest benefit to them. In other cases, the systems selected for commissioning may be specified by code or standard, such as projects that are being conducted under the requirements of IgCC/189.1. Long-term owners have an advantage and can apply their experience of where they have historically encountered problems and elect to commission only those systems. Others who do not have that depth of experience may wish to talk with long-term owners or insurance providers to gain perspective.

In recent years, there has been a growing recognition of the importance of building envelope commissioning. Typically, envelope commissioning is provided by third-party specialists and is often a separate contract from the commissioning of other systems.

Many factors define which building systems should be commissioned. It often depends on the associated risk of not commissioning. Errors and omissions (E&O) insurance providers publish graphs of claims against design professionals by discipline. Interestingly, many litigation claims against architects are for moisture intrusion, thus indicating a need for considering building envelope commissioning. In addition, the US EPA noted that during the initial concerns about sick building syndrome in the 1980s, the World Health Organization (WHO) suggested that up to 30% of new and remodeled buildings worldwide may be the subject of excessive complaints related to IAQ. The reasons for these *sick buildings* include inadequate ventilation, chemical pollutants from both indoor and outdoor sources, and biological contaminants. So, these are key areas to consider for commissioning. A link to the EPA site is included in the References section at the end of this chapter.

Commissioning provides several benefits, two of which are risk reduction and generally an overall lower total cost of ownership. Based on a specific climate, such as Phoenix, AZ, the risk of not commissioning the building envelope is much less than in Miami, FL, or Bangkok (because of humidity concerns). Based on functional requirements, declining to commission the security systems in a conventional office building may have minimum risk compared to a federal courthouse. So, what should be commissioned?

The best time for determining what systems should be commissioned is during the development of the OPR document. Generally, there are three main system categories that, as a minimum, should be commissioned: building envelope, mechanical and plumbing systems, and electrical systems. If the building project includes an on-site renewable energy system, that should also be considered a definite candidate for commissioning. Depending on the functional requirements of a building and the complexity of systems, additional systems that may be commissioned include security, voice/data, selected elements of fire and life safety, irrigation and/or process water systems, energy or water monitoring systems, and daylighting controls.

In some cases, these systems may be commissioned by the manufacturer's installer, such as is the case with fire and life safety systems where specific licenses and certification are required. IgCC/189.1 is more specific on the systems that should be commissioned and could be considered a good general guideline. Some building systems are installed with oversight and field testing by the manufacturer (elevators, for example), and these systems do not normally require a third-party commissioning provider.

USGBC's LEED rating system recognizes the benefits of commissioning and its importance to green-building design, construction, and operation. As such, the LEED reference guide implies that building systems that affect energy consumption, water usage, and indoor environmental quality should be commissioned.

Each element of green design needs verification to ensure that the design, construction, and operation of the high-performance building meet the team's expectations and realize the financial return envisioned by the owner.

Commissioning Models

If an owner does not have capability or resources to lead their own commissioning effort, an independent third-party commissioning provider is the preferred commissioning approach. This model reduces the potential for conflict of interest and puts a quality advocate squarely in the owner's corner. It also allows for integration of commissioning professionals specialized to meet a project's specific needs concerning the building envelope, security systems, labs, etc.

Owners are often tempted to place the CxP Team role under the contract of another project entity, such as the design firm or general contractor. Having commissioning be part of the general contractor's responsibility has many of the same problems as a model using the design professional. Contractors, by the very nature of the construction business, are focused on schedule and budget. This focus is not always in the owner's best long-term interest. Most contractors are quality-minded and do their best to identify problems and assist with resolutions (though often to their detriment because they inadvertently take responsibility for the design in doing so). If a constructability issue arises that will adversely affect the schedule or budget, the contractor may choose to fix the issue and hope that it does not create a

warranty callback. The main problem is that many of the issues are discovered too late in the process, again resulting in change orders, construction delays, additional costs, and building operational problems.

To truly be an owner's advocate, the CxP Team must owe allegiance to no one but the owner. A third-party CxP Team will verify that the goals defined by the owner and integrated by the design and construction team are achieved as intended from the first day of occupancy. If the CxP Team is separate from the design professional or contractor, they will provide unbiased reporting of issues to the team and will guide them toward timely solutions without finger-pointing, delays, and liability.

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Digging Deeper

**ONE FIRM'S COMMISSIONING CHECKLIST
(ALIGNS WITH LEED CX ACTIVITIES)**

- Begin the commissioning process during the predesign phase; carry out a full commissioning process from lighting to energy systems to occupancy sensors.
- Engage a CxP team that is independent of both the design and construction team.
- Develop an OPR document and review designer's basis of design to verify requirements have been met.
- Develop and use a commissioning plan.
- Incorporate commissioning requirements into project contract documents.
- Verify that fundamental building elements and systems are designed, installed, and calibrated to operate as intended.
- Verify installation, functional performance, training, and Operations and Maintenance (O&M) documentation.
- Complete a commissioning report.
- For enhanced commissioning:
 - Conduct a focused review of the design prior to the construction documents phase.
 - Conduct a detailed review of the construction documents when these are considered nearly complete and prior to their issuance for construction.
 - Conduct reviews of contractor submittals that are relevant to systems being commissioned.
 - Provide information required for recommissioning systems in a single document to the owner.
- Have a contract in place to review with operations staff the actual building operation and any outstanding issues identified during commissioning, and to provide assistance resolving these issues within the warranty period.
- Encourage long-term energy management strategies.
 - Provide for the ongoing accountability and optimization of building energy and water consumption performance.
 - Design and specify equipment to be installed in base building systems to allow for comparison, management, and optimization of actual vs. estimated energy and water performance.
 - Use M&V functions where applicable.
 - Tie contractor final payments to documented M&V system performance and include in the commissioning report.
 - Provide for an ongoing M&V system maintenance and operating plan in building O&M maintenance manuals.

Digging Deeper

- Operate the building ventilation system at maximum fresh air for at least several days (and ideally several weeks) after final finish materials have been installed before occupancy.
- Provide for the ongoing accountability of waste streams, including hazardous pollutants.
- Use environmentally safe cleaning materials.
- Train O&M workers.

CHAPTER SIX

CONCEPTUAL ENGINEERING DESIGN— LOAD DETERMINATION

Designing low-energy buildings requires the engineer to have a thorough understanding of the dynamic nature of the interactions of the building with the environment and the occupants. ASHRAE's *Load Calculation Applications Manual* (Spitler 2014) focuses on the most current load calculation methods: the heat balance method, and the radiant time series method. To optimize the design, detailed computer simulations that use these methods allow the engineer to accurately model the major loads and interactions.

The charts in Figure 6-1 show how average energy use breaks down in commercial and residential buildings. As designs are developed, breakdowns such as these should be kept in mind so that the energy-using areas that matter most are given priority in the design process.

When trying to minimize energy use in buildings, the first step is to identify which aspects of building operation offer the greatest energy-saving opportunities. For example, as shown in Figure 6-1, space heating and cooling, lighting, and water heating make up a combined 51% of energy use in the average commercial building in the United States. Similar breakdown is also provided for European buildings. Beyond the anticipated diversity of specific end-uses for different commercial building types, lighting and HVAC constitute the most important energy end uses; overall, space heating and hot water remain the main end uses.

Another important aspect of this exercise in the design process is that it allows the design team, along with the owner, to set the appropriate goal for energy usage. Many organizations and institutions have adopted the Architecture 2030 Challenge (see the References and Resources section at the end of the chapter for more information). Conceptual load calculations help to determine if a specific building design concept meets these requirements.

To find energy end-use statistics for many types of buildings (e.g., office, education, health care, lodging, retail, etc.), based on building location, age, size, and principal energy sources, consult the Commercial Building Energy Consumption Survey data published by the US Energy Information Administra-

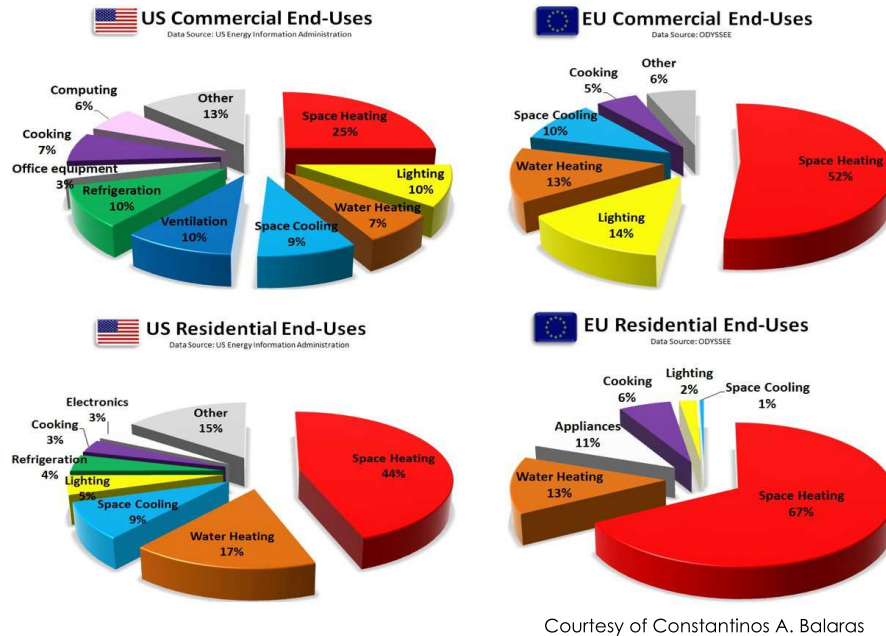


Figure 6-1 Average commercial and residential building energy use in the United States.

tion at www.eia.gov/consumption/commercial. In Europe, the ODYSSEE database (www.odyssee-mure.eu) contains detailed data on the energy consumption drivers by end-use (Figure 6-1) and CO₂-related indicators, and is regularly updated by national representatives, such as energy agencies or statistical organizations, from all 28 EU Member States and Norway. Various data resources are also available from the Buildings Performance Institute Europe (BPIE) under the BPIE data hub for the energy performance of buildings (<http://bpie.eu/focus-areas/buildings-data-and-tools/>).

DETERMINING THE LOAD DRIVERS WITH PARAMETRIC SIMULATIONS

To gain an understanding of how the proposed design of the building affects energy use, the engineer should perform a series of parametric simulations. This process involves sequentially removing each load from the energy balance individually to determine the effect on overall energy use. The simulations that show the greatest energy reductions identify which loads are driving the building's energy consumption.

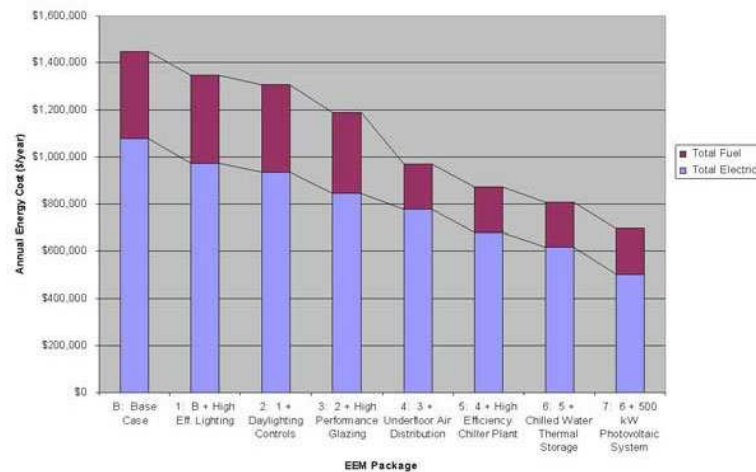


Image courtesy of CTG Energetics, Inc.

Figure 6-2 Parametric analysis for comparing various sustainability options.

For instance, to effectively remove wall conductive heat transfer from the energy balance, set the wall thermal resistance to a very high value (such as R-100 [R-17.6]). Run the simulation model, and note the building energy requirements. Then, reset the wall insulation back to the actual R-value and proceed to the next parameter. Continue to do this individually with the floors, roofs, and windows. Then remove the window solar gain, daylighting, and other site-specific shading that may be involved. Assess the impact of infiltration and the effect of ventilation air by setting them sequentially to zero.

Parametric simulations should be completed for the internal loads in a process similar to that described in Chapter 5. Set the lighting load to zero, set the equipment load to zero, and then take all the people out of the building. In this manner, the engineer can understand what is driving the energy use in the building.

Look for creative solutions to minimize the impact of each load, starting with those with the largest impact, or those that are the easiest to implement. From the parametric analysis example in Figure 6-2, adding underfloor air distribution results in the largest impact on annual energy use, so it should be one of the first solutions considered. Alternatively, a solution such as high-efficiency lighting may not result in as large of an impact, but may be easier to implement.

ENERGY IMPACTS OF ARCHITECTURAL FEATURES

It is important to collaborate with the architects to help guide decisions that will improve the thermal envelope's performance. Determine the greatest sources of heat gains and losses through the building's skin, and look for opportunities to minimize the effect.

Solar radiation through the windows can be one of the largest gains during the summer cooling season. Providing external shading can effectively minimize these gains. Horizontal shading, or overhangs, on the south face of the building will block the high sun during the day for much of the year, and vertical shading on the east and west can reduce gains early and late in the day as the sun rises and sets. However, the microclimate around the building should be completely analyzed to ensure any external shading actually works as intended. For example, in areas where the summer months are mostly foggy (e.g., Santa Barbara, CA), providing external shading for high angle summer sun may not be very effective.

Another means to control solar gains is to specify high-performance glazing with a low solar heat gain coefficient. These glazing options can be either tinted glass, or spectrally selective glass. The benefit of the spectrally selective option is that they have a clear appearance and a high visible light transmittance, allowing for greater daylighting potential and views to the exterior. However, they are generally the more costly option.

In climates where heating the building is of primary concern, it can often be beneficial to allow solar heat gain into the building as it acts as a free heating source. In climates where heating and cooling are both significant concerns, use a building simulation software program to understand the trade-offs associated with various solar heat gain coefficient values.

Conduction gains through the building skin are also significant in the overall heat balance equation. Where possible, try to reduce the window-to-wall ratio. Even the best-performing glass selections cannot compare to the thermal characteristics of an insulated wall.

Glass selections with low U-factors will reduce the heat gains and losses. Also, try to minimize the U-factors of the walls and roof by using insulation with high R-values. Where thermal bridging may occur due to structural elements of the building, provide a continuous interior layer of insulation to minimize this effect.

It is very important for designers to look at the entire window assembly properties, including the frame and the spacers and not only for the glazing. Good glazing U-factors can be severely compromised by not having thermally broken frames.

Lastly, try to minimize infiltration gains from leakage of untreated air into the building. Positively pressurizing the building with the HVAC systems will minimize this impact; however, stack-driven and wind-driven pressure differentials will still cause exterior air to infiltrate the building. Opening and closing of doors to the exterior will also contribute to infiltration gains. Specify a continuous air barrier to

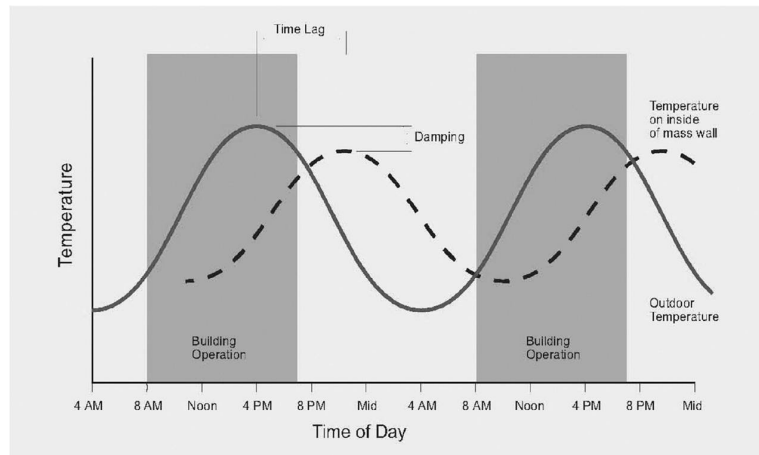


Image courtesy of U.S. Department of Energy Efficiency and Renewable Energy

Figure 6-3 The effects of thermal mass.

minimize air infiltration through the building skin, and install entry vestibules or revolving doors to minimize airflow into the building through open doors.

THERMAL/MASS TRANSFER OF ENVELOPE

Basic, steady-state energy transfer through building envelopes is well known, well understood, and easy to calculate. Increased R-values are certainly beneficial in heating climates and can also help in cooling-load-dominated climates. Use as a minimum the recommended amounts spelled out in ASHRAE's energy standard (Standard 90.1 [ASHRAE 2019a], latest approved edition). While values above those recommended can be beneficial in simple structures, high values can be counterproductive over a heating/cooling season in more complex structures. It is always wise to evaluate R-value benefits through the application of load and energy simulation programs.

The effects of thermal mass are sometimes not as easy to gauge intuitively (see Figure 6-3). Therefore, the previously mentioned simulation programs, when properly applied, are very useful in this regard. If thermal mass is significant in the building being planned (or if increased mass would be easy to vary as optional design choices), then such programs are essential for evaluating the flywheel effects of thermal mass on both loads and longer-term energy use.

GreenTip #6-1 describes a technique for combining nighttime ventilation with a building's thermal mass to achieve load and/or energy savings.

ENGINEERING INTERNAL LOAD-DETERMINING FACTORS

Internal loads are significant contributors to the energy balance, but can be effectively reduced during the design phase. For office buildings and other buildings in mild climates, lights are usually the major culprits. Therefore, optimize the day-lighting and electric lighting design. Refer to Chapter 11 for a detailed discussion on lighting systems.

Likewise, evaluate office equipment loads. Make recommendations about the effects of the choices of computers, monitors, printers, and other types of equipment. In many offices, this equipment is left on all night. An office building should have very few loads when the building is unoccupied. Leaving an office full of equipment powered up all night and on weekends can easily add up to large energy consumption.

For example, assume one 34,000 ft² (3159 m²) office building has nighttime plug loads of 10 kW, and assume the building is unoccupied for 14 h/day during the week and 24 h/day on the weekend. This adds up to around 6000 h/yr and 60,000 kWh—or \$4200 (at \$0.07/kWh)—of electricity that could easily be reduced. It is important for the engineer to bring up these issues during the design stage (and later, during the operation) of the building, because no one else may be paying attention to such details. Designing and building a great building is only half the job; operating it in the correct manner is the other—and often more important—half. The engineer can make better operation possible by designing piping, wiring, and controls capable of easily turning things off when not being used.

Educate owners about efficient office equipment and appliances to reduce plug loads, covering such things as flat screen computer monitors, laptops vs. desktop central processing units, copy machines, refrigerators, and process equipment (e.g., lab equipment, health care machinery, etc.). Consider measuring usage in one of the clients' existing buildings to get an accurate picture of load distribution and population profiles. Attempt to develop a total building electric load profile for every minute of one week.

Since 2010, ANSI/ASHRAE/IES Standard 90.1 and California Title 24 Part 6 require permanently installed plug load controls in new construction. This has been maintained and expanded in subsequent editions. The 2018 edition of the *International Energy Conservation Code (IECC)* does not include plug load control but some states (such as Florida and Washington) have amended their adoption of the IECC to include plug load control.

ASHRAE GreenTip #6-1

Night Precooling

GENERAL DESCRIPTION

Night precooling involves the circulation of cool air within a building during nighttime hours with the intent of cooling the structure. The cooled structure is then able to serve as a heat sink during the daytime hours, reducing the mechanical cooling required. The naturally occurring thermal storage capacity of the building is thereby used to smooth the load curve and for potential energy savings. More details on the concept of thermal mass on building loads are included in Chapter 5, Architectural Design and Planning Impacts.

There are two variations on night precooling. One, termed *night ventilation precooling*, involves the circulation of outdoor air into the space during the naturally cooler nighttime hours. This can be considered a passive technique, except for any fan power requirement needed to circulate the outdoor air through the space. The night ventilation precooling system benefits the building IAQ through the cleansing effect of introducing more ventilation air. With the other variation, *mechanical precooling*, the building mechanical cooling system is operated during the nighttime hours to precool the building space to a setpoint that is usually lower than that of normal daytime hours.

Consider these key parameters when evaluating either concept:

- Local diurnal temperature variation
- Ambient humidity levels
- Thermal coupling of the circulated air to the building mass

The electric utility rate structure for peak and off-peak loads also is important when determining cost-effectiveness, in particular for a mechanical precooling scheme.

A number of published studies show significant reductions in overall operating costs by the proper precooling and discharge of building thermal storage. The lower overall costs result from load shifting from the day to the nighttime with its associated off-peak utility rates. For example, Braun (1990) showed significant energy cost savings of 10% to 50% and peak power requirements of 10% to 35% over a traditional nighttime setup control strategy. The per-

cent savings were found to be most significant when lower ambient temperatures allowed night ventilation cooling to be performed.

For a system incorporating precooling to be considered a truly green design concept, the total energy used through the entire 24-hour day should be lower than without precooling. A system that uses outdoor air to do the precooling only requires the relatively lower power needed to drive the circulation fans, compared to a system that incorporates mechanical precooling. Electrical energy provided by the utility during peak demand periods also may be dirtier than that provided during normal periods, depending on the utility and circumstances.

The system designer needs to be aware of the introduction of additional humidity into the space with the use of night ventilation. Thus, the concept of night ventilation precooling is better suited for drier climates. A mechanical nighttime precooling system will prevent the introduction of additional humidity into the space by the natural dehumidification it provides, but at the expense of greater energy usage compared to night ventilation alone.

Both variations (i.e., night ventilation and night mechanical precooling) are not 100% efficient in the thermal energy storage in the building mass, particularly if the building is highly coupled (thermally) with the outside environment. Certain building concepts used in Europe are designed to increase the exposure of the air supply or return with the interior building mass (see, for example, Andersson et al. [1979]). This concept will increase the overall efficiency of the thermal storage mass.

For either type of system, the designer must carefully analyze the structure and interaction with the HVAC system air supply using transient simulations. A number of techniques and commercially available computer codes exist for this analysis (Balaras 1995).

WHEN/WHERE IT'S APPLICABLE

Night precooling would be applicable in the following circumstances:

- When the ambient nighttime temperatures are low enough to provide sufficient opportunity to cool the building structure through ventilation air. Ideally, a low ambient humidity level would also occur. A hot, dry environment, such as the southwestern United States, is an ideal potential area for this concept.

- When the building occupants would be more tolerant of the potential for slightly cooler temperatures during the morning hours.
- When the owner and design team are willing to include such a precooling system concept and to commit to (1) a proper analysis of the dynamics of the building's thermal performance and (2) the refinement of the control strategy (upon implementation) to fine-tune the system performance.
- More massive buildings, or those built with heavier construction materials such as concrete or stone, have a greater potential for benefits. Just as important, is the interaction of the building mass with the building internal and HVAC system circulating air. This interaction may allow for more efficient transfer of thermal energy between the structure and the air space.

PRO

- Night ventilation precooling has good potential for net energy savings because the power required to circulate the cooler nighttime air through the building is relatively low compared to the power required to mechanically cool the space during the day-time hours.
- Mechanical precooling could lead to net energy savings, although there will likely be a net increase in total energy use due to the less-than-100% thermal energy storage efficiency in the building mass.
- Both variations require only minor, if any, change to the overall building and system design. Any changes required are primarily in the control scheme.
- Night ventilation can provide a better IAQ environment, due to increased circulation of air during the night. A greater potential exists with the ventilation precooling concept. Both will be better than if the system was completely shut off during unoccupied hours.

CON

- Temperature control should be monitored carefully. The potential exists for the building environment to be too cool for the occupants’ comfort during the early hours of the occupied period. This will result in increased service calls or complaints and may end with the night precooling being bypassed or deactivated.
- The increased run time on the equipment could lead to lower equipment life expectancy or increased frequency in maintenance. Careful attention should be given to the resulting temperature profile through the day during the commissioning process. Adjustments to the control schedule may be necessary to keep the building within the thermal comfort zone.
- Proper orientation must be given to the building operator so he or she can understand how the control concept affects the overall system operation throughout the day.
- Future turnovers in building ownership or operating personnel could negatively affect how successfully the system performs.
- Occupants would probably need at least some orientation so that they would understand and be tolerant of the differences in conditions that may prevail with such a system. Future occupants may not have the benefit of such orientation.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a nighttime precooling scheme from a conventional one and gives an indication of whether the net cost for the precooling option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Mechanical ventilation system elements	S
• Architectural design features	S
• System controls	H
• Analysis and design fees	H

Recurring Cost

- Energy for mechanical portion of system
 - Ventilation precooling L
 - Mechanical precooling S/H
- Total cost to operate cooling system L
- Maintenance of mechanical ventilation and cooling system S/H
- Training of building operators H
- Orientation of building occupants H
- Commissioning cost H
- Occupant productivity S

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ASHRAE GreenTip #6-2

Night-Sky Cooling

GENERAL DESCRIPTION

When using chilled-water-based cooling systems, peak load reduction opportunities exist through the use of thermal storage systems. Many thermal storage systems use installed chiller capacity to charge the storage system during off-peak periods. However, while this takes advantage of cheaper energy during off-peak periods, it can actually increase overall energy consumption. Yet, as nighttime utility generation capacity is generally from cleaner sources than during peak periods, thermal storage systems can be an effective way to reduce greenhouse gas emissions as well as save operating costs.

Another good way to create a source of cooling is to use a roof spray cooling system. This system would spray water on a roof that is cooled by evaporation and radiation heat transfer. Such a system would work best in areas with limited cloud cover at night and with lower humidity, thus limiting where it would be effective. The consumption of water is also a concern that needs to be balanced with the energy effectiveness.

The cooled water from the roof spray system is collected from the roof surface, filtered and stored for use the following day. Researchers at UC Davis' Western Cooling Efficiency Center have reported Annual Energy Efficiency Ratios (EERs) of 40 to 150 for night-sky radiant cooling roof spray systems, versus EERs of 13 to 20 for ground-source heat pump systems (generally considered a highly efficient system). One manufacturer of these systems claims EERs of 50 to 100.

The roof spray cooling system consists of a piping grid and conventional water spray nozzles located on the roof surface and connected to a water pumping and filtration system. During the cooling season, water is sprayed over the roof surface at night. This water is first cooled by evaporation during the spray process and then further cooled by radiation to the night sky. The water is recirculated through this spray-cooling process until it is cooled and then stored for later use in providing cooling to the building. Studies have shown that the minimum water temperature reached during operation can be 5°F to 10°F (3°C to 5°C) less than the minimum dry-bulb air temperature reached at night.

WHEN/WHERE IT'S APPLICABLE

Research data suggests that, where summer dry-bulb temperatures fall below 65°F (18°C) at night, system capacities can be expected to be approximately 25 ton-hours per 1000 ft² of roof area (300 Btu/ft² [0.95 kWh/m²]). Another report places capacities at approximately 290 Btu/ft² (0.9 kWh/m²).

Cooling via night-sky radiation relies on the fact that the effective temperature of the night sky can be significantly cooler than the ambient air temperature. Thus, an object set outside at night will radiate more heat to the night sky than it will absorb from the night sky and the net loss of heat will cause the object to cool below the surrounding air temperature.

Most of the cooling via night-sky radiation occurs as the water film left on the roof from the spray process exchanges radiant heat with the night sky. The typically large roof areas available allow for substantial radiative cooling at relatively little additional building cost. The effective nighttime sky temperature is a function of both the dry-bulb air temperature and the humidity content of the air, with higher humidity reducing the differential between the effective sky temperature and dry-bulb air temperature. Although not an easily measured parameter, sky temperature data are available in typical meteorological year (TMY) weather data files or can be estimated from other weather parameters using established algorithms.

PRO

- Very high efficiency cooling system.
- Enhances redundancy of systems.

CON

- Higher first cost, unless chiller capacity can be reduced by the peak tons available from the chilled-water storage system.
- Sensitive to quality of the potable water used for makeup (e.g., clogging of spray nozzles).
- Requires good design of stratified thermal storage tank.
- Available capacity subject to weather patterns.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a night sky radiant cooling system from a conventional one and an indication of whether the net cost for an option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely and it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Chilled-water storage system H
- Interface of chilled-water storage to cooling system H
- Roof spray system H
- Controls and instrumentation H

Recurring Cost

- Energy consumption L
- Testing and balancing (TAB) S
- Maintenance S/H
- Commissioning H

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ASHRAE GreenTip #6-3

Plug Loads

GENERAL DESCRIPTION

As the efficiency of various energy-using systems (i.e., HVAC, lighting, or building envelopes) improves, the impact of plug loads on the total annual building energy usage increases. This is accelerated by the rapidly growing use of computers and other electronic equipment in most building types. The purpose of this GreenTip is to identify some key issues to watch for that are relative to plug loads.

TYPICAL PLUG LOAD ENERGY BUDGETS

Historically, plug loads in office buildings have been designed to support connected loads in the 2 to 5 W/ft² (20 to 50 W/m²) range. For laboratories or computing-intensive buildings, this can go up to 10 to 15 W/ft² (100 to 150 W/m²). The electrical distribution system must be designed to support this level of load, in compliance with the *National Electrical Code*® (NFPA 2014). Yet the actual diversified load exerted on the building electrical demand and upon the HVAC system will more likely be 1 to 1.5 W/ft² (10 to 15 W/m²) or even less for highly efficient installations, as described below.

DIFFERENCE BETWEEN CONNECTED LOAD AND EFFECTIVE LOAD

The reason for this disparity is the fundamental difference between connected load for electrical equipment and the effective load imposed on the HVAC systems and electrical systems by the actual equipment when diversity of use is taken into account. The nameplate ratings of equipment are not representative of the actual energy usage of that equipment, which is typically a fraction of nameplate on average. Thus, if energy usage and cooling loads from office equipment and other plug loads are based upon nameplate, they can be overestimated by 200% to 500%.

There is debate about how much further plug loads are likely to drop in the future, as ever-improving efficiencies of equipment are being offset by increasing amounts of equipment being used. Programs like the U.S. EPA's ENERGY STAR program will continue to improve the energy efficiency of individual pieces of equipment.

CONTROLS OF PLUG LOADS

One of the key factors in reducing effective plug loads is the impact of controls on the equipment loads. The primary issue is the power management controls now built into all computers and most other office equipment—putting the equipment in standby mode or completely shutting it off after preset intervals of no activity. Another way to control plug load is at the receptacle level, and this can be accomplished in three ways:

- **Schedule-based:** Also called *timer-based*, this type of control turns off receptacles at specific times. This is usually the simplest way to control plug power. A best practice is to make half of the receptacles time-based. No occupancy sensors or building-level control systems are needed. Receptacles can, for example, be programmed to turn off from 6:00 a.m. to 6:00 p.m. One of the disadvantages of schedule- or time-based control is that if a space is unoccupied, the power will not be turned off.
- **Occupancy-based:** A sensor turns off receptacles within a certain time (e.g., ASHRAE/IES Standard 90.1 requires 20 minutes) of all occupants leaving a space. This approach is familiar because of the popularity of occupancy sensors for lighting. When no one is in a space with an occupancy-based plug load control, the equipment connected to the receptacle will turn off. This is a key advantage of this method as opposed to a scheduled-based approach. Occupancy-based plug load control can integrate with the lighting controls so that the same sensor can be used. This can be done with either digital or analog controls. For simple retrofits where ceiling sensors already exist for lighting control, a device can be wired to the sensor, which, in turn, transmits a wireless signal to a receptacle in the space. This receptacle is then capable of switching a 15 amp load on or off based on occupancy. The same approach can be taken using digital controls and a building automation system through a network and a power pack that connects in-line with the receptacles that are to be controlled. In this case, a category cable connects to the building control system, and facility managers can then control the power pack, which in turn controls the receptacles.

- **System-based:** Another control or alarm system sends an automated signal that shall turn off receptacles within 20 minutes after determining all occupants have left the space. This system is usually part of the broad building management system (BMS). It's common for lighting and plug load to use the same occupancy sensors and come bundled. These systems are usually controlled by web-enabled software with user-friendly interfaces. An advantage to this method is the data gained from the BMS, which gives a detailed analysis of energy consumption and occupant behavior. This data empowers owners, facility managers, and artificial intelligence (AI) engines to forecast and implement energy-saving plans to reduce overall operating costs and improve the sustainability of the building.

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ASHRAE GreenTip #6-4

Dynamic Glazing

GENERAL DESCRIPTION

Dynamic architectural glazing uses electrochromic technology to darken the interior of a piece of glass, enabling a thin coating to change from clear to tinted when small electrical voltage is applied. A demonstration of this technology is eyeglasses that darken when one goes outdoors. Dynamic glass for architectural applications can transform into four darkness levels depending on the season, being darker in summer to keep solar gain out and minimize glare. In addition, because the glazing becomes darker in the summer when exposed to sun, its use will generally minimize radiation heat transfer and help improve thermal comfort in the space. Typically, the tint corresponds to 4%, 20%, 40%, and 60% visible light transmittance T_{vis} depending on manufacturers. Dynamical glazing promotes a reduced carbon footprint, helps achieve LEED certifications, and reduces energy costs by reducing solar heat gain (i.e., the amount of heat that enters a glass structure naturally from the sun). The dynamic glazing is usually controlled by a low voltage current and can be controlled either manually through a switch or linked into an automatic building management system (BMS).

APPLICABILITY

Dynamic glazing is usually the most feasible on large glazing facades not do not face north. It works well on east and west orientations since these are difficult to horizontally shade. It could also be used efficiently on south facades that are not shaded.

PROS

- Reduced energy consumption
- Reduced glare
- Improved comfort
- Reduced carbon footprint

CONS

- Higher first cost
- Requires electrical voltage to operate

The following provides a possible breakdown of the various cost elements that might differentiate a night sky radiant cooling system from a conventional one and an indication of whether the net cost for an option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely and may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Glazing H

Recurring Cost

- Energy consumption L
- Maintenance L
- Commissioning L

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US Environmental Protection Agency
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CHAPTER SEVEN

SUSTAINABLE SITES

One interesting phenomenon that has come out of the encompassing of the sustainable design and integrated design processes is that design professionals are becoming more aware of the work done by disciplines outside their own. The *ASHRAE GreenGuide* is primarily focused on the needs of its members and disciplines related to green-building design projects. It is important to have at least a basic knowledge of all aspects of green design. In 2012, ASHRAE announced a rebranding of the Society toward becoming a sustainability resource for the industry, which included changing the Society's tagline to "Shaping Tomorrow's Built Environment Today."

Sustainability is an integral part in the design of all features of the built environment, and this includes site development. In addition to the LEED rating system, ANSI/ASHRAE/USGBC/IES Standard 189.1 and the *International Green Construction Code* (IgCC) both include whole sections on "Sustainable Sites." Much of the material in this chapter addresses the major issues associated with site sustainability.

This chapter provides a summary of the key issues in the following topical areas:

- Site selection and building project location
- Site inventory and landscaping
- Urban heat island mitigation
- Exterior light pollution
- Transportation impact mitigation

Each of these is briefly summarized in the following sections.

SITE SELECTION AND BUILDING PROJECT LOCATION

For most locations, at least in most developed countries, local or regional regulations and agencies control many decisions related to land use and zoning restrictions, including building location on site, height, area, density, setbacks,

site access, parking, walkways, lighting, and landscaping. Land-use regulations determine where and what can be developed on any particular site with the jurisdiction for compatibility of building uses in a given area.

Land-use planning involves compatible zoning districts for such uses as single-family homes, multifamily residential, retail, services, entertainment, medical, recreational, manufacturing, and institutional. As an example, land-use regulations would not allow a factory or manufacturing facility to be built next to a residential community since they are noncompatible uses. On the other hand, a neighborhood-scale shopping center is compatible with a residential neighborhood and would provide local services to residents in the area within easy walking distance. In addition, land-use regulations can restrict development on environmentally sensitive areas such as wetlands or wildlife habitat conservation areas. Depending on the region, land-use regulations can be fairly strict or more lenient. However, it is safe to say that this is primarily a locally or regionally controlled decision.

Even if the zoning of a potential site is compatible with a building project's intended use, the site may not be compatible for a sustainable building project. For example, consider a high-performance office building developed in a remote rural area far from any existing businesses, services, or residential developments. Would that building be considered a viable green project if all the employees and customers had to drive private vehicles to the site on a regular basis? There is no right or wrong answer to that question as all projects are unique, but certainly services in the immediate vicinity and transportation to the site is a consideration. Thus, urban sprawl is another topic for consideration to moving toward a more sustainable built environment. Urban sprawl can have a significant impact on the quality of life and the health of our environment, including commuting time and vehicle emissions. Location of the building on a greenfield site (i.e., a site that has not been previously developed) will also have a higher potential for negative environmental impacts than if the building were to be located on a previously developed site (i.e., a greyfield site) in an urban setting.

The decisions and issues associated with this topic go well beyond just the design of the physical building structure and systems and thus are somewhat beyond the scope of this book. However, the design professional needs to consider these issues as part of their professional practices.

SITE INVENTORY AND LANDSCAPING

Once the building project site has been determined, the project team should arrange for a predesign site inventory and assessment of the natural resources of the site. This would include identifying any invasive plant species as well as plant species that are native to the region, or other special features of the site that should be preserved if possible. Any invasive plant species identified on site should be removed and destroyed during the site preparation process. Efforts should also be taken in the building site layout and design to minimize disruption of existing

native or adapted plants. For portions of the site that will be replanted after construction, strong consideration should be given for plants that are native or adapt to the region as well as identifying areas for use as rain gardens or bioretention areas that will contribute to stormwater management of stormwater on the site.

Once the site inventory and assessment are complete, a site waste management plan should be prepared to manage any waste generated during site preparation. Similar to the construction waste management plan, the site waste plan should have a goal of diverting as much waste as possible from landfills. The plan needs to address land clearing debris (rock, soil, tree stumps), invasive plant disposal, contaminated soil removal, and the handling of woody waste. Methods of minimizing waste include the storing of soils for subsequent use on the project site or off-site.

URBAN HEAT ISLAND EFFECT

The urban heat island effect is the physical effect of urban areas to have ambient air temperatures higher than the surrounding rural areas in the same region. This is a complex topic, and the contributors to the urban heat are many. Those who have participated in a building project that was achieving LEED certification, or compliance with one of the other green-building standards or programs, are most likely aware of the credits offered that are intended to address the urban heat island effect. Those credits address one of the main contributors to the urban heat island effect, that is, the tendency of buildings and the site hardscape areas to absorb and retain heat from the sun.

There are many other contributors, or potential contributors, to the urban heat island effect that are beyond the control of the building designers. These include items like regional industrial activity, existing streets, exposed parking lots, and motor vehicle transportation. And of course, outdoor condensing units play a big role in the development of the urban heat island effect as all the thermal energy from inside the building (plus the energy used to power the refrigeration system that provided that cooling) is transported to the ambient air.

Heat Island Mitigation Methods Associated with a Building Project

Users of this guide are likely familiar with methods that the building designer has available to help minimize the heat island effect in the locality where the building project is sited. In fact, much of the benefit from measures that reduce the urban heat island effect, such as a cool roof or hardscape with a lower solar reflective index (SRI) hardscape, is experienced by all in the local area and not by just the users of the building project. Therefore, this is a subject that can be beneficial to the region as a whole. One of the primary methods includes the use of materials that have a higher SRI. The SRI is a metric that indicates the ability of a material to absorb the sun's heat (in terms of the absorptivity of the material) as well as the ability to lose heat by thermal radiation, which is determined by the thermal emis-

sivity of the material. Other methods include shading building walls and the hardscapes, porous paving materials, and green roof systems. All these methods reduce the solar heat absorption thereby minimizing the heat island effect.

The SRI values are determined on materials associated with a building project (such as roofing or hardscape such as paving materials) using standardized testing methods. For roofing materials, this would be ANSI/CRRC Standard S100, *Standard Test Methods for Determining Radiative Properties of Materials*, which was produced by Cool Roof Rating Council. These values also need to be determined based on a three-year aged value for those materials, since as the products age their thermal reflectance values will change (decrease). For materials others than those used on roofs, the SRI rating is determined based on the solar reflectance as determined by standard methods such as those produced by the ASTM (formerly known as the American Society of Testing and Materials), such as Standards E1918 and C1549.

The general consensus for SRI values to strive for in materials used in the site hardscape or building walls should be at least an SRI of 29. For relative comparison purposes, new grey concrete (without colorant added) is assumed to have a default SRI value of 35, so 29 is not that stringent. For roofs, there are different best practice criteria for low-sloped roofs (a slope less than 2:12) and steep-sloped roofs. This reason for the different consideration is that different material solutions are available for the two situations. For a low-slope roof, an SRI of at least 29 should be specified since these might commonly involve a roofing shingle or metal roof concept. For a low-slope or flat roof, the designer/architect should specify a roofing system with a minimum three-year aged SRI value of 64. A roofing system with three-year aged SRI 64 will be a “white” color, but roofing products with SRI of 29 are available with different color options, for example see the roof shingle materials shown in Figure 7-1 that has a SRI rating of 29. We should note that there also is some controversy about what climate zones cool roofs should be specified, since in colder climates there is a potential for water problems under the roof since there is less potential for the roof to be warmed in the winter sun and hence dry out. Based on the requirements listed in IgCC/189.1 (ICC 2021), cool roofing products should be specified at least in Climate Zones 0 through 4.

The Interrelationship of Urban Heat Island and Building Heat Gain

There is a complicated relationship between the use of materials that have a higher SRI value and their impact on the building heat gain (and hence cooling load) and the urban heat island effect. The use of higher-SRI materials will have varying impact on the building heat gain, depending on how thermally coupled the building interior is with the roof and walls. In some structures, the reduction in heat gain is practically insignificant, while in other cases it could help reduce the overall cooling load to a noticeable degree. However, green-building standards and pro-



(a)



(b)

Images courtesy of Tom Lawrence and Anthony Floyd

Figure 7-1 Example of (a) roof shingle with an SRI of 29 and (b) flat cool roof bottom.

grams are concerned not only with the building heat gain but also with the contribution of the building structure and associated hardscape with the heat island effect. The heat island effect is a sites issue, rather than strictly a building energy issue, although criteria such as a high SRI roof can affect both. That is why criteria are included in the sites section in green-building rating systems and standards. This also helps explain the differences in why the heat island requirements, specifically those for the roof materials, differ between ANSI/ASHRAE/IES Standard 90.1 and

IgCC/189.1. Standard 90.1 is solely focused on the impact on the building heat gain and cooling load, while IgCC/189.1 is intended to provide a balanced approach to treating environmental issues. Thus, IgCC/189.1 contains more stringent requirements in the heat island section because it is intended to consider both building energy as well as the heat island effect.

A second consideration that is starting to gain attention is the reverse: the impact of anthropogenic waste heat on the urban heat island. Heat rejected by building air-conditioning systems, transportation, and industrial processes does not just disappear into thin air, especially in dense urban environments. Thus, whatever can be done to reduce energy consumption and improve efficiency of HVAC&R systems can also have the positive benefit of reducing the addition to the overall thermal energy balance of urban areas.

EXTERIOR LIGHTING

Similar to the heat island issue, the design of exterior lighting levels and lighting fixture selection for a green building involves both consideration of lighting power (for total energy consumption) and the impact of the building and its systems on the surrounding locality. In the case of exterior lighting and the building site, it is also a matter of how the lighting is directed to the area intended to be lit.

To prevent light from escaping the building project property boundary to areas that would be adversely affected by that light, the lighting design should specify fixtures that meet low-impact site lighting standards. Exterior lighting fixtures are rated on how well they perform in terms of backlight, uplight, and glare (“BUG” ratings). It is important to consider the location of the building site. In some urban areas, there may already be an excessive amount of light pollution problem from all the other surrounding sites and overall night sky would result in light pollution. Special attention should be required in the selection and placement of lighting fixtures to illuminate only where needed while limiting illumination beyond the property boundary.

A number of references are available from organizations that are concerned with exterior lighting. For sustainable site considerations (above and beyond just the energy consumption aspects), the International Dark Sky Association provides a series of resources. See the references listed at the end of this chapter for a link to this valuable resource.

STORMWATER MANAGEMENT

Development of properties for buildings and associated hardscapes have led to the creation of impervious surfaces that contribute to increased surface runoff into surface waterways. That increased runoff is the cause, or at least a significant contributor, to flooding problems downstream of any given site. In most localities, requirements are in place for addressing this issue. This is one area where the design features of the building project have a measurable positive contribution to

the local environment. While many of these measures are outside the normal responsibility of the building systems design engineers and are more the responsibility of the civil engineer and landscape architect, some of the measures can also be used to collect rainwater runoff and serve as an alternative source of water for landscape irrigation and water closet/urinal flushing to reduce the overall demand for potable water.

Prescriptive Versus Performance Focus

Existing green-building rating systems, codes, and standards approach the stormwater management issue from various perspectives. One approach is to specify or require the building project achieve a particular performance basis. This approach will seek to address the amount and quality of stormwater runoff based on comparison to a baseline criterion. For example, there could be a target for the project design team to end up with the postdevelopment runoff amount to not exceed that which would have occurred from the same site if left in an undisturbed, predevelopment state. A performance approach is what is used by U.S. Green Building Council LEED rating systems. Performance is what ultimately counts, but this is achieved by the actual design and selection of specific measures.

A different approach could be taken, one prescriptive in nature. Instead of specifying specific performance criteria to be achieved, this alternative approach would require the inclusion of best management practices that have been proven to address the problems caused by unmitigated stormwater from the built environment. This approach is described as being prescriptive in nature, as it prescribes specific technologies or practices to be implemented. Some of these practices are briefly outlined in the section that follows.

Stormwater Mitigation Techniques

The best designs for minimizing stormwater impact will result in no more surface runoff from that property than would have occurred from a natural, undisturbed landscape at that same location. This can be achieved by a combination of one or more of the following design strategies.

Maintaining a Larger Portion of the Project Site as Vegetation. Obviously, maintaining as much as possible of the site with some form of vegetation is a prime consideration. However, some project sites offer limited, if any, potential for this, so additional measures are needed.

Minimizing Impervious Surfaces and Compaction of the Soil. Impervious surfaces, such as roofs and concrete or asphalt pavements, generate runoff and do not allow precipitation to infiltrate into the ground. In addition, during the site preparation and construction process, soil is compacted. Compacted soil reduces water infiltration while increasing surface runoff. By careful planning and construction management, unnecessary compaction can be minimized. The site devel-



Image courtesy Tom Lawrence

Figure 7-2 Example of rain garden used to manage stormwater runoff from a building roof.

opment plan should also consider the use of porous concrete or pavers, and other methods to increase the on-site rainfall absorption and thus minimize runoff.

Rain Gardens. Rain gardens are low-lying regions on the property located to collect surface runoff from impervious surfaces (such as parking areas) slowing down that runoff enough to allow for a large portion of it to naturally infiltrate into the soil or leave by evaporation or transpiration from plants in the rain garden. In this regard, rain gardens provide a similar function as a traditional retention pond on site, but with the additional benefits of providing a natural landscape and avoiding some of the negative aspects of retention ponds such as liability concerns and fence enclosures. Rain gardens are the subject of GreenTip # 7-1 at the end of this section.

Rainwater Harvesting. Rainwater collection and storage for later use on site or in a building has two sustainability-related benefits. First, this water would typically be collected from impervious surfaces, such as hardscape or a rooftop (Figure 7-2). The collected rainwater is diverted from quickly running off the property and contributing to local stormwater pollution downstream (this is thus a sustainable site issue.) If the collected water is used to displace potable water, for example, as flushing toilets or as cooling tower makeup water, then rainwater harvesting also contributes toward water efficiency. Rainwater harvesting is covered in more detail in Chapter 12.

Green Roofs. Green or vegetated roofs provide the ability to absorb at least a portion of the precipitation that falls on the roof. The amount collected and stored is a function of soil depth, condition of the soil before the storm event (whether dry or saturated), and the type of soil in the green-roof system. Green roofs have been recognized by green building rating systems and standards



Image courtesy of Tom Lawrence

Figure 7-3 Example green roof planted with native or adapted species.

(LEED, Standard 189.1, IgCC) as having a positive effect of reducing the local urban heat island, but the amount of this benefit depends on the moisture content of the soil and any shading from vegetation on the green roof. Green roofs provide additional environmental benefits, but can also increase water consumption if not properly designed and requires proper irrigation. To minimize these negative impacts, the design team should select native plants to minimize water consumption and, depending on the green roof type, may need to consider the load-bearing capacity of the roof (especially for existing buildings) along with the need for waterproofing material, drainage, and other necessary improvements. An example of a green roof over an underground parking structure with native or adapted species planted can be seen in Figure 7-3.

Regulations and guidelines for green roofs are available in some countries, for example, the first one published in the mid-1990s in Germany (FLL 2002); the UK guidelines on best practices for the design, installation, and maintenance of green roofs (NFRC 2014); and ASTM. In North America, the top five ranked cities with the most amount of green roofs are Washington, DC; Toronto, ON; Philadelphia, PA; Chicago, IL; and New York, NY with over 4.3 million ft² (0.4 million m²). Most of these municipalities support green roofs directly through policy, rebate programs, tax credits or other incentives.

In Germany, the market boomed beginning in the 1980s and recent estimates place the total install green roof area in Germany at between 100 and 150 million m² or between about 1 and 1.5 billion square feet (China Dialogue 2017). More than 75 European municipalities currently provide incentives or requirements for green roofs. Copenhagen, Denmark, which has set an ambitious target to become the world's first carbon-neutral capital by 2025, mandates all new flat roofs at or under a 30° pitch have a green roof. Other leading European cities include Berlin and Stuttgart, Germany along with Linz and Vienna, Austria (Inhabitat 2010).

TRANSPORTATION IMPACT MITIGATION

Whenever practical and possible, the site design should factor in how the building and its occupants will interact with the local transportation network, which includes pedestrian walking, bicycles, private vehicle and public transportation. For example, public-use walkways (usually sidewalks adjoining streets) should be provided along the length of public-way frontage with the building project site. Some designers are concerned with providing “sidewalks to nowhere” but adding these will help make the community more pedestrian connected and walkable. Bicycle parking should be provided for all buildings that are within the range of a reasonable bicycle commuter. In addition, building projects that provide parking spaces should be equipped with a percentage of electric vehicle charging parking spaces for residents in residential projects and for employees and customers in commercial buildings. At a minimum, the parking area should be made “EV ready” by including infrastructure for future charging capability including electrical raceways and a design load of at least 40 amps per parking space at a supply voltage of 208 or 240 VAC for Level 2 charging.

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ASHRAE GreenTip #7-1

Rain Gardens

GENERAL DESCRIPTION

In 1990, in response to a demand for better stormwater management in Prince George's County, Maryland, bioretention systems, or rain gardens, were used as a financial and aesthetic solution (Prince George's County 2014). Since their utilization in Maryland, case studies and research have taken place to determine the potential impacts that rain gardens can have on decreasing the amount of stormwater runoff in local areas, as well as the amount of pollutants that can be absorbed by the vegetation in rain garden designs. The results of these studies have been positive.

The concepts of a rain gardens are basic. Where there are impervious structures that rain water encounters, there will be runoff. This runoff is often directed to infrastructure designed to carry runoff (and associated contaminants) to nearby waterways. Rain gardens intercept runoff before reaching those systems and filter a portion of the runoff using soil, mulch, and vegetation. In order for runoff to be captured, rain gardens must be on a shallow slope away from the aforementioned impervious structures in the direction runoff flows toward stormwater management systems (EPA 2013b).

Rain gardens most often include a variety of native plants which are drought tolerant and wet tolerant that are found in low areas (Cleanwater Campaign 2012). They can be installed in different soils, including sandy and clay soils. Their size can vary depending on the catchment area, and they can be installed in lawns, roadsides, or parking lot islands (North Carolina State University 2001). Most are dug approximately 4 to 6 in. (100 to 150 mm) deep with mulch and specific vegetation used to absorb water and filter pollutants. During a typical rain event, the first 1 in. (25 mm) of rain washes away the majority of pollutants from roof tops, roads, parking lots and other structures. Rain gardens are generally designed to hold water from a 1 in. (25 mm) rainstorm event. During that time, pollutants are absorbed and filtered through the mulch and vegetation instead of entering the stormwater drains and ultimately the local waterways (University of Rhode Island 2013). The design is shallow

enough that rain will not collect and stay for more than 24 hours so that mosquitoes and other insects are unable to breed, nest, and lay eggs (Cleanwater Campaign 2012). Rain gardens will provide more absorption and filtration than common grass lawns while providing a more diverse landscape (University of Rhode Island 2013). The absorption rate of rain gardens will decrease over time, so application of fresh mulch will help replenish the soil's capacity to filter pollutants. An overflow with outlet pipe is recommended to divert excess water out of the rain garden, especially in clay soils. The top of the pipe can be set at the desired maximum water depth (ranges from 6 to 12 in. [150 to 300 mm], with 9 in. [225 mm] considered standard depth).

WHEN AND WHERE THEY ARE APPLICABLE

While some alterations may need to be made in colder climates (snow and salt content must be considered), rain gardens are applicable almost anywhere in the United States (EPA 2013b). In most cases, the existing soil type will not prohibit designs, since the areas are dug out first and a specific soil mixture is added onto the cleared ground. An ideal soil mixture suitable for rain gardens is a mix of 50% to 60% sand, 20% to 30% topsoil, and 20% to 30% compost (Cleanwater Campaign 2012). Slightly depressed areas are ideal locations, but a flat site can work if depressed areas do not exist on site.

PRO

- Design and development is similar to that of common landscape projects which require no major infrastructure.
- Due to the plant type requirements, rain gardens require little maintenance over time other than observation for erosion and clogging.
- With adequate planning and implementation, they can be built to serve most regions and soil types.
- While providing water management and pollutant filtration, rain gardens are most often aesthetically pleasing to the owner.
- Rain gardens can be designed on new developments or retrofitted to existing developments (Oklahoma Farm to School 2013).

CONS

- If not designed properly, standing water or increased erosion can occur (Oklahoma Farm to School 2013). These issues should be avoidable by following guidelines provided by local, state, or national entities such as the Environmental Protection Agency.

KEY ELEMENTS OF COST

First Cost

- Soil amendment mix (specific mix dependent upon local soil conditions)
- Possible excavation and hauling away existing soil
- Pipe and filter fabric for the overflow
- Mulch
- Desired vegetation
- Initial daily watering for approximately two weeks) (Engineering Technologies Associates and Biohabitats 1993)

Recurring Cost

- Remulching to maintain spoil function
- Treating diseased vegetation
- Replacement of tree stakes and wiring as needed (Engineering Technologies Associates and Biohabitats 1993)
- Removal of invasive plants or weeds as needed

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ASHRAE GreenTip #7-2

Green-Roof Systems

GENERAL DESCRIPTION

A green-roof system consists of a vegetative surface on a building rooftop and are classified in two categories based upon soil depth:

Intensive:

- Minimum soil depth: 12 in. (300 mm)
- Capable of housing large trees, shrubs and recreational facilities
- Heavy; requiring structural reinforcement, 80 to 150 lb/ft² (400 to 750 kg/m²)

Extensive:

- Average soil depth: 1 to 6 in. (25 to 150 mm)
- Often installed using modular plots
- Lighter; less of everything, 10 to 15 lb/ft² (50 to 75 kg/m²)

Green-roof systems are composed of several critical layers to support the growth of vegetation while managing the collection of rainwater and providing a thermal and water-resistant roof barrier. The uppermost layer is the vegetation. This layer varies the most in application due to climatic factors and depth of soil. Maintenance required is determined by the types of plant life used; an intensive system will require more attention than an extensive system. The second layer is the growth media consisting of the soil mix in which the vegetation grows. This layer will also vary with location as different soil types will require a variation in the soil mix ratio.

In extensive systems, under the growth media is typically a layer of filter fabric. This filter allows for water penetration, but must be tough to withstand pressure. Typical materials for filter fabric systems are geosynthetic fabrics or geotextiles.

In intensive systems, the filtration system is a part of the drainage system. A layer of gravel beneath the fabric-protected growth media allows tree roots to grow down and increase the stability of the plant layer above. A root barrier is layered beneath the gravel. Water can be stored in the gravel, drained to an outlet, or, in the case of extensive systems, be retained in a molded modular storage

unit system. This is also the layer in which irrigation can take place to access and encourage deep roots.

Beneath the drainage layers of green-roof systems is a waterproofing layer. Watertight materials can be applied as a liquid-applied membrane, a single-ply specialty sheet, or a three-layer laminated roof system. One or more layers of insulation can be installed to provide reduced heat transfer through the roof as well as mitigate sound transmission.

WHEN AND WHERE THEY ARE APPLICABLE

Green-roof systems are particularly well-suited for dense urban application. Unused rooftops can become productive spaces. Structural constraints make retrofit projects more difficult for the implementation of a green-roof system, but a new building can account for structural loading during the design phase.

Climate plays a crucial role in the actual return on investment. For example, stormwater or rainwater retention may be less of a benefit for a green roof located in low rainfall areas or regions where rainfall tends to be concentrated in the winter months.

KEY ELEMENTS OF COST

The climate region in which a green-roof system is located in will determine actual cost and savings as the same system will not perform identically in different regions. Using L to represent lower cost, H to represent higher cost, and S to represent the same cost; here is a brief comparison of several expenditure types:

First Cost

- Installation H/S (H in retrofits)
- Design feesS

Recurring Cost

- Overall energy costs L
- Water costs L
(if rainwater harvesting is done)
- Training for operations H
- Overall maintenance costs H

Table 7-1: Potential Benefits and Drawbacks of Green-Roof Systems

Advantages	Disadvantages
Stormwater runoff reduction	Additional structural load
Reduced heat gains (during summer) and lower heat loss (during winter) to interior conditioned spaces	Cost
Longer life for the base roofing system (may not apply to an intensive green roof)	Additional maintenance, ranging from limited for an extensive green roof with low-maintenance plants to high for a manicured landscape intensive roof
Heat island mitigation and reduced sound transmission from outside	Results depend on the roof type, plant materials, and soil depths
Aesthetic and health benefits for people in and around the building with greenery, flowers, and the pollution-absorbing ability of vegetation	Documentation of benefits such health and well-being has not been universally proven
Other general environmental benefits, such as reduced nitrogen runoff (bird droppings), potential carbon sink, and insect and bird habitat	Unintentional haven for rodents, pests, and other possibly disruptive insects and animals

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CHAPTER EIGHT

INDOOR ENVIRONMENTAL QUALITY

INTRODUCTION

The primary functions of an occupied building are to provide shelter from natural elements and as healthy an indoor environment as possible for the occupants. Indoor environmental quality (IEQ) is the overall condition of an indoor space as it relates to the health and wellbeing of the occupants. The four key factors of IEQ are indoor air quality (IAQ), thermal comfort, lighting quality, and acoustic comfort. The interaction among these key factors and the occupants also plays a vital role in overall IEQ. ASHRAE Guideline 10-2016, *Interactions Affecting the Achievement of Acceptable Indoor Environments*, is devoted to the considerations important for designers as well as building operators (ASHRAE 2016). IEQ also depends on several additional factors—indoor water quality, ergonomics, aesthetics, and safety. Some of these factors are subjective, while others can be determined objectively.

To provide enhanced IEQ, the process must begin early in the design phase and be carried through to the operation and maintenance of the building. The most effective way to accomplish enhanced IEQ is to assemble key stakeholders from the design team at the beginning of the project and brainstorm siting, overall building configuration and zoning for intended building use, ventilation, thermal control, and illumination goals as a group. These goals should also be considered in conjunction with energy and water utilization, material selection, and aesthetics.

BENEFITS OF ENHANCED INDOOR ENVIRONMENTAL QUALITY

Providing enhanced IEQ directly impacts the health and wellness of the building occupants. Four categories of contaminants affect the quality of our indoor environments—inorganic, organic, biological, and combustion-generated contaminants. The most common contaminants from each of these categories are listed in Table 8-1 with their associated health effects. The severity of health effects from

Table 8-1: Indoor Environment Contaminants

Contaminant Category	Contaminant Descriptions	Health Effects
Inorganic	Asbestos	Asbestosis, pleural disease, lung cancer and mesothelioma
	Radon	Lung cancer
	Lead	Damages to brain, nervous, renal, reproductive, and cardiovascular systems
Organic (common sources: paint, finishes, cleaning products)	Formaldehyde	Neurotoxic effects, asthma, cancer,
	Volatile organic compound (VOC)	Allergy, asthma, respiratory symptoms
	Pesticides	Skin and respiratory irritations, cancer
Biological	Bacteria	Infectious disease, Legionnaire's disease
	Viruses	Cold, flu, infectious disease
	Mold	Mycotic diseases, mycotoxicosis
Combustion-generated contaminants (common sources: gas stoves, gas fireplaces, candles, and incense)	Carbon monoxide	Damages to central nervous system, cardiovascular morbidity
	Nitrogen oxides	Pulmonary symptoms, asthma

contaminant exposure is dose-dependent, which varies from person to person. *Indoor Environmental Quality* (Godish 2001) discusses these contaminant categories and illustrates their health impacts in detail.

In addition to mitigating acute and chronic health effects from contaminant exposure, enhanced IEQ has been linked to increased cognitive functions and productivity in several studies in the last two decades. Nationwide improvements in health and productivity were identified with improvements related to thermal comfort, lighting, and daylighting (Fisk 2002). *The Journal of Clinical Sleep Medicine* included research demonstrating the impacts of windows and daylight exposure on office workers' overall health and sleep quality. This research revealed that office workers in windowless environments reported poorer health and vitality scores and poorer sleep quality than their counterparts (Boubekri et al. 2014).

The Department of Environmental Health at Harvard University compared the health impacts of six green-certified buildings with enhanced IEQ (increased venti-

lation, controllability of lighting and thermal comfort, daylighting, and views) against four buildings with increased ventilation only. This study demonstrated that occupants in the green-certified buildings with enhanced IEQ had 26.4% higher cognitive test scores, 6.4% higher sleep quality scores, and 30% fewer sick building symptoms than occupants in buildings that were not green certified, where some or more of the following IEQ strategies were not implemented—controllability of thermal and visual comforts and daylighting and views (Macnaughton et al. 2017).

The US General Services Administration (GSA) measured the daytime alertness, energy, and vitality levels of participants working in three US Department of State buildings to validate that dynamic lighting systems tuned to circadian rhythm provided measurable health benefits; the measured results from this study showed that the participants felt higher levels of alertness during the workday, fell asleep faster at night, and woke up earlier the next day (GSA 2017). Finally, in 2020, the *International Journal of Indoor Environment and Health* published a study illustrating the stress effects of speech and noise while performing tasks requiring concentration. This study revealed that working in open-office environments with audible conversations caused more physiological stress (i.e., elevated heart variability and raised cortisol levels) than other sound conditions (Radun et al. 2020).

This chapter focuses on the primary factors of IEQ and details the strategies to enhance them. Since building operation is dynamic and indoor conditions are always changing, periodic IEQ occupant surveys should be conducted to evaluate the state of the indoor environment. Refer to the post-occupancy IEQ survey requirements listed in IgCC/189.1 for additional details (ICC 2021).

INDOOR AIR QUALITY

In the context of *ASHRAE GreenGuide*, indoor air quality (IAQ) refers to the quality of the air in buildings intended for nonindustrial use. Good IAQ is defined by the absence of contaminants at concentrations likely to be harmful and the absence of conditions that are likely to be associated with occupant health or comfort complaints. The major means for achieving enhanced IAQ are eliminating or reducing the sources of pollution in building materials and furnishings and from appliances, equipment, and consumer products. After vigorous efforts to eliminate pollutant sources, ventilation is applied to remove unavoidable pollutants, including the metabolic products from occupants and those from materials and furnishings used. Finally, if possible, measurements of indoor contaminant concentrations should be made and compared with design goals or available benchmarks to verify that enhanced IAQ is achieved as intended.

From Design to Completion: Meeting IAQ Objectives

During predesign, the commissioning authority (CxA) should help the owner articulate the key functional requirements for the project. For IAQ, this could include such things as ensuring that the building enclosure keeps out moisture that

may cause mold and moisture problems (e.g., by installing an air-vapor barrier), ensuring that outdoor air intakes are located to minimize the introduction of outdoor contaminants, and specifying low-emitting building materials during the design phase and ensuring they are actually installed. During predesign, the CxA should also review and provide input to the project schedule to ensure that the key steps required to achieve the owner's objectives are incorporated. For example, commissioning of the building enclosure may require that mock-ups be built and tested or that assemblies be inspected while they are still open and visible. Additional discussion on commissioning is found in Chapter 5 of this book.

Compressed scheduling, improper sequencing of work, poor construction management, and not specifying proper building materials can cause IAQ problems. For example, an unrealistic timeline or a bonus for early completion can create pressure to complete work while materials or equipment may still be exposed to moisture. Ductwork stored outdoors can accumulate dirt that facilitates future growth and circulation of microorganisms, even though high-efficiency filtration is used in the finished project. Operating HVAC equipment for temporary heating or cooling during construction or in occupied areas in a partially completed building can cause widespread system contamination and transfer of construction dust and volatile organic compounds (VOC) to the occupied area. The selection of carpet is not only a large source of VOC, but it is often harder to clean and maintain compared to hard surfaces such as tile.

As an example, the levels of VOC, SVOC (semi-volatile organic compounds), particulates, dust, and mold in two building sites under construction were measured by Gallon et al. (2020). At the office building site, formaldehyde was highest after the application of final painting and relatively high after delivery of the building even though the outdoor ventilation system was operational. Formaldehyde is a known carcinogen (EPA 1989). High concentrations of PM10 (particulate matter smaller than 10 μm in diameter) were also measured on-site due to the use of tobacco products. The earliest stages of construction were related to the highest increase in moisture content. While most tested VOC did not exceed existing guidelines on allowable concentrations upon delivery, there are currently no exposure limits on SVOC, even though some SVOC have been shown to be endocrine disruptors. Thus, proper cleaning, ventilation, and moisture management of construction sites should be maintained to protect those on the job site and those who will occupy the building when it is complete.

Limit Entry of Outdoor Contaminants

Because epidemiological studies linking ambient fine particles, ozone levels, and other contaminants with morbidity and premature mortality have generated increased concern, the entry of outdoor contaminants through the building enclosure and ventilation equipment should be limited.

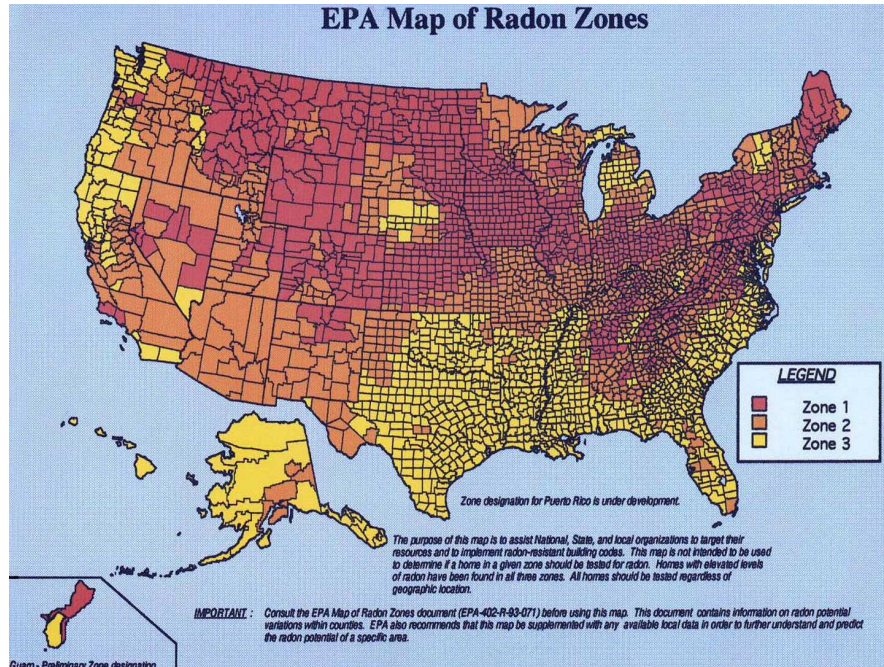
Provide Effective Track-Off System at Entryways. Tracked-in dirt contains contaminants that can result in health effects for the occupants, contains abrasives that contribute physical damage to floor finishes, and is reported to be the source of the majority of the dirt and dust that must be cleaned from buildings. The simplest and most effective way to reduce this impact is to design the landscape and entryways to prevent dirt entry. Suggestions for the design of entryways can be found in Strategy 3.5 of the *Indoor Air Quality Guide* (ASHRAE 2009) and IgCC/189.1 (ICC 2021).

Control Entry of Radon and Vapor Intrusion of Other Subsurface Contaminants. Radon is a radioactive gas formed from the decay of uranium in rock, soil, and groundwater. Radon exposure is the second leading cause of lung cancer in the US after cigarette smoking. Radon most commonly enters buildings in soil gas drawn through joints, cracks, penetrations, or porous regions of building foundations when the building is at a negative pressure relative to the ground. The potential for high radon levels varies regionally (Figure 8-1), seasonally, and with discrete weather events. Even within the same region, there can be variations from building to building.

Design for control of radon entry has three major elements: (1) active soil depressurization (ASD), (2) sealing radon entry routes, and (3) use of HVAC systems to maintain a positive pressure in ground-contact rooms (Figure 8-2). Details on these control strategies can be found in Strategy 3.3 of the *Indoor Air Quality Guide* (ASHRAE 2009).

Vapor intrusion is a concern because of chronic health effects caused by long-term exposure to low-level contaminants. Vapor intrusion of other organic vapors from subsurface soils or groundwater is also important to control because contaminants can travel in groundwater plumes for several miles (ASHRAE 2009) from accidental spills, improper disposal, leaking landfills, or leaking storage tanks (both below and above grade). ASTM developed a standard for assessing vapor intrusion on properties involved in real estate transactions (ASTM 2012a).

Air Barriers, Vapor Barriers, and Water Resistive Barriers. It is also important to have an effective, continuously sealed air barrier covering all six sides of the building envelope to address infiltration/exfiltration issues and avoid interstitial moisture accumulation in building materials, as well as on cold interior surfaces (Chapter 45 of ASHRAE 2021b, ICC 2021). There is often confusion among these terms because they are used interchangeably. As the Air Barrier Association of America (ABAA) states, air barriers reduce airflow through the building envelope (both into and out of a building), vapor barriers reduce the flow of water vapor, and water resistive barriers reduce the flow of liquid water (ABAA 2019). These barriers have the potential to reduce the chances of thermal comfort complaints, energy used to condition the building, the chances of condensation inside enclosure assemblies in both heating and air-conditioning mode, and chances of ice dam problems



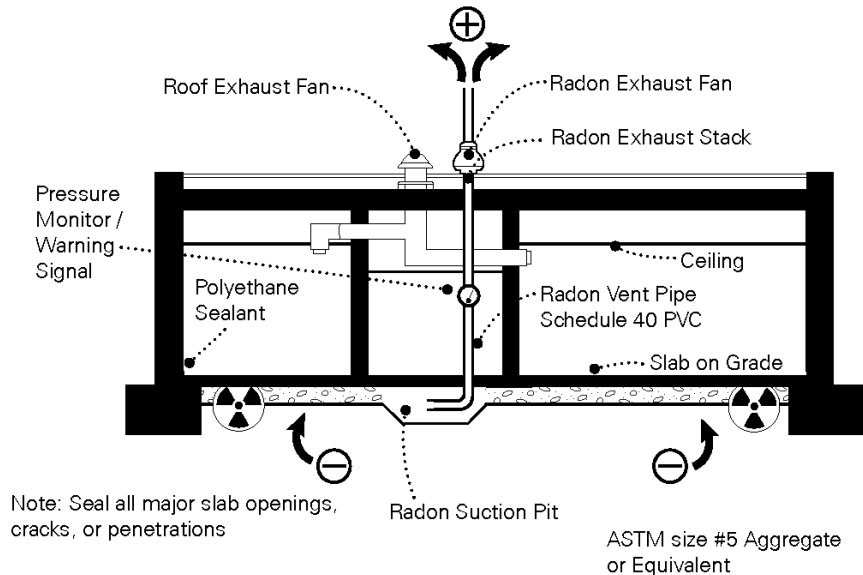
Source: EPA

Figure 8-1 EPA map of radon zones in the United States.

in snowy climates. With these benefits also come increased building material durability. These barriers are also effective against pest intrusion.

Airtight enclosures, specifically, benefit by making it easier to manage the building pressurization relative to the outdoors and between spaces and floors of multi-story buildings, allowing ventilation systems to perform more effectively. Keep in mind that the need for mechanical ventilation systems will increase as enclosures are made more airtight. Target airtightness levels developed by three building programs as follows:

- 0.40 CFM75/ft² (2.0 L/s·m² at 75 Pa) enclosure used by the Government Services Administration (GSA 2018) and the 2018 International Energy Conservation Code (ICC 2018), where CFM75 refers to the amount of air required to maintain an indoor-pressure difference of 75 Pa.
- 0.25 CFM75/ft² (1.27 L/s·m² at 75 Pa) enclosure used by the Army Corps of Engineers (USACE 2012)
- 0.60 CFM50/ft² or 0.80 CFM75/ft² ((3 L/s·m² at 75 Pa or 4 L/s·m² at 75 Pa) used by the Passive House Institute U.S. (PHIUS 2018)



Source: *Indoor Air Quality Guide* (ASHRAE 2009)

Figure 8-2 Schematic of an active soil depressurization scheme for control of radon entry into buildings.

For data on the measured airtightness of commercial buildings in the United States, refer to Emmerich and Persily (2014). ABAA describes commonly used air barrier assemblies and defines their properties in *Technical Note 4—Air Barrier Assemblies* (ABAA 2019). Vapor permeance is often expressed in units of $\text{ng}/\text{Pa}\cdot\text{s}\cdot\text{m}^2$ (or perms in the US). Water resistive barriers are tested for water penetration.

Oak Ridge National Laboratory (ORNL), in cooperation with the National Institute of Standards and Technology (NIST) and ABAA, developed an online calculator that estimates the savings based on the airtightening of seven commercial prototype buildings developed by the US Department of Energy. The tool estimates the savings in electricity and gas usage for HVAC systems, as well as estimates the amount of reduced moisture transfer due to reduced infiltration. Users select one of seven prototype buildings, a city from a list of 52 US cities (or one of five cities in Canada or China), enter a baseline and target airtightness, and enter electricity and gas prices in their area of interest. To access this tool, visit <https://airleakage-calc.ornl.gov/#/>.

In addition to vapor and water resistive barriers, other ways to limit moisture intrusion in buildings is through drainage and proper material selection. Sometimes

sumps and pumps are needed to drain subgrade foundations, but precautions should be in place so that they operate when needed even when no one is available to physically turn them on. Use flashing, overhangs, and drip edges to direct water away from vulnerable joints, intersections, and penetrations. Stone, concrete, brick, decay-resistant woods, paints and coatings, synthetic membranes and boards, glass, corrosion resistant metals, composite wood, and fiber- and cement-based materials have all been successfully used as exterior materials on buildings. These measures are primarily aimed at avoiding water damage and long-term wetting that may result in microbial growth. These measures should also help in avoiding thermal bridges. For more information, see Strategy 2.1 in the *Indoor Air Quality Guide* (ASHRAE 2009) and ASHRAE Position Document on Limiting Indoor Mold and Dampness in Buildings (ASHRAE 2021c).

There are potential advantages and disadvantages associated with plants as a component of the building envelope (e.g., green roofs or vertical gardens) or in other interior spaces (e.g., atrium gardens and living walls). However, the building architect and the landscape (garden) architect need to work together to ensure that the waterproofing membrane is installed with excellent craft and that penetrations through the membrane are avoided.

Limit Contaminants from Indoor Sources

Understanding the emission characteristics of various indoor sources is an important step in devising strategies to limit contaminant emissions. In this section, we first classify the typical indoor contaminant sources in terms of their emission behavior and discuss the major influencing factors and general control strategies. We then provide more specific guides for selecting low-emitting materials and methods for limiting the impact of the emissions. In addition, the following discussion is intended as an example rather than an extensive list, though the compounds listed are important in various IAQ guides or emission testing protocols. It should be emphasized that there is still more to learn in understanding indoor emissions, including secondary emissions and mixtures.

Passive Sources. These are the building materials, finishes, and furnishings that do not involve occupants and exist in buildings regardless of the activities of the building occupants or the operation of the ventilation system. Major contaminants of concern from these sources include VOC and SVOC. The emission rates are generally highest following installation or application and then decrease over time throughout a building's service life. The marketing of "low" or "no VOC" paint, finishes, and flooring in recent years can be misleading because there are no standardized lists of what VOC (and how much of them) make up any "low VOC" products.

Similarly, green labeling on products does not guarantee that they are "green" or "low VOC" because, again, there is no standard definition of these terms. At best,

these labeling programs can be used for relative comparison among the same type of materials or products. A manufacturer's materials safety data sheet (MSDS) may only be useful for initial screening. Only chemicals with more than 0.1% of the material mass are listed, and the requirements for listing are limited to hazardous chemicals identified by the US Occupational Safety and Health Administration (OSHA). Keep in mind that chemicals of IAQ concern often occur in much smaller mass amounts than those required to be reported.

Building materials also contain VOCs. Actual emission patterns strongly depend on the material and its position in a material assembly, the chemical compound of interest, and the environmental conditions (temperature, relative humidity, and surrounding air velocity and concentration level). For example, architectural coatings such as paint, wood stain, and varnishes that are applied wet can initially have emission rates that are several orders of magnitude higher than dry materials such as engineered wood products but then decrease quickly. After several weeks, the emission rate of the dry material may be an order of magnitude higher than the wet material. The emission rates of dry materials start at a relatively low level but can persist over a long period of time (months to years). The types of emitted compounds also vary dramatically among different material types (ASHRAE 2009). Oil-based wet coating materials, which use petroleum products as raw materials, emit a significantly higher number of VOC compared to water-based coating materials. These latter materials generally have fewer VOC and lower emission rates.

Selecting low-emitting materials/products in building design can result in the reduction of indoor contaminant concentrations by a factor of two or more (ASHRAE 2009). Standard test methods and guideline emission limits have been established for many building materials, furnishings, furniture, copiers and printers, and computers (e.g., California Department of Public Health, the Collaborative for High Performance Schools, GreenGuard, ASTM, Carpet and Rug Institute, and Business and Institutional Furniture Manufacturers Association). Emission test methods measure the emission rate per unit of materials or products tested (emission factors). Green-building rating programs such as Leadership in Energy and Environmental Design (LEED), Living Building Challenge (ILFI 2020), and WELL (IBWI 2020) have assigned credits for using materials and products that have measured emission factors less than the established limits to encourage the use of low-emitting materials and products.

To reduce the impact of passive sources, allowing a period for the emission rates to decline immediately following the production or installation of materials is an effective strategy. Ventilating the whole building with the highest practical outdoor air ventilation rate for a period of time before occupancy will also help reduce the occupants' exposure to the indoor source contaminants. The "bakeout procedure," i.e., airing the building at elevated temperature, is not recommended because of the potential of increasing emissions.

Active Sources. Examples of active sources include computers, office equipment, cleaning products, room air cleaners, and cooking. These can emit particles, especially ultrafine particulate matter (particles less than 0.1 μm in diameter), as well as VOC and SVOC. Since these sources are associated with occupant activities, their emission rates are highly dependent on the timing of their respective activities or operation. While the proper selection of materials or equipment can reduce emissions from these sources, using local exhaust or increased ventilation for these sources can limit the contamination. Also, consider the careful placement of these sources to minimize impacts on the occupants.

For example, 3-D printers are becoming more commonplace in offices, schools, and homes, but they are often not provided adequate ventilation to reduce the user's exposure to particles and VOC (Davis et al. 2019). Cleaning schools and commercial buildings are often done after hours when outdoor ventilation rates may be reduced because the building is "unoccupied." Room air cleaners can have negative impacts on the IAQ if they produce ozone. Large exhaust ventilation hoods in kitchens may be used properly to remove particulates from cooking. But if adequate makeup air is not provided, then depressurization of the kitchen and adjacent zones will lead to increased infiltration. This infiltrated air travels, unfiltered, through the building envelope, potentially bringing in outdoor contaminants and contaminants from the building envelope itself.

There are also active sources that are unique to certain building types. For instance, in homes, cooking and the use of personal care (perfumes, colognes, deodorant, haircare products) and cleaning products may generate additional contaminants. In grocery stores, bakeries are the predominant source of acetaldehyde and acrolein. Retail stores stock new merchandise regularly, which is a major source of formaldehyde (Chan et al. 2014).

Occupants. Contaminants from occupants are mainly bioeffluents (including exhaled breath, sweat, and shed skin cells) and depend on personal hygiene, health conditions, and the immediate environment they were in before entering the space or building of interest. The contaminants can include VOC, SVOC, and both viable and nonviable particles. There are also emissions from clothes, such as dry-cleaning chemicals and chemicals adsorbed from the air during previous exposure situations. Education and increased awareness of these contaminants may help building occupants be informed about the possible health effects of their personal care products and fragrances they use in their homes and bring into commercial/public spaces.

Secondary Sources. Ozone-initiated gas-phase and surface reactions, producing ultrafine particles, formaldehyde, and other aldehydes, are examples of a secondary source. The most effective approach to reducing secondary sources is to limit sources of ozone—both outdoor and indoors.

Environmental Tobacco Smoke (ETS) and Vaping. Emissions from smokers, even when they are not smoking (e.g., from their clothing), can still be significant.

A study at NIST found that emissions from nonsmoldering cigarette butts can still be a significant source of the same chemicals in mainstream smoke (Poppendieck et al. 2016). Thus, disposal containers for cigarette butts need to be located away from outdoor air intakes, and, preferably, the cigarette butts should be sealed so they cannot emit chemicals into the air.

Control High Indoor Humidity. When humid indoor air comes in contact with cold surfaces (exterior and interior), condensation can occur. Excessive moisture accumulation on sensitive building materials or furnishings can also lead to degradation of the material and health issues related to mold exposure (ASHRAE 2021a). That is why keeping the indoor dew point below the temperatures of cold surfaces is critical. Sources of indoor humidity can be outdoor air through the mechanical ventilation system (if not conditioned); leakage of outdoor air through the building envelope, windows, doors, and other openings; and occupant-related events such as cooking and showering. As previously discussed, controlling indoor humidity is another reason airtight building envelopes and localized exhaust are important for reducing indoor contaminants. When considering control options for avoiding excessive indoor humidity, it is also important not to overcool. Mechanically cooled commercial buildings must maintain a dew point of 60°F (15°C) during both occupied and unoccupied hours whenever the outdoor air dew point is above 60°F (15°C) (ASHRAE 2019a). However, the thermal comfort acceptability of tropically acclimatized subjects may be different than their temperate climate counterparts. Warmer and drier thermal environments or a cooler microenvironment (immediate breathing zone) coupled with warmer ambient conditions may be more acceptable. In hot, humid climates, relative humidity control is a priority without overcooling.

Control Low Indoor Humidity. Humidity control is less of an issue in cold climates where humidification is used. Though there are no existing standards for low humidity limits, there is some evidence that airborne pathogens may survive longer in low-humidity indoor environments, possibly increasing disease transmission (Derby et al. 2017). Thus, if the building occupants are part of an at-risk population group, humidification may need to be considered to preserve their health.

Pay Attention to Wetted Areas. For areas inside buildings that will be wet for extended periods of time (bathrooms, showers, spas, indoor pools, kitchens, entryways, custodial closets), use materials that can tolerate regular wetting without damage and that can dry quickly enough to avoid moisture-related problems. Specify mold-resistance testing criteria that are appropriate for materials (e.g., a score of 10 when tested using ASTM D3273, *Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber* [ASTM 2012b]).

Moisture and dirt in air handlers can lead to several problems. Moisture can build up at several locations within the air handlers, including at the outdoor air intake, in the condensate pans, and downstream from the air humidification unit. Moisture and dirt can facilitate microbial growth in the air-handling unit, in turn lead-

ing to the release of potentially irritating or disease-causing biological and chemical agents into the occupied spaces. ASHRAE/ACCA/ANSI Standard 180 (ASHRAE 2018b) identifies ten inspection/maintenance tasks relating to the control of dirt, microbial growth, and/or excess moisture in air handlers.

Mold growth can occur on cold water pipes or cold air supply ducts with inadequate thermal insulation or a failed vapor retarder and result in material damage, IAQ problems, and adverse health impacts on occupants. Implementing design strategies that limit condensation on cold-water piping and ducts and reduce the likelihood of piping leaks hidden in building infrastructure will lessen the likelihood of these potential problems.

Operation for IAQ

All building systems will in some way contribute to the contaminant emissions in a building over time, whether they are passive or active sources, particulate or gaseous, or moisture-related. Therefore, maintaining the proper operation of building systems is key to maintaining IAQ.

Identify Local Sources of Outdoor Pollution. While delivering outdoor air into buildings is effective at diluting indoor concentrations of pollutants, it is only effective if the outdoor concentrations are lower than they are indoors. For instance, the U. S. Environmental Protection Agency (EPA) sets National Ambient Air Quality Standards (NAAQS) for six criteria pollutants: carbon monoxide (CO), lead, nitrogen dioxide (NO₂), ozone (O₃), particulates PM_{2.5} (particles less than 2.5 µm in diameter) and PM₁₀, and sulfur dioxide (SO₂). The EPA designates areas in the US as attainment or nonattainment areas, depending on whether they are below or above the limits set in NAAQS, respectively. There are also areas designated unclassifiable based on the measurements in the area. Even if your building is in an attainment area, a survey of local contaminant sources (such as traffic or industrial and commercial operations) needs to be completed during the hours when the building will be normally occupied in accordance with the requirements in ASHRAE Standard 62.1 (ASHRAE 2022). All this information must be used to incorporate design elements (e.g., increased filtration, air cleaning) and/or operational changes (e.g., reducing outdoor air volume supply to the minimum amount when experiencing poor outdoor air quality) to mitigate the delivery of outdoor contaminants indoors that may adversely affect its occupants.

Locate Outdoor Air Intakes to Minimize Introduction of Contaminants. Whenever possible, outdoor air entry locations should be separated from known external pollutant sources such as loading docks, exhaust stacks from the building itself and others in its vicinity, and regions of heavy vehicular traffic. Industrial processes in the vicinity can also be important pollutant sources from which building air intakes should be shielded. Pollutant sources and prevailing wind conditions should be evaluated together. ASHRAE Standard 62.1 (2022) and Strategy 3.2 of

the *Indoor Air Quality Guide* (ASHRAE 2009) discuss minimum distances between outdoor air intakes and contamination sources.

Continuously Monitor and Control Outdoor Air Delivery. Accurate monitoring and control of outdoor air intake at the air handler is important for providing the correct amount of outdoor airflow to a building (not overventilating or underventilating). In particular, it has been common practice for designers to use fixed minimum outdoor air dampers. However, the approach does not necessarily provide good control of outdoor air intake rates, particularly in VAV systems (ASHRAE 2009).

Continuous monitoring of the outdoor air rates at the air handler does not guarantee that the proper amount of ventilation is delivered locally within the building. Poor air mixing both in the ductwork and in the occupied space, especially in larger and more complex air distribution systems, can result in parts of a building receiving less than the design minimum amount of ventilation.

Use Air Filtration/Cleaning to Remove Contaminants in Outdoor Supply Air. Typically, filtration of outdoor particles includes the use of media filters. Filters tested by ANSI/ASHRAE Standard 52.2-2020, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size* (ASHRAE 2020a) are assigned minimum efficiency reporting value (MERV) ratings. Filters need to be at least MERV 8 to have any effective removal efficiency on the smaller particles (PM₁₀), and filters with MERV 13 are much more effective at reducing PM_{2.5}. The breakdown of particle distribution by size, count, and weight in typical outdoor air systems is found in Figure 8-3, and the particle capture efficiencies are listed in Table 8-1 for the various filter ratings.

The high-efficiency particulate air (HEPA) filter is the best-known air filter. To qualify as a true HEPA filter, it must capture at least 99.9997% of all particles 0.3 μm or larger in diameter. Increased filter efficiency has been shown to increase the pressure drop through the filter and reduce airflow between 7% and 10% (Stephens et al. 2010). Ensure selected HVAC systems can handle higher-efficiency filters without negative impacts to pressure differentials and/or air flow rates. The overall effectiveness of reducing particle concentrations depends on several factors, including filter efficiency, airflow rate through the filter, particle sizes, and the location of the filter in the HVAC system. No matter the filter level, it is important to ensure that filter banks are sealed so that no air bypasses the filter. It is also important to regularly change the filters to preserve the operation of downstream air-handling components, maintain airflow rates, and minimize energy waste due to increased fan power when filters are clogged.

Gas-phase air cleaners reduce nitrogen dioxide in the air through adsorption and VOCs through processes like chemisorption filtration and photocatalytic oxidation. Some carbon/sorbent impregnated fibers can also remove particles and will have a MERV rating associated with them. The disadvantages of adsorption filters are that they become ineffective over time, requiring regular replacement, and the disad-

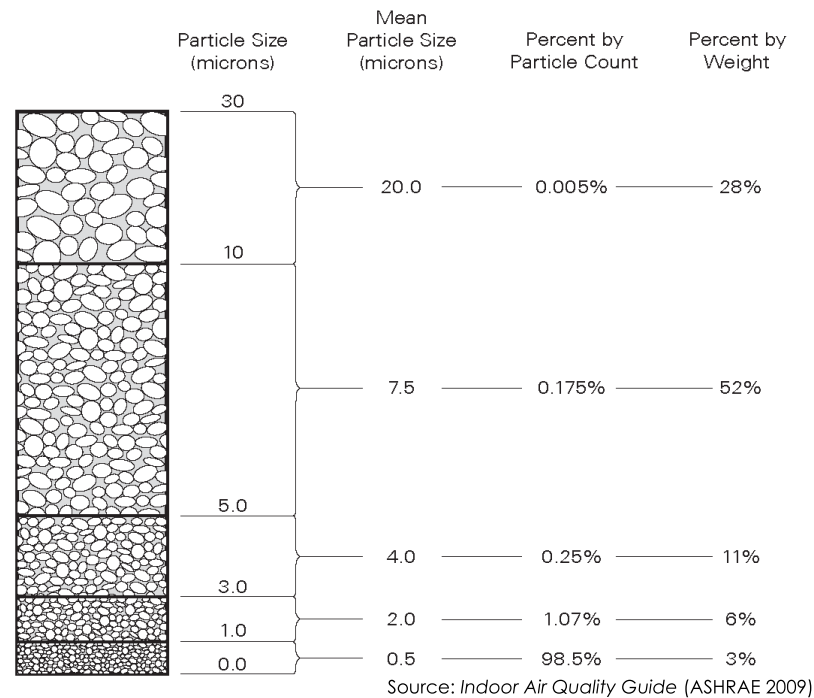


Figure 8-3 Particle distribution by size, count, and weight in typical outdoor air samples.

vantage of photocatalytic oxidation technology is that it produces ozone. Incorporating filtration and/or air-cleaning systems for particle and gas contaminant removal in any building requires investment in design, labor, equipment, and maintenance, and, as for all building systems, must be evaluated in economic terms. A few published studies have reported the cost/benefits of indoor air cleaning with regard to airborne particle removal (e.g., Fisk et al. 2011). These studies have reported insignificant filtration costs relative to salaries, rent, health insurance costs, loss of productivity, morbidity, and mortality.

Electrostatic precipitators use electrical charges to attract and deposit particles on their collection plates. Ion generators use corona discharge to generate ions with the intention of charging and clumping particles until they are settled to the ground or other room surfaces due to gravity, which has to be cleared away. A disadvantage of electrostatic precipitators and ion generators is that almost all of them create small amounts of ozone or ultrafine particles (Morrison et al. 2014).

Consider Ultraviolet Germicidal Irradiation. Ultraviolet germicidal irradiation (UVGI) has been used successfully to control airborne pathogens such as

Table 8-2: Comparison of MERV Level, Prior Rating, and Efficiency by Particle Size

MERV Level	Dust Spot %	Typical Particulate Filter Type	% 0.3–1 μm	% 1–3 μm	% 3–10 μm
1	N/A	Low-efficiency fiber glass and synthetic media, disposable panels, cleanable filters, and electrostatic charged media panels	Too low efficiency to be applicable to ASHRAE Standard 52.2 determination		
2	N/A				
3	N/A				
4	N/A				
5	N/A	Pleated filters, cartridge/cube filters, and disposable multidensity synthetic link panels			20–35
6*	N/A				36–50
7	25%–30%				50–70
8	30%–35%				>70
9	35%–40%	Enhanced media pleated filters, bag filters of either fiberglass or synthetic media, rigid box filters, using lofted or paper media		>50	>85
10	50%–55%			50–65	>85
11	60%–65%			65–85	>85
12	70%–75%			>80	>90
13	80%–85%	Bag filters, rigid box filters, minipleat cartridge filters	>75	>90	>90
14	90%–95%		75–85	>90	>90
15	>95%		85–95	<90	>90
16	98%		>95	>95	>95
The following classes are determined by a different methodology than that of ASHRAE Standard 52.2.					
N/A	N/A	HEPA/ULPA filters evaluated using IEST Recommended Practice CC001.3 (IEST 1993). Types A through D yield efficiencies at 0.3 mm and Type F at 0.1 mm	99.97% IEST Type A		
N/A	N/A		99.99% IEST Type C		
N/A	N/A		99.999% IEST Type D		
N/A	N/A		99.999% IEST Type F		

* MERV 6 is prescribed by ASHRAE Standard 62.1 for minimum protection of HVAC Systems.

Mycobacterium tuberculosis, the bacterium that causes tuberculosis. Commercially available lamps tend to be low-pressure mercury vapor, which emit UV primarily at 254 nm and damages the DNA of irradiated microorganisms, rendering them unable to reproduce.

In addition to inactivating airborne microorganisms, UVGI directed at environmental surfaces can damage microorganisms present or growing on the surface. Lower-intensity UVGI is effective for surface inactivation because irradiation is applied continuously. UVGI from lamps in air-handling unit (AHU) plenums has been used successfully to inactivate microorganisms present on airstream surfaces such as cooling coils and drain pans. Recent field studies, including ASHRAE RP-

1738 (Bahnfleth and Firrantello 2017), have identified the energy savings potential of UVGI when used to eliminate microorganism growth (biofouling) on cooling coils (Firrantello et al. 2016; Wang et al. 2016).

The designer must be aware that using UVGI lamps in AHUs and ductwork requires careful attention to safety considerations to prevent inadvertent exposure of people to UV light. For example, lockout/tagout procedures are necessary to prevent UVGI lamps from accidentally turning on when facility maintenance personnel are working in AHUs. Refer to Chapter 17 of the *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2020c) and Chapter 62 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2019) for a comprehensive review of other safety considerations. For more complete information, refer to *Indoor Air Quality Guide*, Section 4.5 (ASHRAE 2009).

Properly Vented and Unvented Combustion Equipment. The potentially dangerous pollutants that can be emitted into an indoor space from combustion equipment include carbon monoxide, nitrogen dioxide, particles, and sulfur dioxide. Therefore, the venting system be designed, installed, and maintained.

When natural- or induced-draft-vented combustion appliances are located within the building envelope and installed with venting systems that comply with manufacturer instructions, they will be able to operate in the presence of negative pressures. However, excessive negative pressures may cause backdrafting. This can best be avoided by providing makeup air that is interlocked with the exhaust or otherwise ensuring that extreme negative pressures are not created.

Unvented combustion appliances are designed such that the combustion byproducts are released into the occupied space. One study showed that unvented gas stoves can be primary sources of indoor air pollution, including particulate matter, ultrafine particles, nitrogen oxides, carbon monoxide, and formaldehyde if spaces are not properly ventilated (Seals and Krasner 2020). It is important to follow the manufacturer's installation instructions, which will include information on acceptable room size and provision of adequate ventilation air. Unvented combustion appliances need regularly scheduled maintenance to ensure that emission rates for contaminants remain within allowable tolerances.

Provide Local Capture and Exhaust for Point Sources of Contaminants. It is much more efficient to capture contaminants at the source and directly exhaust them outdoors than it is to allow them to be released into the space and then remove them with dilution ventilation. It is important to ensure that pollutants that have been captured and transported through an exhaust system do not leak back into occupied space or air distribution systems. Exhaust systems should be at a negative pressure relative to surrounding space such that any leaks in the system result in airflow into the exhaust. Alternately, ASHRAE Standard 62.1 requires exhaust systems not negatively pressurized relative to their surroundings to be sealed in accordance with Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) Seal Class A. Local exhaust should be provided for copy rooms, kitchenettes, and janitor's closets.

HVAC System Selection for Optimizing IAQ and the Energy Impacts of Ventilation

HVAC systems provide thermal comfort (e.g., temperature and humidity controls) and maintain IAQ (e.g., reduce the entrance of outdoor contaminants and dilute indoor contaminants). Thus, these systems should be selected as decisions are being made on the use of each space. Some buildings are totally mechanically ventilated, while others are naturally ventilated. Some buildings have hybrid mechanical-natural ventilation systems. Some types of HVAC systems are less able, or even unable, to maintain positive pressurization.

Similarly, HVAC systems vary in their ability to control indoor humidity levels, their flexibility in the location of outdoor air intakes, their ability to provide higher efficiency particle filtration, the time and effort required to perform IAQ-related maintenance, and other factors. HVAC systems also differ in how much energy they consume to deliver the minimum ventilation set by building codes and standards. Commonly installed HVAC systems that can also save energy include dedicated outdoor air systems (DOAS), energy recovering ventilation, and demand-controlled ventilation (DCV) systems. For more details, see Strategy 1.3 and Strategy 8 in the *Indoor Air Quality Guide* (ASHRAE 2009). Two other types of HVAC systems, natural and personalized ventilation, are not as common but are becoming more widely used, so they will be described below.

Naturally ventilated buildings, more commonly used in Europe and other locations with moderate climates, take advantage of and adapt to dynamic ambient conditions to provide outdoor ventilation. Buildings in temperate climate zones can take advantage of natural ventilation strategies for a significant portion of the year. When considering the use of natural ventilation, the prevailing climate (the ambient air temperatures, humidity, cleanliness of the outdoor air, and wind airflow patterns) must be considered. Tools such as the NIST Climate Suitability Tool, developed by and available for free from NIST, can estimate the number of hours per year a building may be able to take advantage of natural ventilation based on a handful of building inputs (internal heat gain, ventilation rate required, and heating/cooling set points).

ASHRAE Standard 62.1-2022 requires that spaces using the natural ventilation procedure also be provided with a mechanical ventilation system for use when natural ventilation is not adequate or appropriate. Sophisticated systems using pressure sensors and motor-driven dampers can be used to control pressures in various parts of buildings and take advantage of stack effect or wind pressure to deliver ventilation where and when needed. Nevertheless, the high potential return in energy performance and IAQ can often justify the extra effort. Strategy 8.4 in the *Indoor Air Quality Guide* (ASHRAE 2009) discusses other key design issues, such as ensuring a satisfactory acoustic environment, security of the building, and smoke control.

The personalized ventilation system (as provided in many automobiles and airplanes, for example) is fundamentally aimed at improving ventilation in the immediate breathing zones of occupants. Personalized ventilation systems can greatly improve ventilation effectiveness, leading to improved contaminant control, which then offers the possibility of reducing the quantity of outdoor air provided by a central ventilation system, as well as its delivered temperature (warmer temperatures in cooling months or cooler temperatures in heating months), both of which can lead to energy savings.

Effectively Distribute Ventilation Air to the Breathing Zone. Ventilation only works when the air is effectively distributed to the breathing zone. Different methods of air distribution have different efficiencies. The airflow rate that needs to be distributed to a zone varies by the effectiveness E_z of the distribution within the room. For an inefficient system, the quantity of outdoor air at the air handler needs to be increased to provide the minimum quantities in the breathing zone required by code and ASHRAE Standard 62.1 (ASHRAE 2022). Values of $E_z > 1.2$ are attributed to systems with superior distribution, such as low-velocity displacement ventilation (DV). Values of $E_z = 1.0$ are attributed to systems with effective distribution, such as mixing ventilation (MV) air distribution systems (ceiling supply of cool air and ceiling return, ceiling supply of warm air and floor return, and UFAD systems).

Maintain Proper Building Pressurization. Maintaining proper pressure relationships ensures that air flows in desirable directions. For instance, it is critical to ensure that air in a space with high contaminant levels does not escape into adjacent spaces that are expected or required to be cleaner. Facilities built for health care, laboratory, food service, swimming (natatoriums), and many industrial uses have spaces that require negative pressurization. Pressurization is also used to minimize the flow of warm, humid air through the building envelope toward cooler surfaces, which may result in condensation inside the envelope and microbial growth. ASHRAE Guideline 10-2016 (ASHRAE 2016) provides guidance on pressure relationships.

Pressurization is achieved by maintaining supply airflow higher than exhaust and return airflow in positively pressurized spaces and higher exhaust flows than supply flow in negatively pressurized spaces. Stack effects and wind pressures, however, must also be considered and overcome when determining system flow rates (Persily 2004). Thus, the effectiveness of a building pressurization strategy will be greatly enhanced by building an airtight enclosure, as discussed earlier in this chapter.

Consider Long-Term and Periodic IAQ Monitoring. While IAQ monitoring is not required by code and is often optional for green building certification programs, it can be a useful tool to identify both short-term and long-term issues. Short-term (or periodic monitoring) can be performed before and after construction or remodeling events to ensure that baseline performance is

returned upon completion of work. Long-term monitoring can help to identify drops in outdoor ventilation rates and/or increases in occupancy that may require re-evaluating outdoor ventilation rates. Refer to the ASHRAE *Performance Measurement Protocols for Commercial Buildings* for recommendations on IAQ measurements (ASHRAE 2010).

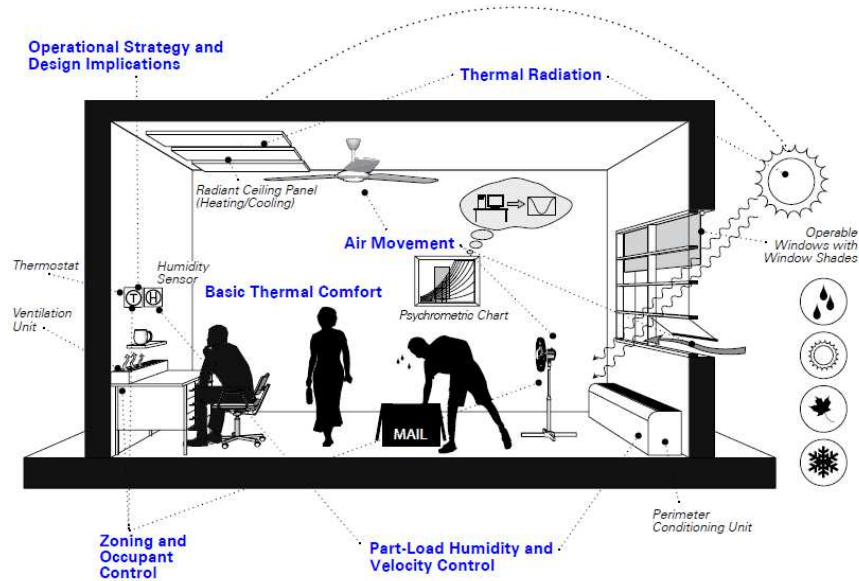
Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance. Access to the HVAC systems at critical locations such as after supply air silencers, junctions, duct interiors, and near duct ends should be made available for regular inspection, cleaning, and maintenance. Regardless of the access means used, the openings should be able to be closed airtight. There should be no obstruction or alteration to the airflows and no degradation to the thermal or functional integrity of the HVAC system.

Consider Re-Commissioning. With improvements, renovations, and change of occupancy in many commercial buildings, it may be beneficial to re-commission HVAC and water systems to meet current codes and standards. Doing this can also improve occupant health and thermal comfort, which has been shown to also improve productivity (Kaushik et al. 2020).

THERMAL COMFORT

Thermal comfort is a key metric of a building's overall IEQ and influences the health and productive performance of building occupants. ANSI/ASHRAE Standard 55-2020, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2020b) defines *thermal comfort* as *that condition of mind that expresses satisfaction with the thermal environment*. Six primary factors affect the conditions for thermal comfort of occupants. The environmental factors are dry-bulb air temperature, radiant temperature, air speed, and relative humidity. The personal factors are metabolic rate and thermal insulation of clothing (Figure 8-4). Recent research published in *Nature* observed that the quantity of daylight may affect occupant thermal comfort perceptions and, therefore, should be considered a factor for future thermal comfort analyses (Chinazzo et al. 2019). A joint study by the University of Southern California's School of Business and the WZB Berlin Social Science Center observed the effects of differences in temperature on gender (Chang and Kajackaite 2019). It was observed that women's work performance increased significantly with higher space temperature, while men's work performance decreased slightly with higher space temperature. The authors of this study noted that gender-mixed workplaces have the potential to increase productivity by increasing the thermostat set points.

Thermal comfort is often evaluated utilizing the predicted mean vote (PMV) and adaptive methods. The PMV model is used for mechanically conditioned spaces, while the adaptive method is used in naturally conditioned buildings with occupant controls. Both methods are documented in ASHRAE Standard 55-2020 (ASHRAE



Source: *Indoor Air Quality Guide* (ASHRAE 2009), based on a sketch by Larry Schoen

Figure 8-4 Thermal comfort is maintained by correctly understanding all the relationships in the figure and applying effective tools, as illustrated in Strategy 7.6 in *Indoor Air Quality Guide*.

2020). The Standard acknowledges that the sensation of thermal comfort experienced is specific to the individual and that it is difficult to satisfy all occupants. Therefore, the Standard specifies the combination of environmental conditions in relation to a given mix of metabolic rates and clothing ensembles that will satisfy most occupants within the space.

Strategies To Enhance Thermal Comfort

Listed below are some of the suggested strategies that can be considered to enhance thermal comfort:

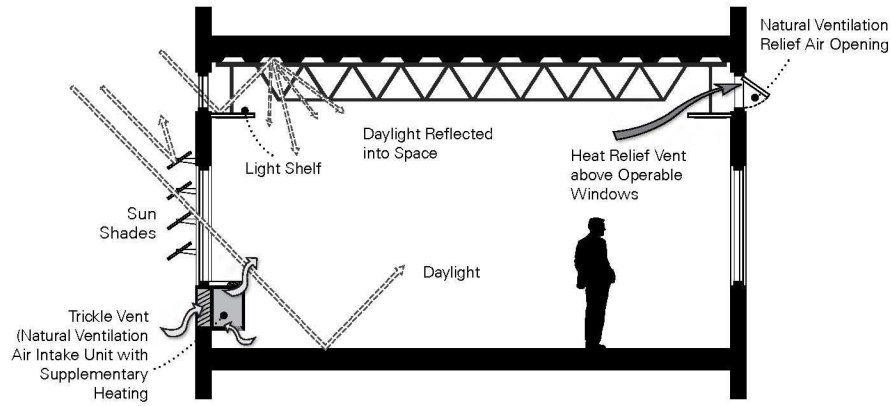
- Reduce external loads by ensuring the envelope is airtight with adequate levels of insulation, optimized solar gain (allow daylighting while minimizing undesirable heat gain and glare) and sufficient thermal mass to maintain indoor temperature setpoints throughout the interior space. These measures also reduce drafts and hot spots/cold spots which may cause discomfort.
- Ensure the occupied space is designed to meet ASHRAE Standard 55; use the Center for the Built Environment's (CBE) Thermal Comfort Tool.

- Conduct surveys to assess occupant satisfaction post occupancy and periodically. Adjust space temperature set points based on feedback from the occupants.
- For buildings located in cooling dominant climates:
 - Evaluate natural ventilation potential with operable windows by reviewing the local climate and air quality
 - Reduce direct solar gain onto occupants by providing exterior shading or internal blinds
 - Provide ceiling fans to extend the thermal comfort range
 - Consider using a radiant cooling system
 - Minimize drafts when utilizing traditional air-based systems
 - Consider the use of thermal mass
 - Provide local controls for occupants—i.e., operable windows, ceiling fan controls, and personal fans
- For buildings located in heating dominant climates:
 - Increase daylighting and passive solar heat gain
 - Provide local controls for occupants
 - Consider using radiant heating system
 - Consider providing additional humidification to space with proper controls to avoid condensation issues
 - Reduce stratification by providing heating at the occupied level

LIGHTING QUALITY AND VISUAL COMFORT

Enhanced lighting quality and visual comfort encompass a mixture of daylight exposure with supplemental electrical illumination, views of nature, and the absence of glare. Exposure to daylighting and views are imperative to occupants' physical health and psychological well-being (Figure 8-5). Maintaining proper light levels is essential for occupied spaces, and insufficient or inappropriate illumination can result in health and safety hazards as well as poor performance.

The quality of lighting design can be measured by the lighting metrics and non-visual outcomes associated with a certain lighting condition. Measurable lighting metrics are color rendering, saturation, spectral power distribution, flicker and glare (illumination source), light pattern, uniformity, controllability (the distribution of light), dimming, and daylighting. Refer to Figure 8-6 for the light spectrum. The nonvisual impacts of a certain lighting condition can range from eye strain to changes in productivity and behavior to circadian health impacts. The Illuminating Engineering Society (IES) is facilitating ongoing research on the impact of light exposure on human health and the value of quality lighting (IES 2016). There is strong evidence that individuals differ in their preferences for illumination levels (Despenic et al. 2017). The opportunity to choose one's own light levels creates a positive mood that carries over into other dimensions of well-being. There is some



Source: *Indoor Air Quality Guide* (ASHRAE 2009)

Figure 8-5 Daylight used in combination with shading and mixed-mode ventilation.

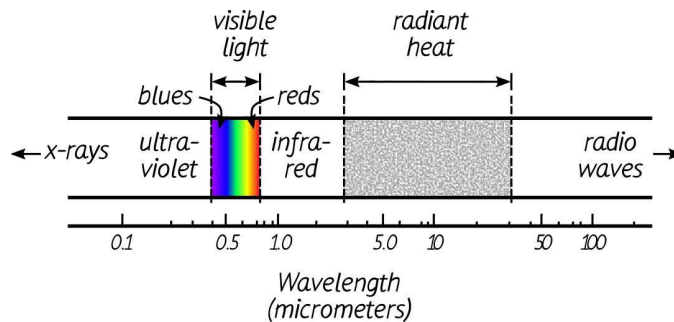


Image courtesy Lisa Ng, adapted from Dean (1981)

Figure 8-6 Light spectrum.

research interest in the possibility that individual control over the light source spectrum, which is possible with LED lighting, might add to these benefits.

IgCC/189.1 (particularly Section 8.3.5) provides more details on daylighting criteria, glare control, lighting controllability, and lighting color rendition; it also lists the critical spaces for exterior views and daylighting (ICC 2021). Additional discussion of lighting systems can be found in Chapter 11 of this book.

Strategies to Enhance Lighting Quality and Visual Comfort

Listed below are some of the suggested strategies that can be considered to enhance lighting quality and visual comfort:

- Balance between maximizing daylighting while minimizing glare for occupied spaces with optimized window or skylight orientations, light shelves, or baffles; pay attention to surface reflectance of furniture finishes and interior partitions.
- Increased shading of windows subject to direct insolation is important, as well as using more sophisticated light guides and interior shade to increase useful daylight while preventing both visual and thermal discomfort. Consider dynamic glazing.
- Supplement daylighting with electric LED lighting; provide effective daylighting and lighting controls.
- Electrical illumination should be accomplished with user-controlled task lighting wherever practical.
- Minimize glare.
- Lighting controls in buildings should be localized and allow variable light levels.
- Provide occupant controls to local lighting.
- Consider dynamic lighting systems tuned to circadian rhythm, especially important for healthcare facilities.
- Provide views of outside nature for occupied spaces.
- Consider skylights, solar tubes, or solar fiber optic lighting for spaces where daylighting is not feasible.
- Design of lighting and performance standards for lighting should be based on light delivered to actual task stations in buildings, not on the illumination of general spaces.

ACOUSTIC COMFORT

Acoustics involves far more than the control of noise emitted from mechanical equipment. Sound intensity, often characterized in decibels, can be too strong or too weak for building occupants to use buildings for their intended purpose successfully. Speech intelligibility requires sufficient volume without competing background noise, while concentration during activity or sleep and relaxation may require significantly quieter conditions. Individuals have different sensitivities to different noise frequencies, so control of the noise spectrum also matters. Acoustic comfort is the absence of noise and aural support that a space provides to let the occupants feel a “sense of place” in their acoustic environment. Some fundamental acoustic metrics for buildings are noise criteria (NC), room reverberation time, sound transmission class, noise isolation class, and impact insulation class.

ANSI/ASA S12.60, by the American Acoustical Society (ASA) is a good resource for acoustic fundamentals (ASA 2010). Other resources that provide

guidelines for mechanical equipment noise and vibration control include Chapter 8, “Sound and Vibration” of *ASHRAE Handbook—Fundamentals* (ASHRAE 2021b) and Chapter 49, “Noise and Vibration Control” of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2019c). IgCC/189.1 covers maximum interior background sound pressure (decibel levels), minimum sound ratings, maximum reverberation time, and maximum sound level at the property line (ICC 2021).

Poor acoustic conditions are cited as the top source of dissatisfaction in many postoccupancy evaluations of building occupants, particularly in green buildings. It is incumbent on architects and designers to consider the resulting acoustic quality during design to improve IEQ and occupant satisfaction.

Strategies To Enhance Acoustic Comfort

Listed below are some of the suggested strategies that can be considered to enhance acoustic comfort:

- During the programming phase of a project, optimize zoning; segregate quiet “library” type spaces away from interactive “bazaar” type spaces.
- Understand the source of sound, the path of travel, and the receiver to define acoustical performance targets.
- Prioritize the following strategies to address noise—absorb, block, and mask.
- Place acoustical absorption on allowable surfaces within spaces and/or consider using hanging acoustical elements such as “clouds,” “flags,” banners, and drapes. Also, explore acoustically absorptive materials that may be more environmentally friendly (i.e., made from recycled content and/or recyclable).
- Block unwanted noise by providing an effective sound “barrier.”
- Consider using a sound-masking system in low-background-noise conditions to improve speech privacy.
- For natural ventilation designs, place ventilation inlets on the building envelope so that they do not face external noise sources (e.g., traffic) and use louvered openings designed for acoustic attenuation purposes on the exterior and interior of the building.
- Avoid low sound transmission class (STC) glazing when trying to minimize undesirable sound transmission.
- Minimize HVAC noise by providing springs or pads.
- Consider meeting noise isolation class (NIC) ratings; NIC ratings are field tested to ensure the designed acoustical performance target is achieved through construction.

INDOOR WATER QUALITY

Legionella in Water Systems. Legionnaires’ disease, also called *Legionellosis*, is a bacterial disease commonly associated with water-based aerosols that have

originated from warm water sources. It is often associated with poorly maintained cooling towers and potable water systems, including from fountains and whirlpool spas. Legionnaires' disease can develop when a susceptible individual inhales or aspirates aerosolized water droplets containing *Legionella* bacteria. The Centers for Disease Control and Prevention (CDC) estimates that 5000 cases of Legionnaires' disease are reported in the United States annually, though many cases may go undiagnosed. Approximately 9% of cases are fatal, though the rate may approach 40% in health-care-acquired cases because of underlying health issues that exist in that population (Garrison et al. 2016).

Strategies To Minimize Legionellosis Risk

Preventive maintenance should be carried out to operate cooling towers and other evaporative equipment effectively. These maintenance activities include using effective drift eliminators, periodical cleaning, and employing a water treatment program with a proper biocide. Many experts recommend regular monitoring of *Legionella* levels in cooling-tower water. ANSI/ASHRAE Standard 188-2018, *Legionellosis: Risk Management for Building Water Systems* (ASHRAE 2018b) and Guideline 12-2020, *Minimizing the Risk of Legionellosis Associated with Building Water Systems* (ASHRAE 2020d) share knowledge about monitoring potential sources of *Legionella* as well as providing technical guidelines for investigation, control, and prevention of Legionnaires' disease. *Developing a Water Management Program to Reduce Legionella Growth and Spread in Buildings: A Practical Guide to Implementing Industry Standards* is a toolkit available from the Centers for Disease Control and Prevention (CDC) website and provides a checklist to help identify if a water management program is needed, where *Legionella* could grow and spread in a building, and ways to reduce risk of contamination. It is important to flush out the stagnant water from all plumbing water systems before reopening a building after an extended shutdown period.

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CHAPTER NINE

ENERGY USE CONVERSION AND DISTRIBUTION SYSTEMS

For there to be heating, cooling, lighting, and electric power throughout a building, the energy required by these functions is usually distributed from one or more central points.

This is usually accomplished through the flow of steam or a hydronic fluid, air, electrons (electricity), and sometimes a refrigerant. Air and hydronic flows in particular also serve the function of disposition of used air (exhaust) or liquid waste. Because the air and hydronic media being moved are often at different thermal levels (i.e., warm or cold), opportunities are offered to incorporate green design techniques. There are several practical techniques whereby energy from one flow stream can be transferred usefully to another.

Several GreenTips on energy recovery systems are included in this chapter.

ENERGY EXCHANGE

Cooling and Dehumidifying Media

Chilled Water (CHW). Circulating CHW is generally the least energy-efficient process for refrigerated air conditioning. However, in many cases it is the most cost effective, particularly for large buildings. The relatively low thermal efficiency results from it being a two-step process. The most common process uses a refrigerant circulated at a low temperature through an electrically powered recycling vapor compression system. The refrigerant then chills a secondary refrigerant (water) to the temperature needed for cooling or both cooling and dehumidifying the air supplied to the occupied zones. CHW can also be produced by a heat-driven absorption process that uses a mixture of water with lithium bromide or ammonia.

Some installations can benefit from energy reduction by using thermal storage using either CHW or ice, if further reduced in temperature and melted for later use.

The CHW is pumped through air-conditioning coils that may be in a central plant room, in several building zones, or in individual rooms. Further energy losses result from heat gained through insulation on the CHW piping.

Liquid Desiccant (LD). Circulating LD is a single-step process that uses heat (i.e., that from natural gas or from liquid petroleum gas [LP], solar, or waste heat sources) when available. LD generally does not need piping to be insulated.

Synthetic Refrigerant (SR). Circulating SR from an electrically powered recycling vapor-compression system can be directly used in air-conditioning coils that are in the same housing or plant room. Alternatively, the SR can be distributed to air-conditioning coils in several building zones or in individual rooms (rooms with variable refrigerant flow [VRF] systems).

Natural Refrigerant (NR). Ammonia, hydrocarbons, and CO₂ should also be considered.

Heating Media

Hot Water. Distributing hot water throughout the building is generally the most efficient heating energy distribution method. Hot-water heating systems are classified as low-, medium-, or high-temperature water:

- Low-temperature water systems operate at temperatures of 250°F (121°C) and below.
- Medium-temperature water systems operate at temperatures between 250°F and 350°F (121°C and 177°C).
- High-temperature water systems operate at temperatures above 350°F (177°C).

ENERGY DELIVERY METHODS

Media Movers (Fans/Pumps)

Chilled-Water Pumps. Historically, a design chilled-water temperature differential ΔT across air-handling unit cooling coils of 10°F (5.5°C) was used, which resulted in a flow rate of 2.4 gpm/ton (2.6 L/min per kW). In recent years, the 60% increase in required minimum chiller efficiency from a 3.8 coefficient of performance (ASHRAE 1975) to a 6.3 coefficient of performance (0.56 kW/ton) for large (>600 ton) water-cooled centrifugal chillers operating at full load (ASHRAE 2016) has led to a reexamination of the assumptions used in designing hydronic media flow paths and in selecting movers (pumps) with an eye to reducing energy consumption.

Taylor et al. (1999) came to the following conclusion:

...the trend for most applications is that higher chilled-water ΔT s result in lower energy costs, and they will always result in the same or lower first costs.

Simply stated, increase the temperature difference in the chilled-water system to reduce the chilled-water pump flow rate and increase chiller efficiency with warmer return water. This reduces installed cost and operating costs. The *CoolTools Chilled Water Plant Design and Performance Specification Guide* (Taylor et al. 1999) recommends starting with a chilled-water temperature difference of 12°F to 20°F (7°C to 11°C). It is important to understand that for the chiller plant to use a higher chilled-water ΔT , you must start at the load coils (i.e., the air-handling units).

Condenser Water Pumps. In the same manner, design for condenser water flow has traditionally been based on a 10°F (5.6°C) ΔT , which equates to 3 gpm/ton (3.2 L/min/kW). Today's chillers will give approximately a 9.4°F (5.2°C) ΔT with that flow rate. The CoolTools guide states, "Higher ΔT s will reduce first cost (because pipes, pumps, and cooling towers are smaller), but the net energy-cost impact may be higher or lower depending on the specific design of the chillers and tower" (Taylor et al. 1999).

The CoolTools document states in its summary that there are times you can "have your cake and eat it too." In most cases larger ΔT s and the associated lower flow rates will not only save installation cost but will usually save energy over the course of the year. This is especially true if a portion of the first cost savings is reinvested in more efficient chillers. (Taylor et al. 1999). The document further recommends a design method that starts with a condenser water temperature difference of 12°F to 18°F (7°C to 10°C).

Thus, reducing chilled- and condenser-water flow rates (conversely, increasing the ΔT s) can not only reduce operating cost but, more importantly, can free funds from being applied to the less-efficient infrastructure and allow them to be applied toward increasing overall efficiency elsewhere.

Variable-Flow Systems. The previous discussion suggests that variable-flow air and water systems are an excellent way to reduce system energy consumption. Variable flow (either air or water) is required by Standard 90.1 (ASHRAE 2016) for many applications, but it may be beneficial in even more applications than the standard requires. Today's most used technology for reducing flow is the variable-frequency drive.

HYDRONICS

Pumping heated water and chilled water is common system design practice in many buildings. Water is often diluted with an antifreeze fluid to avoid freezing in extremely cold conditions. There are many approaches in using these *hydronic* systems.

Optimizing Piping, Flow Rates, and Pumping

Flow rate can easily be reduced by one-half of the 20°F (11.1 K) value by using a 40°F (22.2 K) temperature difference. The impact on pump flow rate is signifi-

cant. The temperature difference selected depends upon the ability of the system to function with lower return water temperatures. Certain types of boilers can function with the low return water temperatures, while others cannot. Care must be taken in selecting the boiler type, coupled with supply and return water design temperatures. In specific instances, a low return water temperature could damage the boiler due to the condensation of combustion gases.

Lower flow rates could allow smaller pipe sizes, and pipe size, along with flow, affects pumping energy. A goal should be established for the pump power to be selected. A small increase in some or all of the pipe distribution sizes could reduce the pump energy needed for the system. When this goal is established and attained in the finished design, the concept and energy usage will be achieved. A reasonable goal can be expressed using the water transport factor equation adjusted to reflect kilowatts (multiply horsepower by 0.746). Measurements of efficient designs indicate a performance of 0.026 kW/ton (0.007 kW/kW_R [with kW_R being refrigeration cooling capacity]) being served as a reasonable goal for 10°F (5.6 K) ΔT systems. Adjusting the flow rate and ΔP variables in this formula will quickly show the benefits of larger pipes or lower flow rates (greater ΔT).

Table 9-1 shows us we can reduce pumping energy by 71% by lowering the TDH from 100 to 30 ft (300 to 90 kPa) and selecting a more efficient pump. One author of this guide has personally measured systems with the characteristics indicated above. If the average cost of electricity per kWh is \$0.08, and we are pumping for a 1000 ton (3517 kW_R) chiller, the annual operating cost difference would be more than \$37,000/yr.

If the system lasts 20 years, the improved system would save \$740,000 in electricity costs. Of course, the obvious question is: “How much does it cost to increase pipe and fitting size and pump efficiency?” The answer will vary by project, but keep in mind that efficient pumps cost no more than inefficient ones. Larger pipes and fittings cost more than smaller pipes and fittings and, in one author’s experience, the cost of increasing the pipe size one size (going from a 10 in. [250 mm] pipe to a 12 in. [300 mm] pipe) is recovered in electrical cost in less than 18 months.

Using the formula above and carefully measuring existing projects, we can establish performance goals for our designs such as the ones in Table 9-1.

The reader is cautioned that the percentage savings shown in Table 9-2 are individual savings from each component and should not be mistaken with the overall building energy performance, which is a more holistic number involving all components.

At times, reductions in pipe sizes to reduce first cost are suggested as value engineering. However, energy usage of the building may be greatly impacted: pump size and horsepower could well be increased. To be truly valid, value engineering should also include refiguring the life-cycle cost of owning and operating the build-

Table 9-1: Impact of Optimizing Pumping Systems

	Standard Design	Low-Energy Design
Condenser Flow, gpm (L/S) per 1 ton (kW _r)	3 (0.054)	3 (0.054)
Condenser Pump Head, ft (kPa)	100 (300)	30 (90)
Pump Efficiency	82%	85%
Motor Efficiency	92%	92%
Resulting Energy, kW, per 1 ton (kW _r) of cooling	0.075 (0.021)	0.022(0.006)

Table 9-2: Example Performance Goals

Components	Typical kW/ton (kW/kW _R)	Efficient kW/ton (kW/kW _R)	Improvement, kW/ton (kW/kW _R)	% Savings
Chiller	0.56 (0.159)	0.42 (0.119)	0.14 (0.04)	25
Cooling tower	0.045 (0.0128)	0.012 (0.0034)	0.033 (0.0094)	73
Condenser water pump	0.0589 (0.0167)	0.022 (0.0063)	0.0369 (0.0104)	63
Chilled-water pump	0.0765 (0.0218)	0.026 (0.0074)	0.0505 (0.0144)	66
Total waterside system	0.7404 (0.210)	0.48 (0.136)	0.2064 (0.0739)	35

ing. These factors can also be applied to chilled-water systems, except that chilled-water systems have a smaller range of temperatures within which to work.

System Volume

In small buildings, water system volume may relate closely to boiler or water-chiller operation. When pipe distribution systems are short and of small water volume, both boilers and water chillers may experience detrimental operating effects. Manufacturers of water chillers state that system water volume should be a minimum of 3 to 10 gal/installed ton of cooling (0.054 to 0.179 L/s·kW_R). In a system smaller than this and under light cooling load conditions, thermal inertia coupled

with the reaction time of chiller controls may cause the units to short-cycle or shut down on low-temperature safety control.

Similar detrimental effects may occur with small modular boilers in small systems. Under light load conditions, boilers may experience frequent short cycles of operation. An increase in system volume may eliminate this condition.

Antifreeze Additions

Fluid properties can greatly affect system performance. Antifreeze generally increases pressure drop and decreases heat transfer effectiveness. This leads to reduced system efficiency and perhaps increased cost because of the need for larger components. Therefore, the design professional should first examine the system to determine if antifreeze is an absolute necessity or whether water, with proper antifreeze safeguards, could be used.

If antifreeze is truly necessary, remember the following:

- Determine whether it is freeze or burst protection that is being sought. If an affected component (such as a chiller) does not need to be operated during freezing conditions, perhaps only burst protection is necessary. The amount of antifreeze needed can be greatly reduced, although slush may form in the pipes.
- Use only the minimum antifreeze necessary to provide protection; higher concentrations will simply reduce performance.
- Balance all environmental aspects of the antifreeze. Understand that while some antifreeze solutions are viewed as less toxic, they can significantly increase system installation and operating costs. Often, the greatest environmental cost of antifreeze is the increased energy consumption.
- Consult the manufacturer for more information on burst and freeze protection.

AIR

Using air as a means of energy distribution is almost universal in buildings, especially as a means of providing distributed cooling to spaces that need it. A key characteristic that makes air so widely used is its importance in maintaining good indoor air quality. Thus, air distribution systems are not only a means for energy distribution, they also serve the essential role of providing fresh or uncontaminated air to occupied spaces.

That said, it is important to understand that properly distributing air to heat and cool spaces in a building is less efficient from an energy usage perspective than using hydronic or steam distribution. Air distribution systems are often challenging to design because, for the energy carried per cross-sectional area, they take up the most space in a ceiling cavity and are frequent causes of space conflicts among disciplines (i.e., structural members, plumbing lines, heating/cooling pipes, light fixtures, etc.). Many approaches have been tried to better coordinate duct runs with other services, or even to integrate them in some cases.

Another challenging aspect of air system design is that there are temperature limitations on supply air (because air is the energy medium that directly contacts occupants). While care must always be taken in how air is introduced into an occupied space, it is especially critical the colder the supply temperature gets. Low-temperature air supply systems offer many advantages in terms of green design, but an especially critical design aspect is avoiding occupant discomfort at the supply air/occupant interface.

Most of the same principles that were discussed under hydronic energy distribution systems apply to air systems with respect to temperature differences, carrier size, and driver power and energy. Thus, there are plenty of opportunities for applying green design techniques to such systems and for seeking innovative solutions.

Optimizing Air Distribution

The *Advanced Variable Air Volume (VAV) Systems Design Guide* (CEC 2005) recommendations for duct design include the following:

- Run ducts as straight as possible to reduce pressure drop, noise, and first cost.
- Use standard length straight ducts and minimize both the number of transitions and joints.
- Use round spiral duct wherever it can fit within space constraints.
- Use radius elbows rather than square elbows with turning vanes whenever space allows.
- Use either conical or 45° taps at VAV box connections to medium pressure duct mains.
- Specify sheet metal inlets to VAV boxes; do not use flex duct.
- Avoid consecutive fittings because they can dramatically increase pressure drop.
- For VAV system supply air duct mains, use a starting friction rate of 0.25 in. to 0.30 in. per 100 feet (2 to 2.5 Pa/m). Gradually reduce the friction rate at each major juncture or transition down to a minimum friction rate of 0.10 in. to 0.15 in. per 100 feet (0.8 to 1.2 Pa/m) at the end of the duct system.
- For return air shaft sizing, maximum velocities should be in the 800 to 1200 fpm (4 to 6 m/s) range through the free area at the top of the shaft (highest airflow rate).
- To avoid system effect, fans should discharge into duct sections that remain straight for as long as possible, up to 10 duct diameters from the fan discharge to allow flow to fully develop.
- Use duct liner only as much as required for adequate sound attenuation. Avoid the use of sound traps.

In addition, the following are additional ways to reduce energy usage when designing air distribution systems:

- Require SMACNA's Seal Class A for all duct systems.
- Use VAV concepts for constant-volume systems.
- Use static pressure reset logic for all VAV applications.
- Minimize pressure drops of air-handling unit components and duct-mounted accessories (e.g., sound attenuators, dampers, diffusers, filter, energy wheels, etc.)

Sources of Further Information

Manufacturers of equipment—fans, ductwork, air-handling units, dampers, and other air devices—are valuable sources. There are also multiple websites that contain system design information. Air systems are also discussed in Chapters 20, “Space Air Diffusers” and 21, “Duct Design” of the 2021 *ASHRAE Handbook—Fundamentals* (ASHRAE 2021) and Chapters 19 through 28 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2020). Another informative source is the Sheet Metal and Air Conditioning Contractors National Association (SMACNA) (www.smacna.org).

Refer also to the *Advanced Variable Air Volume (VAV) System Design Guide* published by the California Energy Commission (CEC 2007) for a detailed discussion of variable-flow air systems.

ENERGY CONVERSION/GENERATION EQUIPMENT

Heat Generators

Considerable improvements in the seasonal efficiency of conventional heating plant equipment (e.g., boilers and furnaces) have been made over the last several decades. Designers should verify claims of equipment manufacturers by reviewing documented data of this equipment to prove the efficiency ratings are accurate.

There are two general types of boilers: fire-tube and water-tube. Boilers are classified as high-pressure or low-pressure and steam boiler or hot-water boiler. Boilers that operate higher than 15 psig (103 kPa) are called high-pressure boilers.

A hot-water boiler, strictly speaking, is not a boiler. It is a fuel-fired hot-water heater. Because of its similarities in many ways to a steam boiler, the term *hot-water boiler* is used.

Among steam, hot-water, water tube, and fire tube boilers, there are conventional atmospheric boilers and condensing boilers. Condensing boilers are far more efficient than conventional atmospheric boilers.

Cooling Generators

Chilled-water plants are most often used in medium to large facilities. Their benefits include higher efficiency, reduced maintenance costs, and redundant capacity (in comparison to decentralized plants).

Because chilled-water temperature can be closely controlled, chilled-water plants have an advantage over direct-expansion systems, because they allow air temperatures to be closely controlled.

Generally, a chilled-water plant consists of the following elements:

- Chillers
- Chilled-water pumps
- Condenser-water pumps (for water-cooled systems)
- Cooling towers (for water-cooled systems) or air-cooled condensers
- Associated piping, connections, and valves

Often, chilled-water plant equipment will be in a single, central location, allowing system control, maintenance, and problem diagnostics to be performed efficiently. Chilled-water plants also allow redundancy to be easily designed into the system by designing for firm capacity. Firm capacity is calculated with the largest piece of equipment not operating. With firm capacity, one piece of equipment can be maintained or repaired and the system still has the ability to meet peak loads.

Heat Pumps. A heat pump is another means of generating cooling as well as heating using the same piece of equipment. There is usually an array of them used for a project, and they are generally distributed throughout the building (i.e., they are not part of a central plant). Buildings that have consistent demands for both chilled and hot water, such as hospitals, are good candidates to use a larger heat pump as a central plant. (See the GreenTips at the end of this chapter on various heat pump system types.)

Thermal Energy Storage (TES). TES is a technique that has been encouraged by electricity pricing schedules where the off-peak rate is considerably lower than the on-peak rate. Cooling, in the form of chilled water or ice, is generated during off-peak hours and stored for use during on-peak hours. Although not refrigeration equipment per se, the technique can usually reduce the size of refrigeration equipment—or obviate the need for adding a chiller to an existing plant.

The characteristics, merits, and cost factors of TES for cooling, as well as numerous reference sources, are presented in GreenTip #9-12.

ENERGY CONVERSION/GENERATION PLANT DESIGN

When a designer puts together a chilled-water plant, there are many design parameters to optimize. They include fluid flow rates and temperatures, pumping options, plant configuration, and control methods. For each specific application, the design professional should understand the client's needs and desires and implement the chiller plant options that best satisfy them.

Between July 2011 and June 2012, *ASHRAE Journal* published a series of five articles describing a systematic approach to the design of chilled-water plants (Taylor 2011a, 2011b, 2011c, 2012a, and 2012b). This series of articles also summa-

rized the ASHRAE Self-Directed Learning (SDL) course Fundamentals of Design and Control of Central Chilled-Water Plants and the research that was performed to support its development.

“Chilled-water distribution system selection” (ASHRAE Journal, July 2011). This article discussed distribution system options, such as primary-secondary and primary-only pumping, and provided a simple application matrix to assist in selecting the best system for the most common applications (Taylor 2011a).

“Condenser water distribution system selection” (ASHRAE Journal, September 2011). This article discussed piping arrangements for chiller-condensers and cooling towers, including the use of variable-speed condenser water pumps and water-side economizers (Taylor 2011b).

“Pipe sizing and optimizing ΔT ” (ASHRAE Journal, December 2011). This article discussed how to size piping using life-cycle costs, then how to use pipe sizing to drive the selection of chilled-water and condenser water temperature differences (ΔT s) (Taylor 2011c).

“Chillers and cooling tower selection” (ASHRAE Journal, March 2012). This article addressed how to select chillers using performance bids and how to select cooling tower type, control devices, tower efficiency, and wet-bulb approach (Taylor 2012a).

“Optimized control sequences” (ASHRAE Journal, June 2012). This article included a discussion of how to optimally control chilled-water plants, focusing on all variable-speed plants (Taylor 2012b).

The intent of the SDL (and these articles) is to provide simple yet accurate advice to help designers and operators of chilled-water plants to optimize life-cycle costs without having to perform rigorous and expensive life-cycle cost analyses for every plant. In preparing the SDL, a significant amount of simulation, cost estimating, and life-cycle cost analysis was performed on the most common water-cooled plant configurations to determine how best to design and control them. The result is a set of improved design parameters and techniques that provide much higher-performing chilled-water plants than common rules-of-thumb and standard practices.

Plant Configuration (Multiple Chillers). The most prevalent chiller plant configuration is the primary-secondary (decoupled) system. This system allows the flow rate through each chiller to remain constant, yet accommodates a reduction in pumping energy, since the system water flow rate varies with the load.

Becoming more common are variable-primary-flow systems that also vary the flow through the chiller evaporators. New chiller controls allow this. Often these systems can be installed at a reduced cost when compared to primary-secondary systems since fewer pumps (and their attendant piping, connections, valves, fittings, and electrical draws) are required. These systems can also save energy in comparison to the primary-secondary configuration, due to more efficient chiller operation and reduced pumping energy.

The designer should always review the overall use of energy within a facility and employ systems (including heat recovery systems) that interact with one another so as to minimize the overall energy consumption of the entire chilled-water plant.

Cooling System Heat Sinks

Designers should pay attention when selecting unconventional heat rejection sources or sinks, as some may have indirect environmental impacts. For example, systems have been installed that use nearby deep water in a lake or ocean as a heat sink, which results in significant energy savings. This technique has been used in Scandinavian systems for approximately 20 years and more recently in colder regions in North America. However, this heat rejection technique, if not studied properly, may increase the water temperature in the source and may affect the aquatic wildlife. The possible net energy savings are impressive, but these must be balanced against potential adverse impacts on local aquatic environment.

Cooling Tower Systems

Cooling towers, which are generally the heat rejection equipment in a water-cooled system, are a very efficient method of heat rejection to air, especially in dry climates. Cooling towers remove heat by evaporation and can cool close to the ambient wet-bulb temperature (the difference between the leaving water and ambient wet-bulb being defined as the *approach temperature*). Unless the air is totally saturated (i.e., 100% relative humidity), the wet-bulb temperature is always lower than the dry-bulb. Thus, water cooling allows more efficient condenser operation than air cooling. In a typical cooling tower operation, about 1% of the recirculated water flow is evaporated. This evaporation will cool the remaining 99% of the water for reuse. In addition to evaporation, some recirculated water must be bled from the system to prevent soluble and semisoluble minerals from reaching too high a concentration. This bleed or blowdown is usually sent to a publicly owned treatment works (POTW). The HVAC designer should always consult with the plumbing engineer on the local regulations governing the discharge of cooling tower blowdown.

Refer to Chapter 12, Water Efficiency, for a more detailed discussion on the water treatment of cooling tower.

Types of Cooling Towers. With respect to drawing air through the tower, there are two types of cooling towers:

- **Natural Draft.** Uses buoyancy via a tall chimney. Warm, moist air naturally rises because of the density differential compared to the dry, cooler outdoor air. Warm, moist air is less dense than drier air at the same pressure. This moist air buoyancy produces an upwards current of air through the tower.
- **Mechanical Draft.** Uses power-driven fan motors to force or draw air through the tower. There are two types of mechanical draft towers:

- *Induced Draft.* A mechanical draft tower with a fan at the discharge (at the top) that pulls air up through the tower. The fan induces hot, moist air out of the discharge. This produces low entering and high exiting air velocities, reducing the possibility of recirculation in which discharged air flows back into the air intake.
- *Forced Draft.* A mechanical draft tower with a blower-type fan at the intake. The fan forces air into the tower, creating high entering and low exiting air velocities. The low exiting velocity is much more susceptible to recirculation. With the fan on the air intake, the fan is more susceptible to complications caused by freezing conditions. Another disadvantage is that a forced draft design typically requires more motor horsepower than an equivalent induced draft design. The benefit of the forced draft design is its ability to work with high static pressure. Such setups can be installed in confined spaces and even in some indoor situations.

With respect to water to air direction of flow, there are two types of cooling towers:

- **Crossflow.** Crossflow is a design in which the airflow is directed perpendicular to the water flow. Airflow enters one or more vertical faces of the cooling tower to meet the fill material. Water flows (perpendicular to the air) through the fill by gravity. The air continues through the fill and thus past the water flow into an open plenum volume. Lastly, a fan forces the air out into the atmosphere.

Advantages of the crossflow design include the following:

- Gravity water distribution allows smaller pumps and maintenance while in use.
- Nonpressurized spray simplifies variable flow.
- **Counterflow.** In a counterflow design, the airflow is directly opposite to the water flow. Airflow first enters an open area beneath the fill media, and is then drawn up vertically. The water is sprayed through pressurized nozzles near the top of the tower, and then flows downward through the fill, opposite to the airflow.

Advantages of the counterflow design include the following:

- Spray water distribution makes the tower more freeze resistant.
- Breakup of water in spray makes heat transfer more efficient.

Maintenance

An often overlooked method for minimizing environmental impact is maintenance. Cooling towers operate outdoors under changing conditions. Wind damage to inlet air louvers, excessive airborne contamination, clogging of water distribution nozzles, and mechanical problems can best be prevented and quickly corrected with periodic inspections and maintenance.

Variable-Speed Fans

The designer is encouraged to include variable-frequency drives (VFDs) on the cooling-tower fans. With the decreasing cost of these drives, their life-cycle cost is likely to be favorable. VFDs on fans can save energy by reducing the fan speed to better match the load, reduce the fan on/off cycling (thus reducing inrush currents), and can accomplish other tasks such as fan rotation reversal (beneficial in cold climates).

DISTRICT ENERGY SYSTEMS

District energy (DE) systems involve the provision of thermal energy (heating and/or cooling) from one or more central energy plants to multiple buildings or facilities via a network of interconnecting thermal piping. Generally, district heating systems deliver heat as steam or hot water, while district cooling systems deliver cooling as chilled water or chilled secondary coolant (such as an aqueous glycol or an aqueous sodium nitrite solution) or even as a refrigerant.

DE systems often deliver multiple significant positive impacts to the local building environments that they serve. These typical impacts include the areas outlined in the following sections.

The Potential for Increased Energy Efficiency with a DE System

Heating and/or cooling buildings using DE systems can affect overall energy consumption in various ways, from modest increases or decreases to very dramatic decreases in fuel and energy consumption. The energy consumed within the boundaries of DE-served buildings will, of course, be dramatically reduced compared to a baseline building with its own dedicated boilers and chillers. This energy reduction within the buildings will be offset by the energy consumed in the central DE plants and in distributing the thermal energy from the central plants to the customer buildings. If the central DE plant uses similar technology (e.g., gas boilers and electric chillers) as otherwise used in the individual buildings, there may be little or no net reduction in energy use. However, the larger (and generally more efficient) DE plant equipment more than offsets extra energy consumed in the distribution of the thermal energy to the buildings for at least a slight net reduction in overall energy consumption. Reductions in overall fuel and energy consumption are achieved through the ability of DE plants to more readily and more economically use alternative technologies than is the case for individual buildings. These technologies include, but are not limited to, dual-fuel boilers; alternative fuel boilers (including renewable fuels such as low-energy landfill gas, municipal solid waste, wood waste, etc.); high-efficiency boilers; high-efficiency chillers; alternative energy-efficient refrigerants (e.g., ammonia); nonelectric chiller plants (e.g., absorption chillers, engine-driven chillers, or turbine-driven chillers); hybrid chiller plants (with various combinations of electric

and nonelectric chillers); energy-efficient series or series-parallel chiller configurations for high ΔT systems; thermal energy storage (TES); cogeneration of combined heating and power (CHP); trigeneration or combined cooling, heating, and power (CCHP); and the use of natural renewable thermal energy (such as geothermal heat for district heating systems and cold deep water sources [e.g., lakes or oceans] for district cooling systems). In addition, DE plants are better able to meet the changing loads of the system.

Central energy plants associated with DE systems (compared to the alternative of dispersed, multiple, smaller boilers and chiller plants within individual buildings), generally have higher levels of operational efficiency and reliability. This is because larger DE plants can more easily justify sophisticated design, automated optimized control systems, more attentive maintenance programs, and more highly trained and focused operations and maintenance personnel. Central energy plants are also better able to match the system load with central equipment versus part load, especially at part load throughout a campus.

Emissions

As is the case with energy consumption, DE serves to eliminate many emissions from the local building environment, such as boiler exhausts and chiller plant heat rejection. Some emissions are of course relocated to the site of the central DE plant. However, just as DE plants tend to have higher levels of energy efficiency, they tend to have lower levels of emissions vs. those associated with individually heated and cooled buildings. And for DE systems utilizing one or more of the alternative technologies (as cited above), the overall emissions can be significantly reduced in terms of air pollutants (i.e., SO_x , NO_x , and precipitates) and greenhouse gases (i.e., CO_2 , NO_x , and some refrigerants).

Where DE Systems are Used

Routinely used on university campuses, DE systems are also often used for other institutional applications (including schools, hospital and medical facilities, airports, military installations, and other federal, state, and local government facilities), for privately owned multibuilding commercial/industrial facilities, and for thermal utilities serving urban business districts. DE systems serve as few as two buildings or as many as many hundreds of buildings. The ideal times to consider utilizing DE for serving the heating and/or cooling needs of a building are either during master planning and new construction or during expansion or renovation of buildings or their HVAC systems.

DISTRIBUTED ELECTRICITY GENERATION

One opportunity for energy conservation in buildings is the use of on-site generation systems to provide both distributed electric power and thermal energy (other-

wise wasted heat from the generation process), which can be used to meet the thermal loads of the building.

Distributed generation (DG) provides electricity directly to the building's electrical systems to offset loads that would otherwise have to be met by the utility grid. The waste heat from that generation process goes through a heat recovery mechanism where it may be provided as heat to meet loads for conventional heating (such as space heating, reheat, and domestic water heating) or for specialized processes. Alternatively, that heat energy, if at a sufficiently high temperature, can be used to power an absorption chiller to produce chilled water to meet either space- or process-cooling loads.

Any timing differences between the generation of the waste heat from the DG system and the thermal needs of the building can be handled by a chilled-water TES system. This concept may also allow downsizing the absorption cooling system (so it does not need to be sized for the peak cooling load).

The overall usable energy value from the fuel input to the generation process is only about 30% (or less) if there is no waste heat recovery, but it can be more than 70% if most or all the waste heat is able to be used. This increased system efficiency can have a radical impact on the economics of the energy systems, because almost two-and-one-half times the useful value is obtained from the fossil fuel purchased. System sizing is generally done by evaluating the relative electrical and thermal loads over the course of the typical operating cycle and then selecting the system capacity to meet the lesser of the thermal or electrical loads.

If the DG system is sized for the greater of the two, then there will be a net waste of energy produced, because it is seldom economical to sell electricity back to the grid. A key design issue that arises here is whether or not the system is being designed to improve efficiency, as discussed above, or as a baseload on-site generation system for purposes of improving the reliability of the electric and/or thermal energy supply. Either of these is a legitimate design criterion, although the goal, from a green design standpoint, almost always focuses on the energy-efficient strategy.

Distributed Generation Technologies

Technologies that can be used for this type of generation include engine-driven generators, microturbine-driven generators, or fuel cells. Typically, each uses natural gas as the input fuel. There are advantages and disadvantages associated with these technologies, which are summarized briefly in Table 9-3.

Engine-Driven Generator (EDG). This technology has been around the longest of the three and is in many ways the least-expensive option. It produces a relatively high temperature of waste heat that can be more effectively used by the heat recovery systems. Disadvantages, however, include air pollution, acoustical impacts, and noise/vibration from the engines. EDG sets are available in sizes ranging from approximately 40 kW to several thousand kilowatts.

Table 9-3: Comparison of Power Generation Options

Generation Option	Efficiency, %	Typical Size	Installed Costs, \$/kW	Operations and Maintenance Costs, \$/kWh
Engine driven natural gas cogeneration with heat recovery	70%–80%	100 kW–5 MW	\$3300–\$1600	\$0.007–\$0.02
Turbine-driven natural gas cogeneration with heat recovery	70%–80%	1 MW–10 MW	\$5000–\$3000	\$0.003–\$0.01
Fuel cell natural gas cogeneration with heat recovery	56%–80%	200 kW–1 MW	\$8000–\$5000	\$0.070–\$0.090
Wind turbine	N/A	5 kW–1 MW	\$8500–\$2500	\$0.001–\$0.007
Photovoltaic	8%–20%	1 kW–2 MW	\$4800–\$3500	\$0.003–\$0.005

Note the following:

Fuel cells vary greatly in cost by type of technology (e.g., phosphoric acid fuel cell [PAFC] at low end, solid oxide fuel cell [SOFC] at high end), size of application, and gas cleanup requirements (e.g., biogas treatment).

Installed and O&M cost information for PV and wind turbine:

<https://www.nrel.gov/analysis/tech-lcoe.html>.

Levelized cost of energy across multiple power options:

<http://en.openei.org/apps/TCDB/>.

Cogeneration information:

Crosby (2004)

Microturbine Generator. As of this writing, microturbine generators are somewhat more expensive in first cost than EDGs, but they have less air pollution and less severe acoustic and vibration impacts than EDGs. They also have longer operating lives and a projected lower cost.

Fuel Cells. Fuel cells are the most advanced form of power generation in terms of being a clean and green technology. They generate virtually no air pollution, have minimal acoustic and vibration impacts, and are considered the wave of the future. At

this point, however, the cost of fuel cell equipment is high, so it is the least attractive of these options from an economic standpoint. It is anticipated that this will change as continued development of the technology evolves over the next several years.

CCHP Systems

Combined heating and power is also referred to as *cogeneration*, and when combined with cooling they are called *trigeneration*. The larger, industrial-scale versions of such integrated energy systems have been in use through most of the 20th century. With the current focus shifting to distributed power generation for the reasons cited above, a new scale of CCHP has emerged, involving more integrated design of the components. These CCHP systems typically consist of one of the DG technologies described above (e.g., reciprocating engines or microturbines [possibly fuel cells, in the future] fired by natural gas, a heat exchanger to recover heat from the exhaust stream and/or jacket water, and, if there is a cooling demand, an absorption chiller). An intermediate medium such as hot water can be used to transfer heat between the exhaust stream of the prime-mover and the chiller, but lately a lot of development has gone into a dedicated heat recovery unit that also forms the generator of the absorption chiller (Rosfjord et al. 2004). Such integrated energy systems are admittedly in their infancy in the United States, but there is a significant drive by organizations including the U.S. Department of Energy (DOE) toward commercializing these systems as packaged systems.

To illustrate the benefits of the DG-based CCHP systems, the following elementary view of the energy efficiencies, both at the component and system level, is offered. A typical reciprocating gas-fired engine has a thermal efficiency of about 35%; 65% of the energy in the fuel is ordinarily not used and wasted through the stack. The exhaust temperatures leaving the engine ($>500^{\circ}\text{F}$ [$>260^{\circ}\text{C}$]) are typically high enough to drive, at the very least, a single-effect absorption chiller with a coefficient of performance (COP) in the vicinity of 0.7. Factoring in the actual amount of available heat in the exhaust stream (temperature/enthalpy and flow rate), this translates to overall fuel utilization rates/efficiencies that are as high as 80%. The ratio of electrical to thermal load carrying capability shifts a bit when the prime mover is a microturbine or a fuel cell, with typical generation efficiencies being 25% (based on higher heating value) and 40%, respectively. However, the overall fuel utilization rate is relatively unchanged. The waste heat can also be directly used for desiccant dehumidification (regeneration).

Thus, the integrated energy systems have achieved the following:

- Brought the power generation closer to the point of application/load (through distributed generation), eliminating transmission and distribution losses, etc.
- Removed or reduced the normal electric and primary fuel consumption by independent pieces of equipment providing cooling, heating, and/or dehumidification

(e.g., separate electric chiller and boiler), thereby substantially improving overall fuel utilization rates, inclusive of the power generation process

- Removed or reduced emissions of CO₂ and other combustion by-products associated with the operation of the cooling, heating, and/or dehumidification equipment

Challenges include the matching of electrical and thermal loads, given the diversity of energy usage patterns in buildings. The consultant/contractor can determine if the heating/cooling components of the CCHP system will play a primary or complementary role (the latter involving other, more conventional equipment to fill in the missing thermal load). Numerous studies were done in this regard, including one by Ryan (2003). Further resources are given in GreenTip #9-7.

ENERGY SAVINGS IN VERTICAL TRANSPORTATION (ELEVATORS/ESCALATORS)

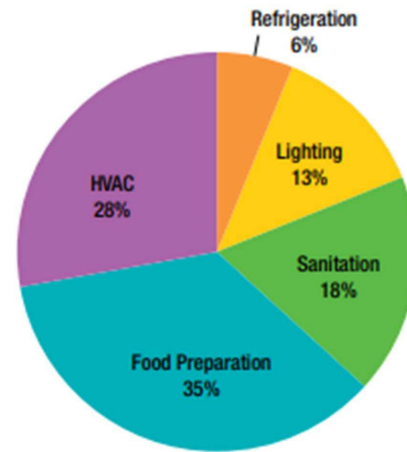
Historically, vertical transportation accounted for less 5% of the energy use in commercial building. However, with building systems becoming increasingly more efficient, this percentage has been increasing. This has prompted some potential for energy savings in elevators, which are centered on three areas:

- **Controls:** Controls need to be microprocessor-based with a software that incorporates algorithms to save energy (typically, around 5% savings relative to systems that operate without such algorithms). This software allows the elevator system to place cars where they are most needed—in the interest of smooth operation with minimal waiting times—and to shut down extra elevators when they are not needed. The algorithms used in such software are based on analyses of elevator usage patterns.
- **Motors:** The most common motor is an induction AC motor that requires a gearbox to reduce the motor speed and produce the required torque to start the elevator car moving. Inefficient (70% efficient) worm gears are typically used for this purpose. Advanced systems have permanent-magnet AC motors with no rotor windings. These systems are 1 to 3 percentage points more efficient than induction motors, and they do not require a gearbox, which further improves efficiency.
- **Lighting:** Elevators cars need to be specified with LED lights.

ENERGY SAVINGS IN COMMERCIAL KITCHENS

Commercial kitchens is one of the most energy and water intensive area in any building and present opportunities to save both energy and water in five areas:

- **Food Preparation:** All equipment used in food preparation need to be Energy Star rates including fryers, griddles, holding cabinets, ovens and steamers.



Source: U.S. EPA. (2010). *ENERGY STAR® Guide for Restaurants - Putting Energy into Profit*. (Figure reproduced)

Figure 9-1 Breakdown of energy cost by kitchen functional area.

Energy Star commercial kitchen appliances can save between 10% to 65% over conventional appliances depending on the type.

- **Ventilation and HVAC:** Consider the use of demand based kitchen exhaust systems that are exhaust systems that vary the exhaust airflow from the hoods based on the intensity of the cooking based on smoke and heat sensors. Also, consider the use of side panels on hoods to cut down spillage without the need to increase exhaust airflow.
- **Refrigeration:** Consider the use of Energy Star qualified commercial refrigerators and freezers which are more energy-efficient because they have components such as electronically commutated motors (ECMs), evaporator and condenser fan motors, hot gas antisweat heaters or high-efficiency compressors. Energy Star qualified commercial refrigerators and freezers can reduce energy costs by as much as 35%.
- **Sanitation:** Consider the use of Energy Star qualified dishwashers which use less energy and less water. When a dishwasher uses less water, energy is also saved by heating less water at the building and booster heater levels. More than 75% of dishwasher operating costs are for heating water with central and booster heaters. Energy Star qualified commercial dishwashers use approximately 25% less energy and water than standard models.
- **Lighting:** The typical commercial kitchen has lights on for 16 to 20 hours per day so consider the use of high efficiency LED lights.

Figure 9-1 shows the typical split of energy user for the above categories.

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ASHRAE GreenTip #9-1

Variable-Refrigerant-Flow (VRF) Systems

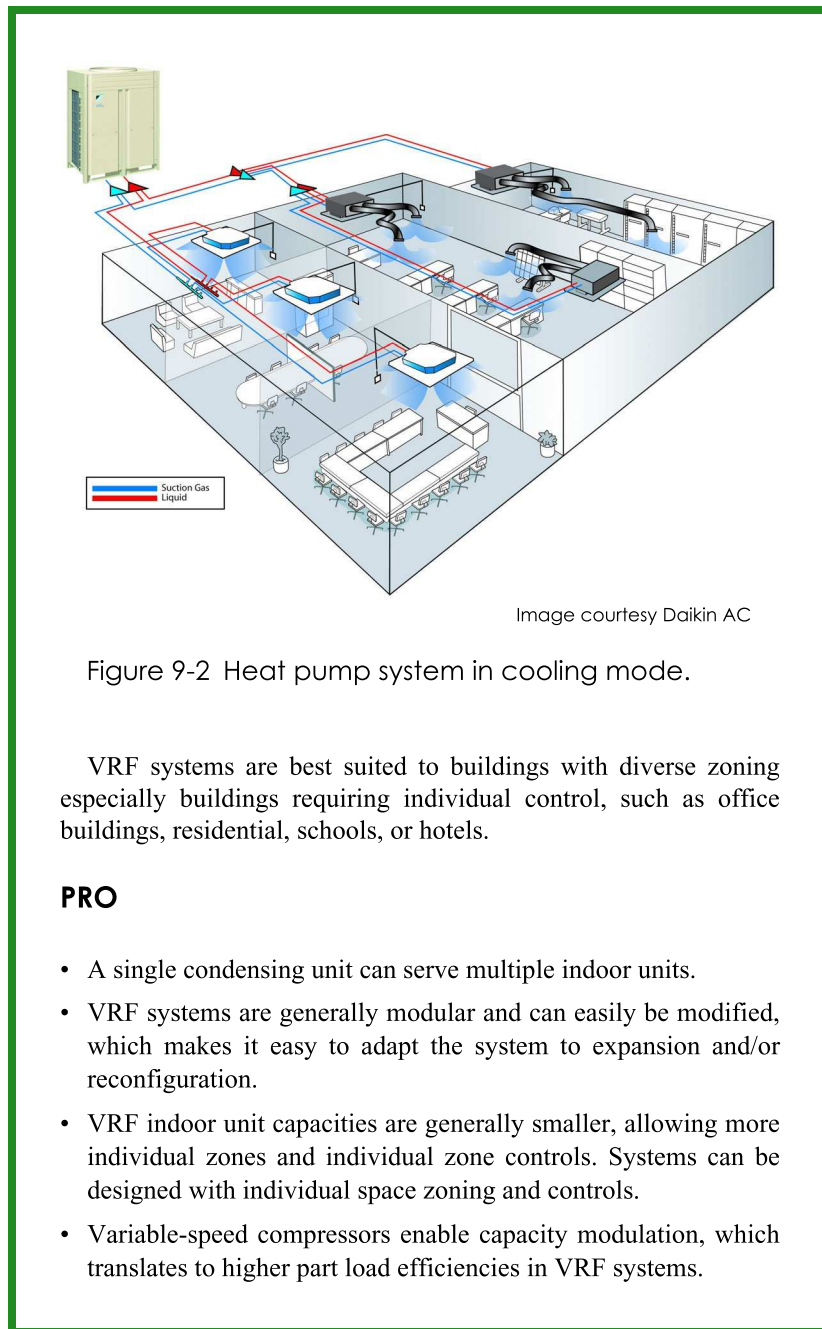
GENERAL DESCRIPTION

VRF systems have been used in Asia and Europe for almost 25 years. The main advantage of a VRF system is its ability to respond to fluctuations in space load conditions. By comparison, conventional direct expansion (DX) systems offer limited or no modulation in response to changes in the space load conditions. The problem worsens when conventional DX units are oversized, or during part-load operation (because the compressors cycle frequently). A simple VRF system is composed of an outdoor condensing unit and several indoor evaporators. The systems are interconnected by refrigerant piping with integrated oil and refrigerant management controls, which allow each individual thermostat to modulate its corresponding electronic expansion valve to maintain its space temperature set point.

There are two basic types of VRF multisplit systems: heat pump and heat recovery (Figure 9-2). Both heat pump and heat recovery VRF systems are available in air-to-air and water-source (water-to-refrigerant) configurations. Heat pumps can operate in heating or cooling mode. A heat recovery system, by managing the refrigerant through a gas flow device, can simultaneously heat and cool, with some indoor fan-coil units in heating and some in cooling, depending on the requirements of each building zone. The majority of VRF systems are equipped with variable-speed compressors. Often called *variable-frequency drives* or *inverter compressors*, this component responds to indoor temperature changes, varying the speed to operate only at the levels necessary to maintain a constant and comfortable indoor environment. Heat recovery systems increase VRF efficiency because, when operating in simultaneous heating and cooling, energy from one zone can be transferred to meet the needs of another.

WHEN/WHERE IT'S APPLICABLE

VRF systems offer controls that match the space heating/cooling loads to that of the indoor coil over a range of operation. Variable-speed compressors and fans in the outdoor units modulate their speed, saving energy at part-load conditions.



CON

- Indoor units in VRF systems generally do not have high latent capacities and are not suitable for applications requiring a high percentage of outdoor air.
- The external static pressure available for ducted indoor sections is limited. For ducted indoor sections, the permissible ductwork lengths and fittings must be kept to a minimum.
- There is the potential for refrigerant leaks in the building.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a VRF system from a conventional one and an indication of whether the net cost for the hybrid option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Conventional heat pumps/DX systems	H
• Ground-source heat pumps	L
• Refrigerant piping	L
• Installation costs	H
• Controls	S
• Design fees	H

Recurring Cost

• Overall energy cost	L
• Maintenance	L

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ASHRAE GreenTip #9-2

Displacement Ventilation

GENERAL DESCRIPTION

With a ceiling supply and return air system, the ventilation effectiveness may be compromised if sufficient mixing does not take place. While there are no data suggesting that cold air supplied at the ceiling will do so, it is possible that a fraction of the supply air may bypass directly to the return inlet (“short circuit”) without mixing at the occupied level when heating from the ceiling. For example, when heating with a typical overhead system with supply temperatures exceeding 15°F (8.3°C) above room temperature, ventilation effectiveness will approach 80% or less. In compliance with Table 6.2 of ASHRAE Standard 62.1-2022, zone air distribution effectiveness is only 0.8, so ventilation rates must be multiplied by 1/0.8 or 1.25. While proper system design and diffuser selection can alleviate this problem, another potential solution is displacement ventilation.

In displacement ventilation, conditioned air with a temperature slightly lower than the desired room temperature is supplied horizontally at low velocities at or near the floor. Returns are located at or near the ceiling. The supply air is spread over the floor and then rises by convection as it picks up the load in the room. Displacement ventilation does not depend on mixing. Instead, the stale, polluted air is literally displaced and forced up and out of the return or exhaust grille. Ventilation effectiveness may actually exceed 100%, and Table 6.2 of ASHRAE Standard 62.1-2022 indicates a zone air distribution effectiveness of 1.2 must be used.

Displacement ventilation is a fairly common practice in Europe, but its acceptance in North America has been slow, primarily because of the conventional placement of ductwork at the ceiling level and North America’s more extreme climatic conditions.

WHEN/WHERE IT’S APPLICABLE

Displacement ventilation is typically used in industrial plants and data centers, but it can be applied in almost any application where a conventional overhead forced-air distribution system could be used and the load permits.

Because the range of supply air temperatures and discharge velocities is limited to avoid discomfort to occupants, displacement ventilation has a limited ability to handle high heating or cooling loads if the space served is occupied. Some designs use chilled ceilings or heated floors to overcome this limitation. When chilled ceilings are used, it is critical that building relative humidity be controlled to avoid condensation. Another means of increasing cooling capacity is to recirculate some of the room air.

Some associate displacement ventilation solely with underfloor air distribution and the perceived higher costs associated with it. In fact, most underfloor pressurized plenum, air distribution systems do not produce true displacement ventilation but, rather, well-mixed airflow in the lower section of the conditioned space. It can, however, be a viable alternative when considering systems for modern office environments where data cabling and flexibility concerns may merit a raised floor.

PRO

- Displacement ventilation offers the potential for improved thermal comfort and IAQ because of increased ventilation effectiveness.
- There is reduced energy use because of extended economizer availability associated with higher supply temperatures.

CON

- It may add complexity to the supply air ducting.
- It is more difficult to address high heating or cooling loads.
- There are perceived higher costs.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a system using displacement ventilation from one that does not and an indication of whether the net cost is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for

a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Controls	S
• Equipment	S
• Distribution ductwork	S/H
• Design fees	S

Recurring Cost

• Energy cost	L
• Maintenance of system	S
• Training of building operators	S/H
• Orientation of building occupants	S/H
• Commissioning cost	S

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ASHRAE GreenTip #9-3

Dedicated Outdoor Air Systems (DOASs)

GENERAL DESCRIPTION

ASHRAE Standard 62.1 describes in detail the ventilation required to provide a healthy indoor environment as it pertains to IAQ. Traditionally, designers have attempted to address both thermal comfort and IAQ with a single mixed-air system. But ventilation becomes less efficient when the mixed-air system serves multiple spaces with differing ventilation needs. If the percentage of outdoor air is simply based on the critical space's need, then all other spaces are overventilated. In turn, providing a separate dedicated outdoor air system (DOAS) may be the only reliable way to meet the true intent of ASHRAE Standard 62.1.

A DOAS uses a separate air handler to condition outdoor ventilation air before delivering it directly to occupied spaces. The air delivered to the space from the DOAS should not adversely affect thermal comfort (i.e., too cold, too warm, too humid); therefore, many designers call for systems that deliver neutral air. However, there is a strong argument for supplying cool dry air and decoupling the latent conditioning as well as the IAQ components from the thermal comfort (sensible only) system.

The only absolute in a DOAS is that the ventilation air must be delivered directly to the space from a separate system. Control strategy, energy recovery, and leaving air conditions are all variables that can be defined by the designer.

WHEN/WHERE IT'S APPLICABLE

While a DOAS can be applied in any design, it is most beneficial in a facility with multiple spaces with differing ventilation needs. A DOAS can be combined with any thermal comfort conditioning system, including, but not limited to, all-air systems, fan-coil units, and hydronic radiant cooling. Note, however, that a design incorporating a separate 100% outdoor air unit delivering air to the mixed-air intakes of other units is not a DOAS as defined here. While this type of system may have benefits, such as using less energy or providing more accurate humidity control, it still suffers from the multiple space dilemma described above.

PRO

- A DOAS ensures compliance with ASHRAE 62.1 for proper multiple space ventilation and adequate IAQ.
- It reduces a building's energy use when compared to mixed-air systems that require overventilation of some spaces in order to ensure adequate ventilation.
- It allows the designer to decouple the latent load from the sensible load, hence providing more accurate space humidity control.
- It allows easy airflow measurement and balance and keeps ventilation loads off main HVAC units.

CON

- Depending on overall design (thermal comfort and IAQ), it may add additional first cost associated with providing parallel systems.
- Depending on overall design, it may require additional materials with their associated embodied energy costs.
- Depending on overall design, there may be more systems to maintain.
- With two airstreams, proper mixing may not occur when distributed to the occupied space.
- The total airflow of two airstreams may exceed airflow of a single system.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a building with a DOAS from one with another system and an indication of whether the net cost is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Controls H
- Equipment S/H
- Distribution ductwork S/H
- Design fees S/H

Recurring Cost

- Energy cost S/L
- Maintenance of system S/H
- Training of building operators S/H
- Orientation of building occupants S
- Commissioning cost S/H

SOURCES OF FURTHER INFORMATION

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ASHRAE GreenTip #9-4

Demand-Controlled Ventilation

GENERAL DESCRIPTION

A significant component of indoor environmental quality (IEQ) is the indoor air quality (IAQ). ASHRAE Standard 62.1 describes in detail the ventilation required to provide a healthy environment. However, providing ventilation based strictly on the peak occupancy using the ventilation rate procedure (Section 6.1) will result in overventilation during some periods. Any positive impact on IAQ brought on by overventilation could be outweighed by the costs associated with the energy required to condition the ventilation air. Demand-controlled ventilation can be done based on a number of different methods to determine the room occupancy, but by far the most common method is through the use of CO₂ measurement.

CO₂ can be used to measure or control the per-person ventilation rate in a given space and, in turn, allow the designer to introduce a ventilation demand control strategy. Simply put, the amount of CO₂ present in the air is an indicator of the number of people in the space relative to the ventilation being provided. In turn, this level can help determine if an adjustment in the amount of ventilation air that is being provided. CO₂-based ventilation control does not affect the peak design ventilation capacity required to serve the space as defined in the ventilation rate procedure, but it does allow the ventilation system to modulate in sync with the building's occupancy.

The key components of a CO₂ demand-based ventilation system are CO₂ sensors and a means by which to control the outdoor air intake (i.e., a damper with a modulating actuator). There are many types of sensors, and the technology is evolving while, at the same time, costs have dropped over the past decade or so. Sensors can be wall-mounted or mounted in the return duct, but it is recommended that the sensor be installed within the occupied space whenever possible.

WHEN/WHERE IT'S APPLICABLE

CO₂ demand control is best suited for buildings with a variable occupancy. The savings will be greatest in spaces that have a wide

variance, such as gymnasiums, large meeting rooms, and auditoriums. For buildings with a constant occupancy rate, such as an office building or school, a simple nighttime setback scenario may be more appropriate for ventilation demand control, but CO₂ monitoring may still be used for verification that high IAQ is achieved.

PRO

- CO₂ demand control reduces a building’s energy use as it relates to providing ventilation above that needed for adequate IAQ.
- It assists in maintaining adequate ventilation levels regardless of occupancy.

CON

- There is an added first cost associated with the sensors and additional controls.
- There are additional materials and their associated embodied energy costs.
- Evolving sensor technology may not be developed to full maturity.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a building using a CO₂ ventilation demand control strategy from one that does not and an indication of whether the net cost is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Controls	H
• Design fees	S/H

Recurring Cost

- Energy cost L
- Maintenance of system S/H
- Training of building operators S/H
- Orientation of building occupants S/H
- Commissioning cost S/H

SOURCES OF FURTHER INFORMATION

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ASHRAE GreenTip #9-5

Hybrid Ventilation

GENERAL DESCRIPTION

A hybrid ventilation system allows the controlled introduction of outdoor air ventilation into a building by both mechanical and passive means; it is sometimes called *mixed-mode ventilation*. It has built-in strategies to allow the mechanical and passive portions to work in conjunction with one another so as to not cause additional ventilation loads compared to what would occur using mechanical ventilation alone. It thus differs from a purely passive ventilation system, consisting of operable windows alone, which has no automatic way of controlling the amount of outdoor air load.

Two variants of hybrid ventilation are the changeover (or complementary) type and the concurrent (or zoned) type. With the former, spaces are ventilated either mechanically or passively, but not both simultaneously. With the latter variant, both methods provide ventilation simultaneously, though usually to zones discrete from one another.

Control of hybrid ventilation is obviously an important feature. With the changeover variant, controls could switch between mechanical and passive ventilation seasonally, diurnally, or based on a measured parameter. In the case of the concurrent variant, appropriate controls are needed to prevent “fighting” between the two ventilation methods.

WHEN/WHERE IT'S APPLICABLE

A hybrid ventilation system may be applicable in the following circumstances:

- When the owner and design team are willing to explore employing a nonconventional building ventilation technique that has the promise of reducing ongoing operating costs as well as providing a healthier, stimulating environment.
- When it is determined that the building occupants would accept the concept of using the outdoor environment to determine (at least, in part) the indoor environment, which may mean greater variation in conditions than with a strictly controlled environment.

- When the design team has the expertise and willingness—and the charge from the owner—to spend the extra effort to create the integrated design needed to make such a technique work successfully.
- Where extreme outside conditions or a specialized type of building use do not preclude the likelihood of the successful application of such a technique.

Buildings with atria are particularly good candidates.

PRO

- Hybrid ventilation is an innovative and potentially energy-efficient way to provide outdoor air ventilation to buildings and, in some conditions, to cool them, thus reducing energy otherwise required from conventional sources (power plant).
- Corollary to the above, it could lead to a lower building life-cycle cost as the operational costs are lower.
- It would generally be expected to create a healthier environment for building occupants.
- It offers a greater sense of occupant satisfaction because of the increased ability to exercise some control over the ventilation provided.
- There is more flexibility in the means of providing ventilation; the passive variant can act as backup to the mechanical system and vice versa.
- It could extend the life of the equipment involved in providing mechanical ventilation because it would be expected to run less.

CON

- Failure to integrate the mechanical aspects of a hybrid ventilation system with the architectural design could result in a poorly functioning system. Some architectural design aspects could be constrained in providing a hybrid ventilation system, such as building orientation, depth of occupied zones, or grouping of spaces.
- Additional first costs could be incurred because two systems are being provided where only a single one would be provided other-

wise, and controls for the passive system could be a major portion of the added cost.

- If automatic operable window openers are used, these could result in security breaches if appropriate safeguards and overrides are not provided.
- If integral building openings are used in lieu of, or in addition to, operable windows, pathways for the entrance of outside pollutants and noise or of unwanted insects, birds, and small animals would exist. If filters are used to prevent this, they could become clogged or could be an additional maintenance item to keep clear.
- Building operators may have to have special training to understand and learn how best to operate the system. Future turnovers in building ownership or operating personnel could negatively affect how successfully the system performs.
- Occupants would probably need at least some orientation so that they would understand and be tolerant of the differences in conditions that may prevail with such a system. Future occupants may not have the benefit of such orientation.
- Special attention would need to be given to certain safety issues, such as fire and smoke propagation in case of a fire.
- Although computer programs (such as computational fluid dynamics) exist to simulate, predict, and understand airflow within the building from passive ventilation systems, it would be difficult to predict conditions under all possible circumstances.
- Few codes and standards in the United States recognize and address the requirements for hybrid ventilation systems. This would likely result in local code enforcement authorities having increased discretion over what is acceptable.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a hybrid ventilation system from a conventional one and an indication of whether the net cost for the hybrid option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Mechanical ventilation system elements S
- Architectural design features H/L
- Operable window operators H
- Integral opening operators/dampers H
- Filters for additional openings H
- Controls for passive system/coordination with mechanical system H
- Design fees H

Recurring Cost

- Energy for mechanical portion of system L
- Maintenance of above L
- Energy used by controls, mechanical operators H
- Maintenance of passive system H
- Training of building operators H
- Orientation of building occupants H
- Commissioning cost H
- Occupant productivity H

SOURCE OF FURTHER INFORMATION

Kosik, W.J. 2001. Design strategies for hybrid ventilation. *ASHRAE Journal* 43(10).

ASHRAE GreenTip #9-6

Combined Heating and Power (CHP) Systems

GENERAL DESCRIPTION

Other abbreviations that have been used to describe CHP systems are CCHP (includes *cooling*) and BCHP (building cooling, heating, and power). The goal, regardless of the abbreviation, is to improve system efficiencies or source fuel utilization by availing of the low-grade heat that is a by-product of the power generation process for heating and/or cooling duty. Fuel utilization efficiencies as high as 80% were reported (Adamson 2002). The resulting savings in operating costs, relative to a conventional system, are then viewed against the first cost, and simple payback periods of less than four years have been anticipated (LeMar 2002). This is particularly important, from a marketing perspective, for both the distributed-generation and the thermal equipment provider. This is because, by themselves, a microturbine manufacturer and an absorption chiller manufacturer, for example, would find it difficult to compete with a utility and an electric chiller manufacturer, respectively, as the provider of low-cost power and cooling. Last, but by no means least, the higher fossil fuel utilization rates result in reduced emissions of CO₂, the greenhouse gas with a more than 55% contribution to global warming (Houghton et al. 1990).

Gas engines, microturbines, and fuel cells have been at the center of CHP activity as the need for reliable power and/or grid independence has recently become evident. These devices are also being promoted to reduce the need for additional central-station peaking power plants. As would be expected, however, they come at a first cost premium, which can range from \$1000 to \$4000/kW (Ellis and Gunes 2002). At the same time, operating (thermal) efficiencies have remained in the vicinity of those of the large, centralized power plants, even after the transmission and distribution losses are taken into account. This is particularly true of engines and microturbines (which have a 25% to 35% thermal efficiency), while fuel cells promise higher efficiencies (of ~50%), albeit at the higher cost premiums (\$3000 to \$4000/kW).

On the thermal side, standard gas-to-liquid or gas-to-gas heat exchanger equipment can be used for the heating component of the CHP system. This transfers the heat from the exhaust gases to the process/hydronic fluid or air, respectively. For the cooling component, the size ranges of distributed power generators offer a unique advantage, in terms of flexibility, in the selection of the chiller equipment. These can be smaller-end (relative to commercial), water-lithium bromide single- or double-effect absorption chillers or larger-end (relative to residential) single-effect or generator-absorber heat exchange ammonia-water absorption chillers (Erickson and Rane 1994). Such chillers have a typical coefficient of performance of 0.7, and, as a rule of thumb, for thermal-to-electrical load matching, for every 4 kW of power generated, 1 ton of cooling may be achieved (Patnaik 2004). Figure 9-3 shows typical operating conditions that an absorption chiller would see with a reciprocating engine.

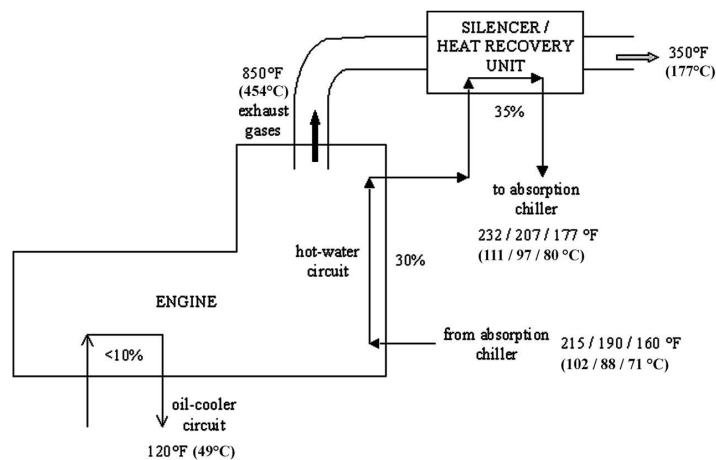


Image courtesy of Vikas Patnaik

Figure 9-3 Schematic of CHP system consisting of a gas-fired reciprocating engine showing typical operating temperatures (Patnaik 2004).

WHEN/WHERE IT'S APPLICABLE

CHP is particularly suited for applications involving distributed power generation. Buildings requiring their own power generation, either due to a stringent power reliability and/or quality requirement or remoteness of location, must also satisfy various thermal loads (i.e., space heating or cooling, water heating, dehumidification). A conventional fossil-fuel-fired boiler and/or electric chiller can be displaced, to some extent if not entirely, by a heat recovery device (e.g., standard heat exchanger) and/or an absorption chiller driven by the waste heat from the power generator. Since the source of heating and/or cooling is waste heat that would ordinarily have been rejected to the surroundings, the operating cost of meeting the thermal demand of the building is significantly mitigated if not eliminated.

Economic analyses suggest that CHP systems are ideally suited for base-loaded distributed power generation and steady thermal (heating and/or cooling) loading. This is also the desirable mode of operation for the absorption chiller. Peak loading is then met by utility power. Alternatively, if utility power is used for base-loading and the DG meets the peaking demand, the thermal availability may be intermittent and require frequent cycling of the primary thermal equipment (i.e., the boiler and/or chiller).

PRO

- One of the primary advantages of CHP systems is the reduction in centralized (utility) peak-load generating capacity. This is especially true because one of the biggest contributors to summer peak loads is the demand for air conditioning. If some of this air-conditioning demand can be met by chillers fired by essentially free energy (waste heat), there is a double benefit.
- Additionally, DG-based CHP systems enable the following:
 - They bring the power generation closer to the point of application/load (i.e., distributed generation), eliminating transmission and distribution losses, etc.
 - They remove or reduce the normal electric and primary fuel consumption by independent pieces of equipment providing cooling, heating, and/or dehumidification (e.g., a separate electric chiller and boiler), thereby substantially improving

overall fuel utilization rates, inclusive of the power generation process.

- They remove or reduce emissions of CO₂ and other combustion by-products associated with the operation of the cooling, heating, and/or dehumidification equipment.

CON

- If the CHP system is to replace a conventional boiler/electric chiller system, the ratio of electrical to thermal load of the building must closely match the relative performance (i.e., efficiencies) of the respective equipment.
- Start-up times for absorption chillers are relatively longer than those for vapor-compression chillers, particularly when coupled to microturbines, which themselves have large time constants. Such systems would require robust and sophisticated controls that take these transients into account.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a CHP system from a conventional one and an indication of whether the net cost for the alternative system is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Distributed power generator	H
• Heat recovery device/heat exchanger	L
• Absorption chiller	H
• Integrating control system	H

Recurring Cost

• Distributed power generator (engine/microturbine/fuel cell)	S/H/L

• Heat recovery device/heat exchanger	None
• Absorption chiller	None
• Integrating control system	H

SOURCES OF FURTHER INFORMATION

Technical sessions in recent meetings have been devoted to CHP, generally sponsored by technical committees on cogeneration systems (TC 1.10) and absorption/sorption heat pumps and refrigeration systems (TC 8.3). Presentations from these should be available on the ASHRAE Technology Portal (<https://technologyportal.ashrae.org/>).

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ASHRAE GreenTip #9-7

Combustion Air Preheating

GENERAL DESCRIPTION

For fuel-fired heating equipment, one of the most potent ways to improve efficiency and productivity is to preheat the combustion air going to the burners. The source of this heat energy is the exhaust gas stream, which leaves the process at elevated temperatures. A heat exchanger, placed in the exhaust stack or ductwork, can extract a large portion of the thermal energy in the flue gases and transfer it to the incoming combustion air.

With natural gas, it is estimated that for each 50°F (10°C) the combustion air is preheated, overall boiler efficiency increases by approximately 1%. This provides a high leverage boiler plant efficiency measure, because increasing boiler efficiency also decreases boiler fuel usage. And, since combustion airflow decreases along with fuel flow, there is a reduction in fan-power usage as well.

There are two types of air preheaters: recuperators and regenerators. Recuperators are gas-to-gas heat exchangers placed on the furnace stack. Internal tubes or plates transfer heat from the outgoing exhaust gas to the incoming combustion air while keeping the two streams from mixing. Regenerators include two or more separate heat storage sections. Flue gases and combustion air take turns flowing through each regenerator, alternatively heating the storage medium and then withdrawing heat from it. For uninterrupted operation, at least two regenerators and their associated burners are required: one regenerator is needed to fire the furnace while the other is recharging.

WHEN/WHERE IT'S APPLICABLE

While theoretically any boiler can use combustion preheating, flue temperature is customarily used as a rough indication of when it will be cost-effective. However, boilers or processes with low flue temperatures but a high exhaust gas flow may still be good candidates and must be evaluated on a case-by-case basis. Financial justification is based on energy saved rather than on temperature differential. Some processes produce dirty or corrosive exhaust gases that can plug or attack a heat exchanger, so material selection is critical.

PRO

- Lowers energy costs.
- Increasing thermal efficiency lowers CO₂ emissions.

CON

- Additional material and equipment costs.
- Corrosion and condensation can add to maintenance costs.
- Low specific heat of air results in relatively low U-factors and less economical heat exchangers.
- Increasing combustion temperature also increases NO_x emissions.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a building with a combustion preheat system from one without and an indication of whether the net cost is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Equipment costs	H
• Controls	S
• Design fees	H

Recurring Cost

• Overall energy cost	L
• Maintenance of system	H
• Training of building operators	H

SOURCES OF FURTHER INFORMATION

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ASHRAE GreenTip #9-8

Combination Space/Water Heaters

GENERAL DESCRIPTION

Combination space and water heating systems consist of a storage water heater, a heat delivery system (e.g., a fan coil or hydronic baseboards), and associated pumps and controls. Typically gas-fired, they provide both space and domestic water heating. The water heater is installed and operated as a conventional water heater. When there is a demand for domestic hot water, cold city water enters the bottom of the tank, and hot water from the top of the tank is delivered to the load. When there is a demand for space heating, a pump circulates water from the top of the tank through fan coils or hydronic baseboards.

The storage tank is maintained at the desired temperature for domestic hot water (e.g., 140°F [60°C]). Because this temperature is cooler than conventional hydronic systems, the space heating delivery system needs to be slightly larger than typical. Alternatively, the storage tank can be operated at a higher water temperature; this requires tempering valves to prevent scalding at the taps.

The water heater can be either a conventional storage-type water heater (either naturally venting or power vented) or a recuperative (condensing) gas boiler. Conventional water heaters have an efficiency of approximately 60%. By adding the space heating load, the energy factor increases because of longer runtimes and reduced standby losses on a percentage basis. Recuperative boilers can have efficiencies approaching 90%.

WHEN/WHERE IT'S APPLICABLE

These units are best suited to buildings that have similar space and water heating loads including dormitories, apartments, and condos. They are suited to all climate types.

PRO

- Reduces floor space requirements.
- Lowers capital cost.
- Improves energy efficiency.
- Increases tank life.

CON

- Only available in small sizes.
- All space heating piping has to be designed for potable water.
- No ferrous metals or lead-based solder can be used.
- All components must be able to withstand prevailing city water pressures.
- Some jurisdictions require a double-wall heat exchanger for such a scheme to be acceptable.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a combination space and water heating system from a conventional one and an indication of whether the net cost for the hybrid option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Conventional heating equipment	L
• Combination space/domestic water heater	H
• Sanitizing/inspecting space heating system	H
• Piping and components able to withstand higher pressures	H
• Floor space used	L

Recurring Cost

• Heating energy	L
• Maintenance	L

SOURCES OF FURTHER INFORMATION

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US Department of Energy, Energy Efficiency and Renewable
Energy
www.eere.energy.gov/.

ASHRAE GreenTip #9-9

Ground-Source Heat Pumps (GSHPs)

GENERAL DESCRIPTION

A GSHP extracts solar heat stored in the upper layers of the earth; the heat is then delivered to a building. Conversely, in the summer season, the heat pump rejects heat removed from the building into the ground rather than into the atmosphere or a body of water.

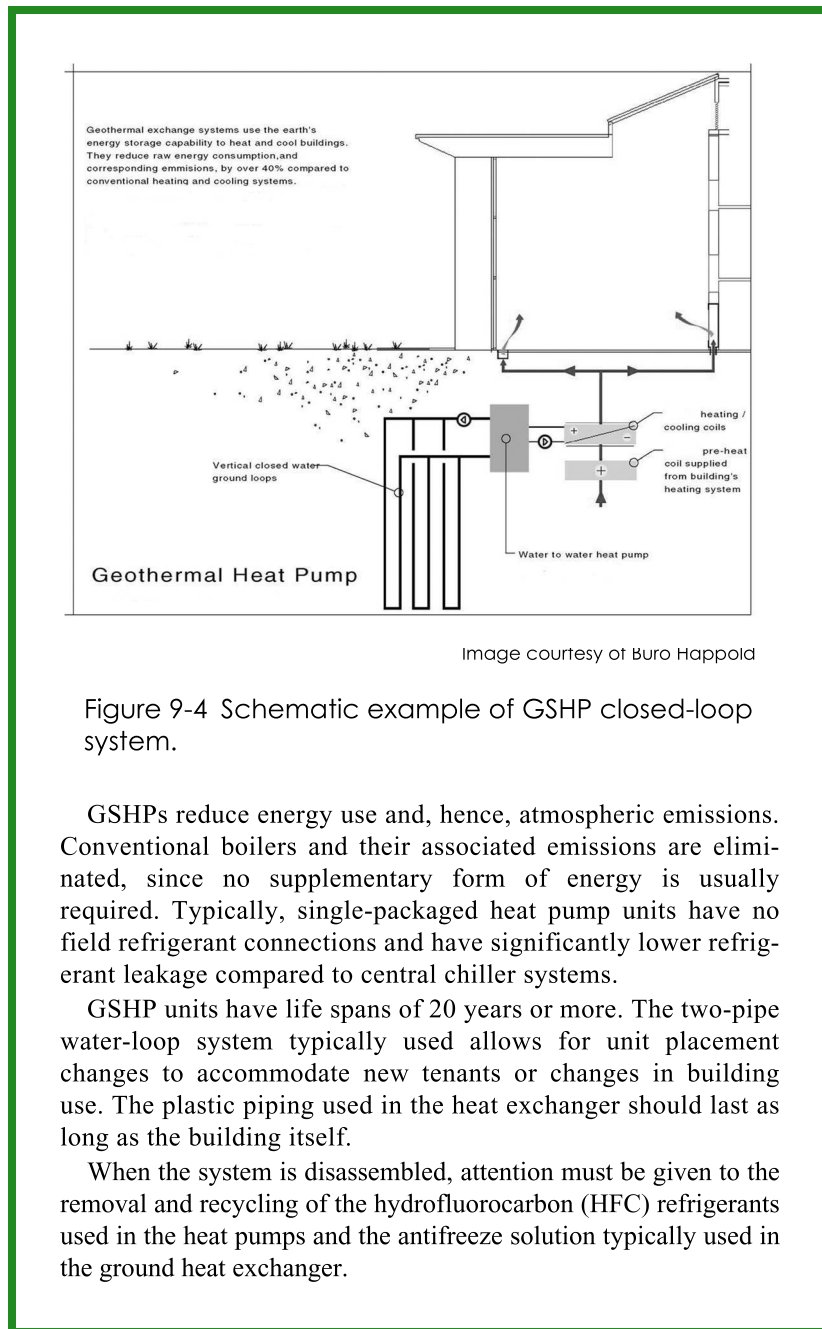
GSHPs can reduce the energy required for space heating, cooling, and service water heating in commercial/institutional buildings by as much as 50%. GSHPs replace the need for a boiler in winter by utilizing heat stored in the ground; this heat is upgraded by a vapor-compressor refrigeration cycle. In summer, heat from a building is rejected to the ground. This eliminates the need for a cooling tower or heat rejection device and also lowers operating costs, because the ground is cooler than the outdoor air. (See Figure 9-4 for an example of a GSHP system.)

There are numerous types of GSHP loop systems. Each has its advantages and disadvantages. Visit the Geoexchange Geothermal Heat Pump Consortium website (www.geoexchange.org) for a more detailed description of the loop options.

Water-to-air heat pumps are typically installed throughout a building with ductwork serving only the immediate zone; a two-pipe water distribution system conveys water to and from the ground-source heat exchanger. The heat exchanger field consists of a grid of vertical boreholes with plastic U-tube heat exchangers connected in parallel.

Simultaneous heating and cooling can occur throughout the building, as individual heat pumps, controlled by zone thermostats, can operate in heating or cooling mode as required.

Unlike conventional boiler/cooling, tower-type, water-loop heat pumps, the heat pumps used in GSHP applications are generally designed to operate at lower inlet water temperature. GSHPs are also more efficient than conventional heat pumps, with higher COPs and energy efficiency ratios. Because there are lower water temperatures in the two-pipe loop, piping needs to be insulated to prevent sweating. In addition, a larger circulation pump is needed because the units are slightly larger in the perimeter zones, requiring larger flows.



WHEN/WHERE IT'S APPLICABLE

The most economical application of GSHPs is in buildings that require significant space/water heating and cooling over extended hours of operation. Examples are retirement communities, multi-family complexes, large office buildings, retail shopping malls, and schools. Building types not well-suited to the technology are buildings where space and water heating loads are relatively small or where hours of use are limited.

GSHPs are generally not suited for all climates, especially ones that are mostly very hot or very cold. In such climates where the total numbers of hours of cooling and heating per year are not close, the ground will not have a healthy charging/discharging cycle and its temperature will be affected over the years, resulting in system performance degradation.

PRO

- Requires less mechanical room space.
- Requires less outdoor equipment.
- Does not require roof penetrations, maintenance decks, or architectural blends.
- Relatively little operational noise.
- Reduces operation and maintenance costs.
- Requires simple controls only.
- Requires less space in ceilings.
- Loop piping, carrying low-temperature water, does not have to be insulated.
- Installation costs are lower than for many central HVAC systems.

CON

- Requires surface area for heat exchanger field.
- Higher initial cost.
- Requires additional site coordination and supervision.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a GSHP system from a conventional one and an indication of whether the net cost for it is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings may also provide some assistance in identifying the cost elements involved.

First Cost

- Conventional heating/cooling generators L
- Heat pumps H
- Outside piping system H
- Heat exchanger field H
- Operator training H
- Design fees H

Recurring Cost

- Energy cost (fossil fuel for conventional) L
- Energy cost (electricity for heat pumps) H
- Maintenance L

SOURCES OF FURTHER INFORMATION

ASHRAE. 2015. *Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems (GSHP)*. Peachtree Corners, GA: ASHRAE.

Earth Energy Society of Canada
www.earthenergy.ca.

Kavanaugh, S.P., and K. Rafferty. 1997. *Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings*. Peachtree Corners, GA: ASHRAE.

Natural Resources Canada, RETScreen
(software for renewable energy analysis)
www.retscreen.net.

ASHRAE GreenTip #9-10

Thermal Energy Storage (TES) for Cooling

GENERAL DESCRIPTION

There are several suitable media for storage of cooling energy, including the following:

- Chilled water
- Ice
- Calcium chloride solutions (brine)
- Glycol solutions
- Concentrated desiccant solutions

Active thermal storage systems use a building's cooling equipment to remove heat, usually at night, from an energy storage medium for later use as a source of cooling. The most common energy storage media are ice and chilled water. These systems decouple the production of cooling from the demand for cooling, (i.e., the plant output does not have to match the instantaneous building cooling load). This decoupling increases flexibility in design and operations, thereby providing an opportunity for a more efficient air-conditioning system than with an alternative that does not include storage. Before applying active thermal storage, however, the design cooling load should be minimized.

Although many operating strategies are possible, the basic principle of a TES system is to reduce peak building cooling loads by shifting a portion of peak cooling production to times when the building cooling load is lower. Energy is typically charged, stored, and discharged on a daily or weekly cycle. The net result is an opportunity to run a chiller plant at peak efficiency during the majority of its operating period. A system without storage, on the other hand, has to follow the building cooling load, and the majority of its operation is at part-load conditions. Part-load operation of chiller plants comes at the expense of efficiency.

Several buildings have demonstrated site energy reductions with the application of TES, as discussed in both the "Pro" and "Sources of Further Information" sections that follow.

In addition to the potential for site energy reduction, operation of TES systems can reduce energy resource consumption. This reduction is due to a shift toward using energy during periods of low aggregate electric utility demand. As a result, transmission and distribution losses are lower and power plant generating efficiencies can be higher because the load is served by base-load plants. Thermal storage can also have beneficial effects on CHP systems by flattening thermal and electric load profiles.

The ASHRAE *Design Guide for Cool Thermal Storage* (Dorgan and Elleson 1993) covers cool storage application issues and design parameters in some detail.

WHEN/WHERE IT'S APPLICABLE

TES systems tend to perform well in situations where there is variability in loads. Successful applications of TES systems have included commercial office buildings, schools, worship facilities, convention centers, hotels, health care facilities, industrial processes, and turbine inlet air cooling.

PRO

- Because TES allows downsizing the refrigeration system, the resulting cost savings (which may include avoiding having to add such equipment on an existing project) may substantially or entirely cover the added incremental cost of the storage system proper (also see the first Con in the next section). However, if the first cost is more than another design option, there are still life-cycle cost benefits due to a significant reduction in utility costs.
- The addition of a TES system allows the size of refrigerating equipment to be reduced, since it will have to meet an average cooling load rather than the peak cooling load. Reduced refrigeration equipment size means less on-site refrigerant usage and a lower probability of environmental impacts due to direct effects.
- Because TES allows operation of the refrigeration system at or near peak efficiency during all operating hours, the annual energy usage may be lower than systems without storage that must operate at lower part-load ratios to meet instantaneous loads. In addition, since off-peak hours are usually at night when

lower ambient temperatures prevail, lower condensing temperatures required for heat rejection would tend to increase refrigeration efficiency. A number of carefully documented examples of energy savings can be found in the literature, including Bahnfleth and Joyce (1994); Fiorino (1994); and Goss et al. (1996).

- Because TES systems shift the consumption of site energy from on-peak to off-peak periods, the total energy resources required to deliver cooling to the facility will be lower (Reindl et al. 1995; Gansler et al. 2001). In addition, in some electric grids, the last generation plants to be used to meet peak loads may be the most polluting per kW of energy produced (Gupta 2002). In such cases, emissions would be further reduced by the use of TES.
- TES enables the practical incorporation of other high-efficiency technologies such as cold-air distribution systems and nighttime heat recovery.
- TES can be effective at preventing or delaying the need to construct additional power generation and transmission equipment.
- Liquid desiccant can be circulated in plastic pipes and does not need insulation.

CON

- Compared to a conventional system, the thermal storage element proper (i.e., the water tank or ice tank) and any associated pumping, piping accessories, and controls add to the incremental capital cost. If the system's refrigeration equipment can be reduced in size sufficiently (see the first Pro listed in the previous section), this burden may be mitigated substantially or balanced out.
- The need to generate cooling at evaporator temperatures lower than conventional ones tends to decrease refrigeration efficiency. This reduction may be overcome, however, by factors that increase efficiency (see the third Pro).
- Successful TES systems require additional efforts in the design phase of a project.
- TES systems will require increased site space usage. The impact of site space usage can be mitigated by considering ice storage technologies.

- Because a thermal storage system departs from the norm of system operation, continued training of facility operations staff is required, as are procedures for propagating system knowledge through a succession of facilities personnel.
- Ice requires special control of the melt rate to prevent uneven melting and to maximize performance.
- Calcium chloride brine needs management to prevent corrosion. Glycol needs management to prevent corrosion and toxicity.
- Liquid desiccant needs small resistant heating to be above 77°F (25°C) to prevent crystallization (similar to compressor sumps to prevent condensation).

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a TES system above from a conventional one and an indication of whether the net cost for the alternative option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

• Storage element (e.g., chilled water, ice, glycol, and brine tanks) (Desiccant cost is higher than chilled water and brine but similar to glycol)	H
• Additional pumping/piping re-storage element	H
• Chiller/heat rejection system	L
• Controls	H
• Electrical (regarding chiller/heat rejection system)	S/L
• Design fees	H
• Operator training	H
• Commissioning	S/H
• Site space	H

Recurring Cost

- Electric energy L
- Gas supply with low electrical demand H
- Operator training (ongoing) H
- Maintenance training L

SOURCES OF FURTHER INFORMATION

ASHRAE. 2019. *ASHRAE Design Guide for Cool Thermal Storage*, Second Edition. Peachtree Corners, GA: ASHRAE.

ASHRAE GreenTip #9-11

Double-Effect Absorption Chillers

GENERAL DESCRIPTION

Chilled-water systems that use fuel types other than electricity can help offset high electric prices, whether those high prices are caused by consumption or demand charges. Absorption chillers use thermal energy (rather than electricity) to produce chilled water. A double-effect absorption chiller using high-pressure steam (115 psig [793 kPa]) has a COP of approximately 1.20. Some double-effect absorption chillers use medium-pressure steam (60 psig [414 kPa]) or 350°F to 370°F (177°C to 188°C) hot water, but with lower efficiency or higher cost. ASHRAE Standard 90.1-2016 requires a minimum $\text{COP} \geq 1.0$ for a double-effect absorption chiller when operating at full load.

Double-effect absorption chillers are available from several manufacturers. Most are limited to chilled-water temperatures of 40°F (4.3°C) or above, since water is the refrigerant. The interior of the chiller experiences corrosive conditions; therefore, the manufacturer's material selection is directly related to the chiller life. The more robust the materials, the longer the life.

WHEN/WHERE IT'S APPLICABLE

Double-effect absorption chillers can be used in the following applications:

- When natural gas prices (used to produce steam) are significantly lower than electric prices.
- When the design team and building owner wish to have fuel flexibility to hedge against changes in future utility prices.
- When there is steam available from an on-site process; an example is steam from a turbine.
- When a steam plant is available but lightly loaded during the cooling season. Many hospitals have large steam plants that run at extremely low loads and low efficiency during the cooling season. By installing an absorption chiller, the steam plant efficiency can be increased significantly during the cooling season.
- At sites that have limited electric power available.

- In locations where district steam is available at a reasonable price (e.g., New York City).

PRO

- Reduces electric charges.
- Allows fuel flexibility, since natural gas, No. 2 fuel oil, propane, or waste steam may be used to supply thermal energy for the absorption chiller.
- Uses water as the refrigerant, making it environmentally friendly.
- Allows system expansion even at sites with limited electric power.
- When the system is designed and controlled properly, it allows versatile use of various power sources.

CON

- Cost of an absorption chiller will be roughly double that of an electric chiller of the same capacity, as opposed to 25% more for a single-effect absorption machine.
- Size of an absorption chiller is larger than an electric chiller of the same capacity.
- Although absorption chiller efficiency has increased in the past decade, the amount of heat rejected is significantly higher than that of an electric chiller of similar capacity. This requires larger cooling towers, condenser pipes, and cooling tower pumps.
- Few plant operators are familiar with absorption technology.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate an absorption chiller system from a conventional one and an indication of whether the net cost for the hybrid option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Absorption chiller H
- Cooling tower and associated equipment H
- Electricity feed L
- Design fees H
- System controls H

Recurring Cost

- Electric costs L
- Chiller maintenance S
- Training of building operators H

SOURCES OF FURTHER INFORMATION

ASHRAE. 2018. Chapter 18, “Absorption Equipment.” In *ASHRAE Handbook—Refrigeration*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2020. Chapter 50, “Room Air Conditioners and Packaged Terminal Air Conditioners.” In *ASHRAE Handbook—HVAC Systems and Equipment*. Peachtree Corners, GA: ASHRAE.

Trane Co. 1999. *Trane Applications Engineering Manual, Absorption Chiller System Design*, SYS-AM-13. Lacrosse, WI: Trane Company.

ASHRAE GreenTip #9-12

Desiccant Cooling and Dehumidification

GENERAL DESCRIPTION

There are two basic types of open-cycle desiccant process: solid and liquid desiccant. Each of these processes has several forms, and these should be investigated to determine the most appropriate for the particular application. Both of these systems need to have the air being conditioned come in good contact with the desiccant, during which moisture is absorbed from the air and the temperatures of both the air and desiccant are coincidentally raised.

The moisture absorption process is caused by desiccant having a lower surface vapor pressure than the air. As the temperature of the desiccant rises, its vapor pressure rises, and its useful absorption capability lessens. Some systems, particularly liquid types, have cooling of air and desiccant coincident with dehumidification. This can allow the need for less space and equipment.

The dehumidified air then has to be cooled by other means. Two supply air arrangements are available. One method uses a mixture of recycled return air and dehumidified outdoor ventilation air as supply air to the building. Moisture and contaminants such as volatile organic compounds can be absorbed by the desiccant and recycled; particles of solid or liquid desiccant may also be carried over into the ducts and to building occupants.

The other arrangement combines energy recovery from building exhaust air that is typically much cooler and less humid than outdoor ventilation air. By dehumidifying the exhaust air to a sufficiently low humidity ratio (i.e., moisture content), it can be used to indirectly cool outdoor air for supply to the building that has not contacted desiccant. Using the recovered energy, this arrangement can be used to process the total ventilation air requirement, even up to 100% from outside.

So that desiccant can be reused, it has to be redried by a heating process generally called *reactivation* or *regeneration* (for solid types) or *reconcentration* (for liquid types). The redrying can be either direct (by contact with heated outdoor air with the desiccant) or indirect. Indirect may be preferable, particularly in high humid climates, because of the higher temperature needed to maximize the vapor difference and dry-

ing potential. The energy storage benefit for liquid desiccant was discussed in GreenTip #9-12.

Rotary desiccant dehumidifiers use solid desiccants such as silica gel to attract water vapor from the moist air. Humid air, generally referred to as *process air*, is dehumidified in one part of the desiccant bed while a different part of the bed is dried for reuse by a second airstream known as *reactivation air*. The desiccant rotates slowly between these two airstreams, so that dry, high-capacity desiccant leaving the reactivation air is available to remove moisture from the moist process air.

Process air that passes through the bed more slowly is dried more deeply, so for air requiring a lower dew point, a larger unit (and slower velocity) is required. The reactivation air inlet temperature changes the outlet moisture content of the process air. In turn, if the designer needs dry air, it is generally more economical to use high reactivation temperatures. On the other hand, if the leaving humidity need not be especially low, inexpensive, low-grade heat sources (e.g., waste heat or rejected cogeneration heat) can be used.

The process air outlet temperature is higher than the inlet temperature primarily because the heat of sorption of the moisture removed is converted to sensible heat. The outlet temperature rises roughly in proportion to the amount of moisture that is removed. In most comfort applications, provisions must be made to remove excess sensible heat from the process air following reactivation. Cooling is accomplished with cooling coils, and the source of this cooling affects the operating economics of the system.

WHEN/WHERE IT'S APPLICABLE

In general, applications that require a dew point at or below 40°F (4.3°C) may be candidates for active desiccant dehumidification. Examples of such candidates include facilities handling hygroscopic materials; film drying; the manufacturing of candy, chocolate, or chewing gum; the manufacturing of drugs and chemicals; the manufacturing of plastic materials; packaging of moisture-sensitive products; and the manufacturing of electronics. Supermarkets often use desiccant dehumidification to avoid condensation on refrigerated casework. And when there is a need for a lower dew point and a convenient source of low-grade heat for reactivation is available, rotary desiccant dehumidifiers can be especially economical.

PRO

- Desiccant equipment tends to be very durable.
- Often this is the most economical means to dehumidify below a 40°F (4.3°C) dew point.
- It eliminates condensate in the airstream, in turn, limiting the opportunity for mold growth.

CON

- Desiccant usually must be replaced, replenished, or reconditioned every 5 to 10 years.
- In comfort applications, simultaneous heating and cooling may be required.
- The process is not especially intuitive, and the controls are relatively complicated.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a building with a rotary desiccant dehumidification system from one without and an indication of whether the net cost is likely to be lower (L), higher (H), or the same (S).

First Cost

• Equipment costs	H
• Regeneration (heat source and supply)	H
• Ductwork	S
• Controls	H
• Design fees	S

Recurring Cost

• Overall energy cost	S/H
• Maintenance of system	H
• Training of building operators	H
• Filters	H

SOURCE OF FURTHER INFORMATION

ASHRAE. 2020. *ASHRAE Handbook—HVAC Systems and Equipment*. Peachtree Corners, GA: ASHRAE.

ASHRAE GreenTip #9-13

Indirect Evaporative Cooling

GENERAL DESCRIPTION

Evaporative cooling of supply air can be used to reduce the amount of energy consumed by mechanical cooling equipment. Two general types of evaporative cooling—direct and indirect—are available. The effectiveness of either of these methods is directly dependent on the extent that dry-bulb temperature exceeds wet-bulb temperature in the supply airstream.

Direct evaporative cooling introduces water directly into the supply airstream, usually with a spray or wetted media. As the water absorbs heat from the air, it evaporates. While this process lowers the dry-bulb temperature of the supply airstream, it also increases the air moisture content.

Two forms of indirect evaporative cooling (IEC) are described below.

1. **Coil/cooling Tower IEC.** This type uses an additional water-side coil to lower supply air temperature. The added coil is placed ahead of the conventional cooling coil in the supply airstream and is piped to a cooling tower where the evaporative process occurs. Because evaporation occurs elsewhere, this method of precooling does not add moisture to the supply air, but it is somewhat less effective than direct evaporative cooling. A conventional cooling coil provides any additional cooling required.
2. **Plate Heat Exchanger IEC.** This is composed of sets of parallel plates arranged into two sets of passages separated from each other. In a typical arrangement, exhaust air from a building is passed through one set of passages, during which it is wetted by water sprays. A stream of outdoor air is coincidentally passed through the other set of passages and is cooled by heat transfer through the plates by the wetted exhaust air before being supplied to the building. Alternatively, the exhaust air may be replaced by a second stream of outdoor air. The wetted air is reduced in dry-bulb temperature to be close to its wet-bulb temperature. The stream of dry air is cooled to be close to the dry-bulb temperature of the wetted exhaust air. In some applications, the cooled stream

of outdoor air is passed through the coil of a direct expansion refrigeration unit, where it is further cooled before being supplied to the building. This system is an efficient way for an all outdoor air supply system. The plates in the heat exchanger can be formed from various metals and polymers. Consideration needs to be given to preventing the plate material from corroding.

WHEN/WHERE IT'S APPLICABLE

This may be used in climates with low wet-bulb temperatures where significant amounts of cooling are available. In such climates, the size of the conventional cooling system can also be reduced.

In more humid climates, indirect evaporative cooling can be applied during nonpeak seasons. It is especially applicable for loads that operate 24 h/day for many days of the year.

PRO

- Indirect evaporative cooling can reduce the size of the conventional cooling system.
- It reduces cooling costs during periods of low wet-bulb temperature.
- It does not add moisture to the supply airstream (in contrast, direct evaporative cooling does add moisture).
- It may be designed into equipment such as self-contained units.
- There is no cooling tower or condenser piping in the plate heat exchanger IEC that is described.

CON

- Air-side pressure drop (typically 0.2 to 0.4 in. of water [50 to 100 Pa]) increases due to an additional coil in the airstream.
- To make water cooler in the coil/cooling tower IEC, the cooling tower fans operate for longer periods of time and consume more energy.
- For the coil/cooling tower IEC, condenser piping and controls must be accounted for during the design process.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate an IEC system from a conventional one and an indication of whether the net cost for the hybrid option is likely to be lower (L), higher (H), or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Indirect cooling coil H
- Decreased conventional cooling system capacity L
- Condenser piping, valves, and control H

Recurring Cost

- Cooling system operating cost L
- Supply fan operating cost H
- Tower fan operating cost H
- Maintenance of indirect coil S

SOURCES OF FURTHER INFORMATION

ASHRAE. 2019. Chapter 52, “Evaporative Cooling.” *ASHRAE Handbook—HVAC Applications*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2020. Chapter 41, “Evaporative Air-Cooling Equipment.” *ASHRAE Handbook—HVAC Systems and Equipment*. Peachtree Corners, GA: ASHRAE.

ASHRAE GreenTip #9-14

Thermally Actuated Diffusers

GENERAL DESCRIPTION

Conventional air distribution systems typically group several rooms into a typical VAV box or zone that is controlled by a single thermostat. Because rooms within the zone can have different heating/cooling requirements, the system's response to heating/cooling loads within the zone may not be consistent with load requirements. The result can be a lack of thermal comfort of the occupants in each room by providing rather all cooling or all heating irrespective of the occupants need. In addition, the re-heat at the VAV box results in increase energy consumption.

Thermally actuated diffusers commonly use thermal actuators to modulate the flow rate of supply air into a room according to a desired temperature setting. The diffuser works independent of a BAS and does not require external power since the close/open action is caused by a thermal gel that is purely mechanical. The diffuser measures the room temperature by inducing room air into the diffuser core and passing it over a thermal actuator. Linkage contained within the core adjusts the damper based on the difference between room and desired set point temperatures. Some advanced models can be connected to the BMS systems.

WHEN/WHERE IT'S APPLICABLE

Thermally actuated diffusers can be used in any all-air systems and are generally found economically feasible when compared to a VAV box is serving less than five air outlets.

PRO

- Improved thermal comfort
- Reduced energy consumption
- With proper zoning, possibility of elimination of the heating hot water system including the boiler.

CON

- Higher first cost
- Required an engineered duct design
- Basic models cannot connect to the BMS

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a building with a rotary desiccant dehumidification system from one without and an indication of whether the net cost is likely to be lower (L), higher (H), or the same (S).

First Cost

- Equipment costs H
- Ductwork S
- Controls S
- Design fees S

Recurring Cost

- Overall energy cost L
- Maintenance of system L
- Training of building operators S
- Filters S

SOURCE OF FURTHER INFORMATION

Engineering Guide VAV diffusers. Price Industries. <https://www.priceindustries.com/content/uploads/assets/literature/engineering-guides/vav-diffusers-engineering-guide.pdf>.

ASHRAE GreenTip #9-15

Automated Refrigerant Leak Detection and Recovery

GENERAL DESCRIPTION

In the past, leaking chillers were acceptable because of the ready supply and the low cost of refrigerant. Today if a refrigerant leaks in chillers (be it R134a, R410a, HFOs), it not only cost the building owner but also the refrigerant released to the atmosphere will cause global warming, increase carbon footprint and in a way affect climate change. This may not be acceptable under the US Clean Air Act.

Automated refrigerant leakage detection and recovery system not only prevent further leakage of refrigerant being dispersed into the atmosphere but also prevent wastage of refrigerant, achieve cost savings, minimize risk and protect the safety of mechanical room personnel and the environment. If owners choose to follow any green building certification, automated refrigerant leakage detection can benefit them not just by being environmentally sound but also by lowering operation cost, reducing carbon footprint, reducing liability and risk, enhancing marketability through higher return on investment and increasing tenant rental.

WHEN/WHERE IT'S APPLICABLE

Automated refrigerant leakage detection and recovery systems are typically used in mechanical rooms where chillers are installed. Some chillers lose 2% to 15% of their refrigerant charge annually through different mechanisms. In the past, all of the lost refrigerant was released to the atmosphere.

Refrigerant loss occurs primarily through four different channels: leaks, poor service procedures, contamination, and purge cycles. Depending on the local service standards, the relative magnitude of these channels can vary widely.

The case of high-pressure chillers is slightly different than low pressure chillers. High pressure chillers maintain positive pressure throughout the refrigerant circuit; therefore, they do not require purge units. Aside from this difference, the refrigerant loss mechanisms are basically the same as in low pressure chillers. All of the losses for both high- and low-pressure chillers can be significantly

reduced by using the auto leakage detection and recovery system installed in the chillers.

The largest source of refrigerant loss from chillers is equipment leakage caused by normal operation and wear. Leaks are most often found in tubing, flanges, O-rings, seals and other connections. Losses from equipment leakage can be greatly reduced if leaks are identified and repaired, though in recent times, leak rate of new chillers are greatly reduced.

DETAILED DESCRIPTION

A complete automated refrigerant leak detection and recovery system will generally consist of:

- nondispersive infrared (NDIR) refrigerant sensors with pump aspirated sampling system
- refrigerant recovery unit
- refrigerant gas cylinders
- steel platform weighing scales to determine amount of refrigerant recovered
- refrigerant ball valves
- electrical enclosure with general alarm
- copper piping and wiring

The refrigerant leakage and recovery system works by constantly monitoring for any refrigerant leak. This is achieved by NDIR sensor with pump aspirated sampling system (per chiller) which is capable of picking up leaks better than a static sensor. Plus, the use of superior NDIR technology ensures there is minimal false leak detection from other VOC's and fumes.

The design for the project will depends on the number of chillers and type of refrigerant used, refrigerant charge and blend of the largest chiller, layout, air circulation, and leakage sensitivity among other key parameters.

Whenever there is a chiller leak, the refrigerant being heavier than air tends to slowly settle down at ground level. Because of that, the refrigerant sensor (based on the particular refrigerant used in the chillers) is generally installed 8 in. (200 mm) above the ground near both ends of every chiller.

In the event of a leak, the gas detection system or fuzzy logic code in the chiller programmable logic controller (PLC) detects a possible leak in progress and a signal will be sent to the Refrigerant Recovery Unit, then a signal in the form of a dry contact closure will be sent to the chiller PLC. Once the chiller has readied itself for refrigerant recovery it sends a signal back confirming that refrigerant recovery may proceed using a high-speed vacuum pump in the refrigerant recovery unit. The activation signal may come from any sensor source. The HVAC engineers, architects along with the BMS engineers will ultimately decide which configuration best suits their needs.

The system will allow refrigerant to flow from the chiller to the refrigerant storage vessels for one minute before its pumping unit begins. The system will recover the refrigerant until a nominal pressure of around 3 to 4 psig (25kPa) is achieved. This value may be altered, however it is desirable to keep this pressure above atmospheric pressure as air may be recovered with the refrigerant; which is undesirable.

The system will remain active until it is reset or switched off. This strategy has been chosen in the event liquid refrigerant remains “trapped” in the chiller after the system has recovered to a nominal pressure of 25kPa. At this pressure during recovery, any liquid refrigerant may likely be very cold. For example, for R134a it is likely to be around -5°F to -10°F (roughly -22°C). Thus, it may be some time before its temperature/pressure increases and therefore the recovery system will need to remain active.

Integral to this system is the measurement of the recovered refrigerant. Each recovered refrigerant has a measuring scale so the recovered refrigerant can be logged and the loss of refrigerant calculated. On the charging cycle, this system accurately measures the charge into the chiller allowing any initial refrigerant loss to be added and logged.

PRO

- Reduce leak refrigerant emission into the atmosphere thereby reducing contribution to greenhouse gas emissions
- Potential for reduced owner operating cost
- Save liabilities and minimize personnel risk working in mechanical room

CON

- May not be as effective if the mechanical room is very well ventilated but the lost refrigerant will be emitted to the atmosphere
- Higher up front first cost for the chiller installation
- Potential for some additional maintenance, such as refrigerant sensor recalibration and system operational checks.

SOURCE OF FURTHER INFORMATION

Australian Green Star Rating Tools

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CHAPTER TEN

ENERGY SOURCES

RENEWABLE AND NONRENEWABLE ENERGY SOURCES

There are often discussions about using renewable energy sources as a way to power the world, but little is done to actually implement it. Various definitions of a renewable energy source (RES) exist. The *International Green Construction Code* (IgCC) defines this as “Energy derived from solar radiation, wind, waves, tides, biogas, biomass, or geothermal energy,” while ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1 emphasizes on-site renewable energy systems defined as “photovoltaic, solar thermal, geothermal energy, and wind energy system...located on the building project.” This contrasts with the common nonrenewable energy sources such as coal, oil, natural gas, and nuclear. This chapter focuses on ways to use renewable energy to offset nonrenewable energy sources.

According to the US Department of Energy’s (DOE) Energy Information Administration (EIA), renewable energy consumption exceeded 11.4 quadrillion Btu in 2018 (EIA 2018) and is expected to account for over 76% of the new electric generating capacity additions. In the European Union (EU), renewable energy contributed about 19% of the gross final energy consumption in 2018 (<https://ec.europa.eu/eurostat>).

Maximizing the building’s energy efficiency first, renewables can be used to cover part, all, or more of its energy needs. High-performance buildings in areas with at least 1.2 kBtu/ft²·day (4.0 kWh/m²·day) daily incident solar radiation on a tilted surface due south at an angle from horizontal equal to the latitude should be renewable ready for annual energy production equivalent of not less than 6.0 kBtu/ft² (20 kWh/m²) for single-story buildings and not less than 10.0 kBtu/ft² (32 kWh/m²) multiplied by the gross roof area for all other buildings (ASHRAE 2020). In a standard approach, the minimum renewable energy requirements range on an annual basis from 14 kBtu/ft² (44 kWh/m²) for offices to 22 kBtu/ft² (68 kWh/m²) for apartment buildings and up to 40 kBtu/ft² (126 kWh/m²) for health care buildings. In the Euro-

pean Union, all new buildings from 2021 are nearly zero-energy buildings with very high energy performance, while the nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby. Considering zero energy buildings, it becomes important to have a clear definition, i.e., “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy” (Peterson et al. 2015).

Other efforts aim toward positive energy districts (PED) or urban neighborhoods that may achieve neutrality or even become energy positive (Magrini et al. 2020). Europe has set an ambitious plan for the deployment and replication of 100 PEDs by 2025 with the support of 20 EU Member States in a program for PEDs and neighborhoods for sustainable urban development. PEDs should minimize the impact on central energy networks by increasing on-site load-matching and self-consumption, using technologies for short- and long-term storage, and providing energy flexibility with smart controls (IEA EBC Annex 83).

While consideration of renewables is a highly touted element of green design, the design team should be well aware of the key characteristics of whichever renewable is being considered and develop creative strategies accordingly. After an initial discussion on the water-energy nexus, in the following sections, we focus on two main renewable energy sources, i.e., solar and wind energy, and how they can be integrated into the building design and operation.

WATER-ENERGY NEXUS

The term *water-energy nexus* is used in reference to the interdependent and inseparable nature of two of our most precious resources, water and energy. From large-scale utilities to the built environment, water usage requires energy to extract and deliver for consumption (e.g., hydraulic fracturing and biofuels), while the generation of electricity and associated energy resources used for that purpose (such as fossil and nuclear fuels) demand significant amounts of water for production. With approximately 8% of global energy generation used for pumping, treatment and transportation of water resources—and approximately 15% of the world's total water usage used for energy production, each resource will continue to face rising demands and constraints as a consequence of economic and population growth and climate change.

Though both water and energy are critical resources today, each has different characteristics. The earth has a fixed amount of water in various forms (such as seas, glaciers, underground aquifers, precipitation, vapor, and that embodied in living organisms). No water in any form leaves or enters the planet. What the earth has is what it must make the best use of.

With a fixed amount of water on earth, the task becomes ensuring that the forms and quality of water available (especially potable water) are sufficient to serve the needs of the population. While water is not consumed in the sense of being “used up,” it can become contaminated, requiring energy and other inputs to clean, or transformed into a form not usable at this location (such as through evaporation). Another key aspect of water is its uneven distribution across the planet, with some areas having plenty and others where water is scarce.

Energy, on the other hand, does leave and impinge on the earth through solar gain and radiation from the earth to space, and has for millennia. Much of the energy that has impacted the earth has been stored over those millennia in the form of fossil fuels and nuclear fuel as well as raised water bodies and waterfalls. We rely to a large degree on these stored energy forms, but energy continues to affect the earth, and humankind has developed means to capture and use a portion of that energy on a timely, albeit small-scale basis (such as solar and wind energy systems).

With that increasing energy demand as well as naturally occurring water constraints such as droughts, heat waves, or human-induced shortages, we can expect the demands on our water resources to increase. In addition to increasing demand, changing temperatures, shifting precipitation patterns, increasing variability, and more extreme weather will yield significant uncertainty regarding water availability.

Water and energy, in their various classifications, have generally been viewed in individual “silos,” which have limited the adoption of integrated solutions. To properly address the challenges and opportunities posed by the water-energy nexus, emphasis on policy incentives and sustainable engineering solutions promoting optimal usage efficiency of each resource, as well as advanced technologies promoting both water and energy conservation, will be required.

See Chapter 12, Water Efficiency, for information on the efficient use of water.

SOLAR

Solar energy is the primary energy source that fuels the growth of the Earth’s natural capital and drives wind and ocean currents that also can provide alternative energy sources. Since the beginning of time, solar energy has been successfully harnessed for human use. Early civilizations and some modern ones used solar energy for many purposes: food and clothes drying, heating water for baths, heating adobe and stone dwellings, etc. Solar energy is free and available to anyone who wishes to use it.

Solar thermal heating for domestic hot-water and space heating has grown considerably over the years and is well established in several countries. Global installed capacity is estimated at about 1648×10^{10} Btu/h (483 gigawatts of thermal energy [GW_{th}]) of which the vast majority are water collectors, including glazed flat-plate collectors (382×10^9 Btu/h [$112 \text{ GW}_{\text{th}}$], evacuated-tube collectors (1160×10^9 Btu/h [$340 \text{ GW}_{\text{th}}$]) and unglazed plastic collectors (102×10^9 Btu/h [$30 \text{ GW}_{\text{th}}$]), and the remaining 0.2% are air collectors reaching only 3.84×10^9 Btu/h ($1.1 \text{ GW}_{\text{th}}$) for

glazed and unglazed units (Weiss et al. 2008). In North America (i.e., United States and Canada), swimming pool heating is dominant with an installed capacity of about 55×10^9 Btu/h (16 GW_{th}) of unglazed plastic collectors. In other countries, flat-plate and evacuated-tube collectors are used to generate hot water for sanitary use and space heating. Solar energy is also used for applications such as industrial or agricultural processes.

For many, a key impediment to increased solar use is economics. The cost of some solar technologies is perceived to be high compared to the fossil-based energy source it is offsetting. For example, while the simple payback of solar PV systems tends to be rather long (although much improvement has occurred over the past couple of decades), the recent increase in the cost of energy and advances in solar energy justify a fresh look at the applications and the engineering behind those applications. In addition, public policy in many areas encourages solar and other renewable energy applications through tax incentives and encouraging or requiring repurchase of excess electrical energy generated by the utility provider.

The applicability and, consequently, the economics and public policy incentives available with different solar energy system types and applications depend greatly on the location, which determines the technical factors (such as solar resources available), as well as the nontechnical (such as the country's political situation). The economics also depend on scale; at the time of writing, the cost for utility-level solar PV was less than the cost of building and operating new coal plants in the US.

Solar Thermal Applications

Solar energy thermal applications range from low-temperature applications (swimming pool heating or domestic hot water) up to medium- or high-temperature applications (space heating, absorption cooling or steam production for electrical generation). Figure 10-1 shows examples of typical installations.

The most common solar energy thermal application is for domestic hot water (DHW) production. Solar hot water can be used as the sole source of domestic hot water or to preheat incoming supply water. This can be as simple as having an uninsulated tank in a hot attic in a southern climate to having a batch water heater on the roof of a building. The same solar collectors can be used to deliver thermal energy for space heating. A typical installation for the combined production of DHW and space heating (i.e., solar combi systems) includes the solar collectors, the heat storage tank, and a boiler used as an auxiliary heater. Combi systems require a larger collector area than a DHW system to meet the higher loads. It is possible to use a heat storage tank and a DHW storage vessel, but it may also be suitable to combine them in a single storage tank (with a high vertical stratification) to meet the different operating temperatures for space heating and DHW. To assess and compare performances of different designs for solar combi systems, the International Energy Agency (IEA) launched Task 26 to address issues in this area (<http://task26.iea-shc.org>). Standardized classification and evaluation processes and design tools

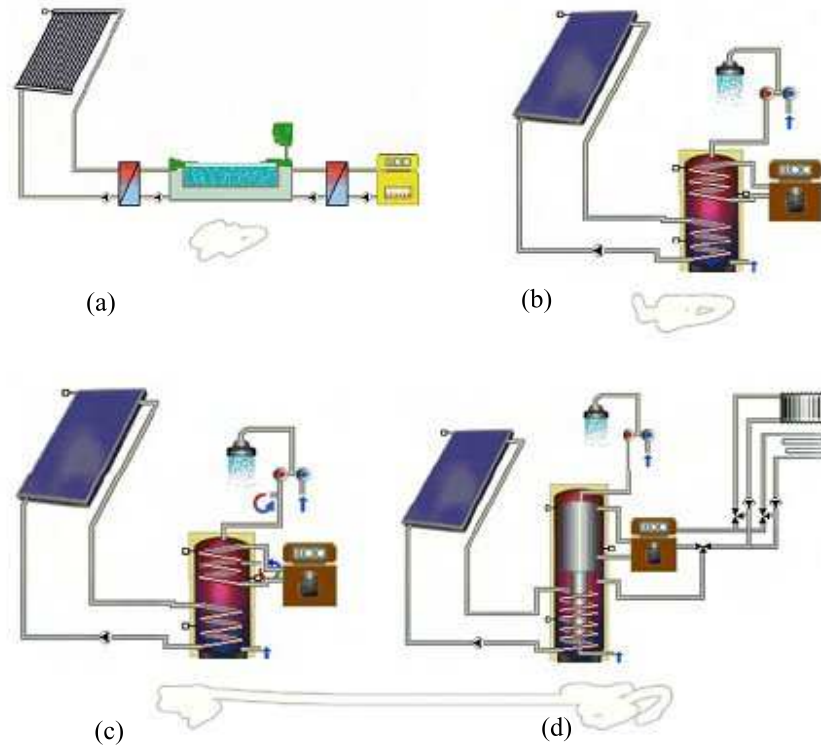


Figure 10-1 Examples of typical solar installations: (a) swimming pool, (b) domestic hot water, (c) domestic hot water for dwellings, and (d) solar combi systems for domestic hot water and space heating for houses. (Images generated using T-SOL 4.5 Expert; Valentin Energie software, www.valentin.de.)

were developed for these systems, along with proposals for the international standardization of combi system test procedures. The primary standard used to define the assessment of solar thermal collector performance is ISO 9806 (ISO 2017). Criteria for the design and installation of solar thermal systems are also defined in ICC 900/SRCC 300-2015 (ICC 2015).

Prior to considering a solar thermal system for only DHW use, perform an energy analysis to see if it may be more economical to use electricity generated from a photovoltaic (PV) solar system to heat the water.

Besides preheating water, solar energy can be used to preheat incoming air before it is introduced to a building using systems integrated with the overall build-

ing design or collectors. This is a simple technological approach that can be economically viable and is well suited for northern climates or areas with high building heating load. The DOE has published a bulletin on these transpired solar collectors (DOE 2006).

The main drawback of solar combi systems has been the fact that during summer the available high solar radiation and the heat produced from the solar collectors cannot be fully used, thus making the system financially less attractive and limiting its use to the low DHW summer demand. In addition, there are some technical problems related to stagnation (when there is low thermal demand and hence low flow through the collector). This could potentially mean that the medium in the solar collector loop vaporizes during a period of low flow rate and high solar radiation availability. This generally should not occur with low-temperature collectors such as unglazed ones, but may be an issue for higher-temperature collectors. The Solar Rating and Certification Corporation Standard 100 specifies that all collectors be designed to withstand stagnation conditions without “significant degradation” (SRCC 2014). That standard defines stagnation as “the solar collector temperature at which the energy gain is balanced by the heat loss.” Because high building cooling loads generally coincide with high solar radiation, the readily available solar heat from the existing solar collectors can be exploited by a heat-driven cooling machine, thus extending the use of the solar field throughout the year (DHW and space heating in winter, DHW and cooling in summer). Combining solar heating and cooling is usually referred to as a solar combi-plus system that can increase the total solar fraction (i.e., the percentage of energy for a use that the solar system can provide, usually expressed on an annual basis).

Europe has the most sophisticated market for different solar thermal applications, including systems for hot-water production, plants for space heating of single- and multifamily houses and hotels, large-scale plants for district heating, and a growing number of systems for air-conditioning, cooling, and industrial applications.

The capital cost of solar thermal systems generally increases with higher working fluid temperatures. The higher the delivery temperature, the lower the efficiency, and the more solar collector area is generally required to deliver the same net energy. This is due to parasitic thermal losses that are inherent in solar collector design. Different solar collector types provide advantages and disadvantages, depending on the application, and there are significant cost differences among each solar collector type. Some common collector types are discussed here. (See Figure 10-2 for examples of hardware.)

Flat-Plate Solar Collectors. These are best suited for processes requiring low-temperature working fluids (80°F to 160°F [27°C to 71°C]) and can deliver 80°F (27°C) fluid temperatures, even during overcast conditions. The term *flat-plate collector* generally refers to a hydronic coil-covered absorber housed in an insulated box with a sin-



Image courtesy of DOE/NREL, Credit Gen-Con, Inc.

(a)



Image courtesy of DOE/NREL, Credit Russ Hewitt

(b)

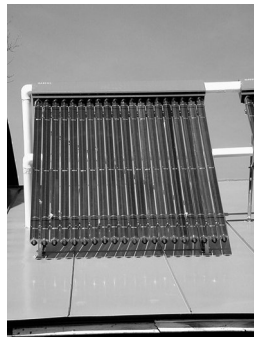


Image courtesy of DOE/NREL, Credit Alan Ford

(c)



Image courtesy of DOE/NREL.

(d)

Figure 10-2 Examples of solar hardware: (a) unglazed plastic collector, (b) glazed flat-plate collector, (c) evacuated-tube collector, and (d) concentrating collectors.

gle- or double-glass cover that allows solar energy to heat the absorber. The glazing used is a special high-transmissivity version. Heat is removed by a fluid running through the hydronic coils. Its design makes it more susceptible to parasitic losses than an evacuated tube collector, but more efficient in solar energy capture, because flat-plate collectors convert both direct and indirect solar radiation into thermal energy. This makes flat-plate collectors the preferred choice for domestic hot-water and other low-temperature heating applications. Coupling a water-source heat pump with low fluid temperatures with solar collectors provides heating efficiencies that are higher than ground-source heat pump (GSHP) applications and standard natural gas furnaces. Typical flat-plate solar collector performance curves are illustrated in Figure 10-3. The collector's efficiency η is expressed as a function of the solar collector's working

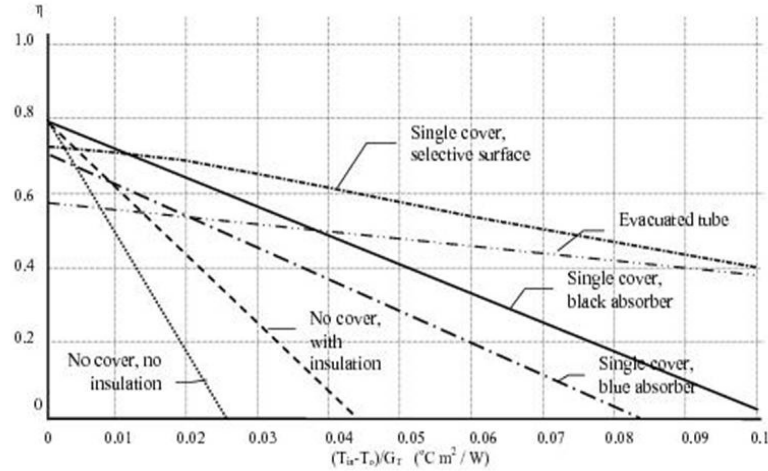


Image courtesy of C.A. Balaras

Figure 10-3 Typical flat-plate solar collector performance curves.

fluid inlet temperature T_{in} , the ambient temperature T_o , and the total solar radiation incident on the collector's surface G_T .

Seeking a very high annual solar savings fraction often leads to disappointment and poor economics, so keep expectations reasonable. Even a 25% annual fraction represents a substantial reduction in conventional energy use. A highly optimized, active solar thermal domestic water-heating system in an appropriate climate often has about a 60% solar fraction.

Evacuated-Tube Collectors. This type of collector involves encasing the absorbing device inside of an evacuated tube. The evacuated tube minimizes parasitic losses even at elevated temperatures. Three different design types are generally used in evacuated tube collectors: U-tubes, flooded and heat pipe. The heat pipe type of collector does not circulate the working fluid through the evacuated tube, but rather relies on the heat pipe to transfer the heat gained to the transfer working fluid.

Another variation on the evacuated-tube type collector involves a series of small absorbers consisting of small-diameter (approximately 3/8 in. [10 mm]) copper tubing encased in a clear, cylindrical, evacuated glass tube. Because of the relatively small absorber area, significantly more collector area is required than with the flat-plate or concentrating collector.

Concentrating Collectors. This refers to the use of a parabolic trough reflector that focuses the solar radiation falling within the reflector area onto a centrally located absorber. Another concentrating collector type uses concentrating lenses

(such as a Fresnel lens) to focus the solar radiation. Concentrating collectors are best suited for processes requiring high-temperature working fluids (300°F to 750°F [150°C to 400°C]) and do not operate under overcast conditions. This type of collector converts only direct solar radiation, which varies dramatically with sky clearness and air quality. Concentrating collectors often will use solar trackers that rotate on one or two axes to track the sun and collect the available direct solar radiation, although some designs do not use tracking.

Other Collector Types. Other types of solar thermal collectors include thermosiphon systems, which use natural convection to circulate the working fluid without a need for a pump. These systems are more common in areas where freezing temperatures are not a concern, and are simple and robust, making them a cost-effective option. Some solar thermal collectors are combined with photovoltaic (PV) panels. One option is where the electricity generated is directly connected to resistive heating elements in a water heater. Another option has a solar thermal collector integrated on the back of a PV module. This allows for an increased overall PV efficiency because of the lower temperatures, although a thermal sink may be needed if no thermal load condition exists to avoid stagnation conditions and resulting higher PV module temperatures.

Pros and cons of different solar collector types and other limitations of active solar systems can be found in a number of sources. Many of the key contributions came during the initial energy concerns of the 1970s, and a few are listed in the References and Resources section at the end of this chapter.

Solar Thermal Systems for Building Cooling

The main heat-driven cooling technologies that can be used for solar cooling include the following:

- Closed-cycle systems (e.g., LiBr/H₂O and H₂O/NH₃ absorption systems [see Chapter 18 of the *ASHRAE Handbook—Refrigeration* {ASHRAE 2022}] and adsorption cycle systems [see Chapter 32 of the *ASHRAE Handbook—Fundamentals* {ASHRAE 2021}]). They produce chilled water that can be used in combination with any air-conditioning equipment, such as air-handling units, fan-coil systems, and chilled ceilings.
- Open-cycle systems (e.g., desiccant systems [see Chapter 32 of the *ASHRAE Handbook—Fundamentals* {ASHRAE 2021}]). The term *open cycle* is used to indicate that the refrigerant is discarded from the system after it provides the cooling effect. New refrigerant is supplied in its place in an open-ended loop.

Solar-assisted cooling systems use solar thermal collectors connected to thermal-driven cooling devices. They consist of several main components (Figure 10-4): solar collectors, heat storage, heat distribution system, heat-driven cooling unit, optional cold storage, an air-conditioning system with appropriate cold distribution,

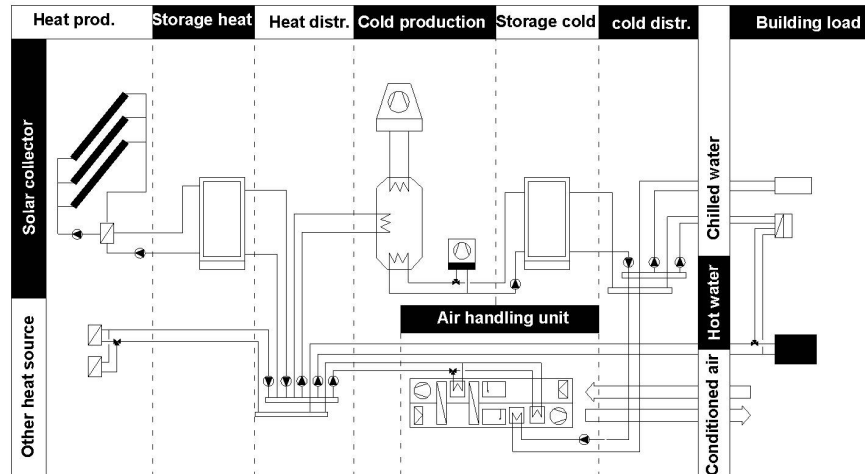


Image courtesy of Hans-Martin Henning

Figure 10-4 Schematic description of a solar air-conditioning system showing the integration of different component options.

and an auxiliary subsystem (which is integrated at different places in the overall system and is used as an auxiliary heater parallel to the collector or the collector/storage, as an auxiliary cooling device, or both). International research and development efforts, case studies, monitoring data, and quality assurance and support measures for solar cooling systems are available from several tasks (e.g., Tasks 53, 48, 38, and 25, respectively) from the International Energy Agency's (IEA) Solar Heating and Cooling Programme.

The average specific solar collector area averages 136 ft²/ton (3.6 m²/kW refrigeration), ranging from 19 to 208 ft²/ton (0.5 to 5.5 m²/kW refrigeration), depending on the employed technology. Adsorption and absorption systems typically use more than 76 ft²/ton (2 m²/kW refrigeration) and usually less than 189 ft²/ton (5 m²/kW refrigeration). Overall, H₂O/NH₃ systems require larger specific collector areas than LiBr/H₂O systems and, as a result, the installations are usually more expensive. The initial overall cost per installed cooling capacity averages about \$13,400/ton or 4000 Euro/kW_R at 2017 exchange rates, excluding the cost for distribution networks among the system and the application and the delivery units.

Each technology has specific characteristics that match the building's HVAC design, loads, and local climatic conditions. A good design must first exploit all available solar radiation and then cover the remaining loads from conventional sources. Proper calculations for collector and storage size depend on the employed solar cooling technology. Hot-water storage may be integrated between the solar

collectors and the heat-driven chiller to dampen the fluctuations in the return temperature of the hot water from the chiller. The storage size depends on the application; if cooling loads mainly occur during the day, then a smaller storage unit will be necessary than when the loads peak in the evening. The goal should be to avoid heating the hot-water storage by the backup heat source as much as possible. The storage's only function is to store excess heat of the solar system and to make it available when sufficient solar heat is not available. An overview of European efforts on solar combi and combi-plus systems, summarizing their main design and operational and performance characteristics, is available in Balaras et al. (2010). New generation solar thermal cooling systems continue driving a strong and sustainable market development of cooling systems throughout the world (<https://task53.iea-shc.org/>).

Evaluation of Solar Thermal Systems

The percentage of energy a solar system can provide is known as the solar fraction. The original method for evaluating solar thermal systems was developed by Sanford Klein at the University of Wisconsin and is known as the F-Chart method (Klein and Beckman 2001). This method provides an accurate assessment of the amount of energy a solar thermal system will provide. This modeling provides the designer the ability to vary system parameters (e.g., collector area, storage volume, operating temperature, and load) to optimize system design. The method was originally developed to aid engineers who did not have computer resources available to do the complex analyses required for solar thermal calculations. More recently, several commercially available software packages have become available that use closed-form energy balance modeling of the system.

The cost effectiveness of thermal solar systems is also dependent on having a constant load for the energy the solar system provides. Since space heating requirements are generally seasonal in most climates, it is advisable that energy from the solar system have more uses than space heating alone. Domestic water heating is usually a much steadier year-round load, though typically not very substantial. Solar cooling can extend use of solar collectors during the summer. The fact that peak cooling demand in summer is associated with high solar radiation availability offers an excellent opportunity to exploit solar energy with heat-driven cooling machines. The cost analysis of a proposed system would evaluate the energy provided with respect to the load variation expected (or known) versus the initial system cost, the cost for supplemental energy and overall solar availability.

Solar-Electric Systems

By far, the most promising application for on-site renewable energy in buildings is through solar photovoltaics (PV). The direct conversion from sunlight to electricity is accomplished with PV systems. These systems continue to drop in price, and many US states, the federal government, and various countries worldwide offer tax incen-



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Technical and legal factors have generally been worked out that have hindered the use of grid-tied solar PV systems in the past. In temperate climates, grid-tied PV systems provide a good method to reduce peak summer electrical demand, since peak solar gains generally correspond to peak air-conditioning demand. This was a major factor that led to the passing of the California Million Solar Roofs initiative in early 2006, a program that far exceeded expectations—reaching 9 GW by the end of 2019, and evolving to a mandate for solar on all new homes as of January 2020. The state rebate reduced the first cost, attracting more homeowners into the market, improving the whole supply chain, and ultimately reducing the price of rooftop solar PVs from \$9.45 per watt in 2006 to \$3.80 per watt in 2018 (<https://environmentcalifornia.org/>).

In Europe, the first large-scale effort was initiated with the German 100,000 Roofs Program (HTDP) in early 1999 to reach a goal of 300 MW. It was successfully completed in 2003 with the parallel introduction of the German Renewable Energy Resources Act (EEG) that came into effect in 2000. The EEG and HTDP program secured commercially oriented PV investors because they received a full investment payback. In the coming years, the pan-European solar rooftop aims to promote the deployment of both PV building installations and distributed storage as an integral part of the upcoming “renovation wave” initiative¹, part of the EU’s Green Deal². The goal is to generate around 680 TWh per year, about a quarter of current electricity consumption, even at a cost lower than the current residential tariffs (Bodis et al. 2019).

The market initially developed with small-scale PV grid-connected installations on buildings, following the so-called “smart- or net-metering” policies. These were adopted by several countries (e.g., US, Canada, Denmark, The Netherlands, Portugal, and Korea) that offered credits for PV-generated electricity that was fed to the grid (IEA 2020). Progressively, the new policies are favoring self- and real-time consumption of the generated electricity, which are complemented with a feed-in tariff for the excess PV electricity that is fed into the grid (IEA 2020). As a result, PV producers are evolving to *prosumers*, a concept that encourages consumers to produce and self-consume electricity, sell the excess to the grid, and when necessary, buy power from the grid. For example, in the EU, the recent measures proposed with the European Green Deal³, among others, rely on smart grid technologies, solutions, and concepts.

According to the International Energy Agency, the cumulative installed capacity of PV systems around the world in 2019 has reached about 627 GWp (peak giga-

1. https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en

2. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

3. Ibid.

watts) (IEA 2020). The PV performance using different technologies and configurations of grid-connected and stand-alone systems can be accessed using a simplified tool called Photovoltaic Geographical Information System (PVGIS). This is a freely available multilanguage web service that provides detailed information on both the solar energy resource and the potential electricity output of PV technologies in Europe, Africa, most of the Americas, and part of Asia.

The economic viability of PV systems is dependent on many factors. Improvements in technology and manufacturing techniques have lowered the cost of PV systems dramatically. The actual prices for installed PV systems vary significantly. For example, the average system price per peak watt for residential systems at the end of 2019 reached 1.03 AUD/Wp in Australia, 3.30 USD/Wp (3.00 €/kWp) in the USA, and 240 JPY/kWp in Japan (Jäger-Waldau 2019).

Increasing the number of PV rooftops may lead to some stability issues and distortions to the power distribution systems. To minimize these problems, it is possible to use batteries coupled with intelligent control systems that utilize and store surplus electricity in grid-interactive installations (Figure 10-5b). This is a practical solution for small-scale storage in low-voltage distribution grids. Battery prices have declined by 85% over the past decade and are expected to drop below 100 USD/kWh by 2025 (Jäger-Waldau 2019). In particular, lithium-ion batteries could reach leveled costs of electricity storage below 0.05 USD/kWh by 2025.

The relative fraction of the total system cost due to the PV modules has dropped significantly as well, with the module plus inverter cost now representing only about one-third to one-half of the total installed cost (depending on if it is a smaller residential scale or larger utility-scale system). The typical PV cell efficiencies (i.e., the ratio of electrical energy produced by a solar cell to the incident solar irradiance) currently range from less than 5% for the first generation of thin-film cells to more than 24% for the most advanced crystalline-silicon cells in laboratory conditions. However, under real outdoor conditions, the actual PV efficiency for a multi-crystalline PV array may be about 18% lower than under standard test conditions (STC) for similar operating conditions (Gaglia et al. 2017). For example, the actual PV efficiency ranged between 6.2% to 10.4% throughout the year, with a mean annual value of 8.7%, compared to STC technical specifications of 9.58% to 11.31%, since the prevailing outdoor conditions are significantly different from the laboratory STC. The PV temperature is the most important parameter that affects its efficiency and results in high variations in the actual power output.

PV module prices have dropped by over 85% in most markets over the past decade. As a result, the benchmark leveled cost of electricity from PVs (i.e., the price at which electricity must be generated to break even over the project's lifetime) has decreased by 80% to 57\$/MWh (52€/MWh) between the end of 2009 and the first half of 2019 (Jäger-Waldau 2019). The cost of PV systems is stabilizing now as the cost of panels is approaching a minimum and the other system costs (e.g., labor) are more or less fixed.



Image courtesy of DOE/NREL, credit Ben Kroposki.

Image courtesy of DOE/NREL, credit Lawrence Berkeley Lab

Figure 10-6 Building-integrated PVs.



Image courtesy of DOE/NREL, Credit United Solar Ovonic

Figure 10-7 Building-integrated PV roofing.

The integration of PV systems with building materials is a new development that may, in the long run, help make PV systems viable in most areas. One of the key ways to incorporate solar energy technologies is to integrate them directly into the architecture of the building (see Figure 10-6). PV panels can become overhangs for the building or parking shading structures. Using these elements as part of the building doubles the value of the systems. An example of these technologies is the concept called *building-integrated PVs (BIPVs)*. A picture of one concept is shown in 10-6 and 10-7. These are being developed by the National Renewable Energy Laboratory (NREL), among others. PV collectors are addressed in GreenTip #10-3. More information on building applied or integrated PVs, design considerations, along with installation and operation guidelines are available in Chapter 36, “Solar Energy Use,” of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2019).

WIND

Using prevailing breezes and wind energy is one of the most promising alternative technologies today. Wind turbine design and power generation have become more reliable over the last 30 years. Consistency and velocity of available breezes are essential to successful application of wind for electrical generation and natural ventilation in buildings. Information on velocities, durations, and direction of winds in a project area is generally available from the National Oceanic and Atmospheric Administration (NOAA). That said, wind power systems installed on buildings or on actual new building project sites are still relatively rare; the wind energy availability is not that great in urban environments. There is also a disadvantage of scale; one or two wind turbines alone are destined to be less cost-effective than a wind farm with hundreds.

From a natural-ventilation perspective for passive cooling of buildings, other factors (e.g., temperature and relative humidity) must also be taken into consideration. Many areas can use outdoor air/natural breezes to provide passive cooling only during a limited period of the year, requiring designers wanting to use natural ventilation to carefully analyze both climatic conditions and cost to implement. The benefits of using natural ventilation must be weighed against the consistency of breezes, potential for higher relative humidity levels (which may affect indoor air quality), and the impact on occupant comfort and HVAC operation.

There are many excellent examples where natural ventilation provides the cooling needed throughout the year, but most are located in cool, arid climates. Even in moderate climates, such as that in Atlanta, GA, natural ventilation can provide passive cooling during some periods of the year, but in doing so, the designer must consider the impact on HVAC operation and building control. These elements may be very difficult to get to work effectively with operable windows. Additional programming and control points are required for successful operation. The potential of natural ventilation, its appropriate use, the design and dimensioning methodologies, the need for an integrated design approach, and how to overcome barriers are available in Etheridge (2012).

Integrating one or more wind turbine generators at a building site is a more active approach. Wind turbines should first be evaluated by looking at the wind resource at the site. Micro-wind turbines are easier to install, having a swept area of less than 270 ft² (25 m²) and rated power up to 6 kW; performance will depend on the roof position, roughness of the upwind area, upward edge rounding, and the yaw of the free stream wind (Serero 2016). The units can be stand-alone or building integrated turbines, some even using commercial-scale wind turbines into a building (Figure 10-8). Vertical axis wind turbines are easier to operate in urban environments since they are not affected by turbulent flows. They tend to be noiseless and have a low cut-in speed and large cut-off speed, resulting in long operating



Figure 10-8 Examples of vertical (top row) and horizontal stand-alone (bottom row) and building-integrated wind turbines.

times. Horizontal axis wind turbines perform well with laminar flows but perform poorly in urban environments with turbulent flows and generate noise as high as 200 dB within a radius of 1640 ft (500 m) (Garcia et al. 2019). For most small-scale wind turbines, steady winds over 20 mph (9 m/s) are preferred to maximize cost-effectiveness. Other issues that add difficulty include noise, vibration, building geometry (if on the building), wind pattern interrupters, wildlife effect, periodic maintenance, safety, visual impact, and community acceptance; these must also be considered.

BUILDING RES GRID INTEGRATION

Buildings are reaching higher energy performance, and progressively more emphasis is placed on transforming buildings from relatively passive loads on the grid to dynamic partners in the electricity sector (Figure 10-9), providing (i.e., selling) electricity and exchanging information that allows for load balancing to support a stable and reliable grid (ASHRAE 2018).

The distributed energy resources in urban areas are usually small electric generation units, for example, from 3 kW to a few megawatts of rooftop or building-integrated PVs, on-site ground-mounted arrays, or even nearby distributed renewable generation. Local electric storage may use batteries and even electric vehicles to help balance the grid and make it more flexible. These elements are combined in small local electrical grids and operated with sophisticated smart controls. They may include very small nanogrids (i.e., residential or single buildings) or larger microgrids (i.e., a neighborhood or a campus with multiple buildings) that employ different generation technologies and enable multiple buildings to share electricity and storage.

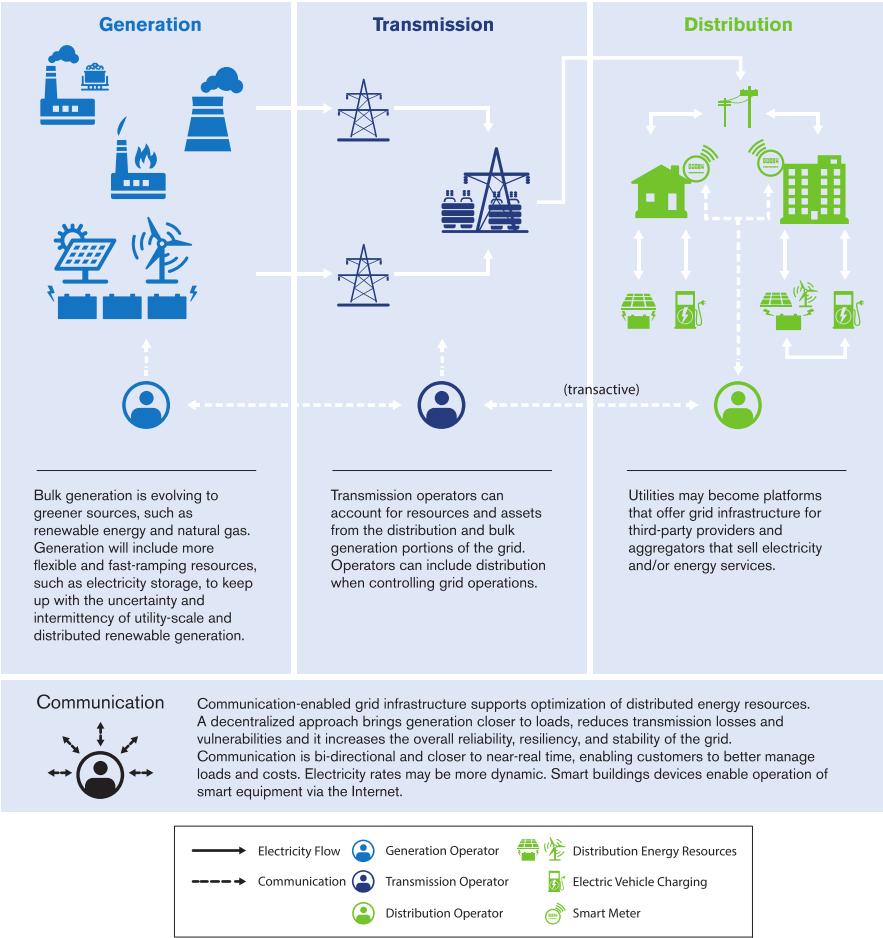


Image Courtesy of ASHRAE/NREL

Figure 10-9 The evolving electrical grid with bidirectional flow of electricity (ASHRAE 2018).

The local grids are connected to the main electrical grid at a point of common coupling through a main switch. The switch can automatically or manually separate the local grids from the main grid, allowing the nanogrid or microgrid to function independently as an island, which is usually referred to as “islanding.” This way, it is possible to maintain the same voltage, align frequency, and disconnect if there is a power outage or need to control electricity flowing back onto the grid. A key element of distributed energy resources is demand control and load management to

secure a stable and reliable power supply. This is accomplished with demand-side management programs, demand response, and energy management technologies.

Grid-interactive efficient buildings are grouped and connected to distributed energy resources (DERs) to collectively manage and optimize their energy performance with community solar, battery and thermal storage, and electric vehicle charging while improving occupant comfort (Fitzsimmons 2020). In the U.S., an exemplary community at Reynolds Landing in Alabama uses 44% less energy and 34% less power demand during winter peak hours than similar all-electric communities (Buckberry et al. 2020). The community has shown its resilience by successfully islanding itself from the grid during outages and “flexed its flexibility” to provide between 100 and 200 kW of grid services on-demand.

BIOMASS

Biomass is the conversion of plant and animal matter into useful energy. Several ideas should be investigated to be considered as an energy source in a building. In the European Union, “bioenergy contributes only to 3.7% of the total primary energy supply; however, it plays a considerable role in several European countries, such as Finland and Sweden where its contribution amounts to respectively 20% and 16% of the gross inland consumption” (Bioenergy Europe).

Wood chip conversion to heat (and possibly then electricity) can replace boiler systems in buildings. Automatic feed systems can now take wood chips and make hot water as conveniently as oil and natural gas systems can. In many locations, wood chips are free for the cost of the transportation, saving further cost. Pellet burners are a similar concept, except for the additional cost of the wood pellets. Burners are also available for corn cobs. In some cases, manufacturers will lease equipment for the energy savings, resulting in no additional cost to the end user.

The production and distribution of bio-oils and biodiesel fuels derived from bio-based materials is growing in momentum. Heating systems are available to burn used vegetable oils. These systems are useful near the point of production of used vegetable oil—usually the food service industry. Grocery stores and restaurants may benefit from such technologies. Most diesel-fueled machines can run on biodiesel without any (or minor) modifications. In addition, hauling and waste costs for the oil are eliminated, increasing the attractiveness of the technology.

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ASHRAE GreenTip #10-1

Passive Solar Thermal Energy Systems

GENERAL DESCRIPTION

Passive solar thermal energy systems use solar energy (mainly for space heating) via little or no use of conventional energy or mechanisms other than the building design and orientation. All above-grade buildings are passive solar. Making buildings collect, store, and use solar energy wisely then becomes the challenge for building designers. A building that intentionally optimizes passive solar heating can visually be a solar building, but many reasonably sized features that enhance energy collection and storage can be integrated into the design without dominating the overall architecture.

To be successful, a well-designed passive solar building needs (1) an appropriate thermal load (e.g., space heating); (2) aperture (e.g., clear, glazed windows); (3) thermal storage to minimize overheating and to use heat at night; (4) control, either manual or automatic, to address overheating; and (5) night insulation of the aperture so that there is not a net heat loss.

HIGH-PERFORMANCE STRATEGIES

The following strategies are general in nature and are presented as guidelines to help maximize the performance of a passive thermal solar design:

- Think about conservation first. Minimizing the heating load will reduce conventional and renewable heating systems' sizes and yield the best economics. Insulate, including the foundation, and seal the building well. Use quality exterior windows and doors.
- In the northern hemisphere, the aperture must face due south for optimal performance. If this is not possible, make it within ± 10 degrees of due south. In the southern hemisphere, this solar aperture looks north.
- Minimize use of east- and west-facing glazing. They admit solar energy at nonoptimal times, at low angles that minimize storage, and are difficult to control by external shading. Also, reduce north glazing in the colder regions of the northern hemisphere because this can lead to high heat loss rates.

- Use optimized and/or movable external shading devices, such as overhangs, awnings, and side fins. Internal shading devices should not be relied upon for passive solar thermal control—they tend to cause overheating.
- Use high-mass direct gain designs. The solar collector (windows) and storage (floors and potentially walls) are part of the occupied space and typically have the highest solar savings fraction, which is the percent of heating load met by solar. Directly irradiated thermal masses are much more effective than indirect, thus, floors or Trombe walls are often best.
- Use vertical glazing. Horizontal or sloped windows and skylights are hard to control and insulate.
- Calculate the optimal thermal mass—often around 8 in. thick (about 200 mm)—high-density concrete for direct-gain floors over conditioned basements. The optimization should direct the designer to a concept that will capture and store the highest amount of solar energy without unnecessarily increasing cost or complexity. For all direct-gain surfaces, ensure they are of high absorptivity (dark color) and are not covered by carpet, tile, much furniture, or other items that prevent or slow solar energy absorption. Be sure the thermal mass is highly insulated from the outdoor air or ground.
- Seeking a very high annual solar savings fraction f_s often leads to disappointment and poor economics, so keep expectations reasonable. Even a 15% annual fraction represents a substantial reduction in conventional heating energy use. In an appropriate climate, a highly optimized passive solar thermal single-family house often only has about a 40% solar fraction. Combining passive with active solar, PVs, wind, and other renewable energy sources is often the most satisfactory way to achieve a very high annual solar savings fraction.

An old solar saying, of unknown origin, is “the more passive a building, the more active the owner.” Operating a passive solar building to optimize collection has thus been called *solar sailing* and requires time and experience. Be sure that passive solar and the building operator are good matches for each other.

CHAPTER ELEVEN

LIGHTING SYSTEMS

OVERVIEW

This chapter is intended to familiarize the reader with the process of sustainable lighting design, which is not only about energy efficiency but also about using light (daylight and electric) and lighting controls to improve the comfort, productivity, and well-being of occupants. While Chapter 8 provided information on lighting quality aspects of sustainable lighting design, this chapter will focus on energy as an aspect of sustainable lighting design.

ELECTRIC LIGHTING

Sustainable Lighting Design

Sustainable lighting design is a comprehensive concept that looks beyond just saving lighting energy to looking at the total life cycle of the lighting systems and how to minimize their impact on the environment. Sustainable lighting solutions address the following:

- Decreased overall environmental impact
- Significant reduction in operating costs
- Safety and security in all parts of an operation
- Good lighting quality (visual acuity with proper illuminance levels, dimmability, color tunability, low visible flicker, and so on [see Chapter 8])
- Reduced carbon footprint
- Responsible disposal at end of life

Other environmental factors to consider when designing or selecting lighting systems and fixtures are as follows:

- Longer lamp life
- Reduced use of hazardous materials (for example, mercury content)
- Higher efficacy

- Lighting controls (controllability of the lighting system [manual and automatic control])
- Proper disposal (recycling)
- Use of recycled materials
 - Preconsumer
 - Postconsumer
 - Packaging materials

Energy-Efficient Lighting Design Standards

The lighting design profession is increasingly focused on providing high-quality visual environments, using energy efficient strategies. Lighting technologies have become more efficient, and expectations for interior illuminance (measured in foot-candles [I-P] or lux [SI] at the task level) have moderated while still meeting the illuminance levels required for the tasks of activities in a given space. Therefore, it is now possible to design high-quality lighting at connected power levels that are much lower than 30 years ago. It is much easier to regulate lighting based on installed lighting power rather than actual illumination levels. A number of governmental entities have incorporated regulatory requirements regarding lighting, often focusing on restrictions limiting the lighting power density (LPD). The LPD is defined as the watts of power allocated for lighting per unit floor area (ft^2 [m^2]) in a building. Some have limited or banned outright the manufacture of lamps with low efficacies (lumen/watt ratio). For example, incandescent lamps that convert only one-tenth of their consumed energy to supply light have been banned in Europe and a phaseout has begun implementation in the United States.

Most energy codes currently have building LPD limits between 0.18 (parking garage) and 0.96 W/ft^2 (hospital) (about 1.9 and 10.3 W/m^2), depending on the occupancy type of the space. All buildings can be efficiently and comfortably illuminated using carefully selected, standard lighting equipment. Successful lighting systems with LPDs of 0.7 to 1.0 W/ft^2 (8 to 11 W/m^2) can be applied to most building types by following basic application design criteria set forth by the Illuminating Engineering Society (IES) and lighting equipment manufacturers. For offices and schools in particular, lighting quality is an important consideration for good overall IEQ. Lighting quality is generally defined as being relatively uniform, visually comfortable, with low glare, and designed to appropriate illuminance levels for the tasks performed. This includes balancing both the horizontal and vertical brightness. See Chapter 8 for more on lighting quality.

ANSI/ASHRAE/IES Standard 90.1-2019 lists LPDs for various types of buildings but excludes some types of specialty lighting from a required maximum LPD (e.g., those used for museum displays, medical procedures, retail display, exit signs, performance theater). Users may use one of two methods to comply: (1) the space-by-space method, which assigns LPDs to individual space types based on the

specific tasks which will occur within, or (2) the building area method, which averages all of a building's space types to a single building LPD. When using the space-by-space method, some spaces within a building are allowed to have much higher or much lower LPD levels than specified for the building through the building area method. How the lighting systems are controlled also may be a factor in determining the final required LPD. The *International Green Construction Code*®, powered by ANSI/ASHRAE/USGBC/IES Standard 189.1-2020, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings*, heretofore called IgCC/189.1, specifies reductions in LPDs from those specified in Standard 90.1 for more aggressive energy savings targets and will be discussed later in this chapter.

The lighting designer will select the appropriate luminaires, sources, and control configurations to create appropriate illuminance levels (measured in footcandles or lux). These selections will be based primarily on the room's intended activity while conforming to the maximum LPD required by code. The fundamental guide used by lighting professionals is the *Lighting Library*®, developed by the Illuminating Engineering Society (IES). The *Lighting Library* comprehensively describes recommended design approaches, illuminance and uniformity levels, power density targets, daylighting integration strategies, luminaire efficiency, and related information necessary for appropriate lighting design.

Efficient Lighting Systems

Lighting has a significant impact on building loads and energy usage. According to the US Energy Information Administration (EIA) Annual Energy Outlook 2021, energy powering lighting accounts for roughly 10% of the total energy used in commercial buildings. This number has come down from about 20% over the years, mainly due to the adoption of energy-efficient light-emitting diode (LED) lighting. However, lighting remains one of the largest end uses of electricity in commercial buildings, second only to the broad category of other electricity end uses. The other category of electricity uses include items such as miscellaneous electric loads (MELs), process equipment, motors, and air compressors. So lighting is still low-hanging fruit for energy savings in commercial buildings, particularly with existing building retrofits.

Lighting also adds heat to the conditioned space—especially when using non-LED lamps. This additional heat increases cooling loads but decreases heating loads. Therefore, the HVAC designer must understand the chosen lighting systems and their effects on HVAC loads. Architectural configurations and interior design decisions dictate the potential to offset electrical lighting needs with daylighting. Consequently, the productive collaboration of all design professionals, including the lighting designer, architect, interior designer, as well as the HVAC, energy, and

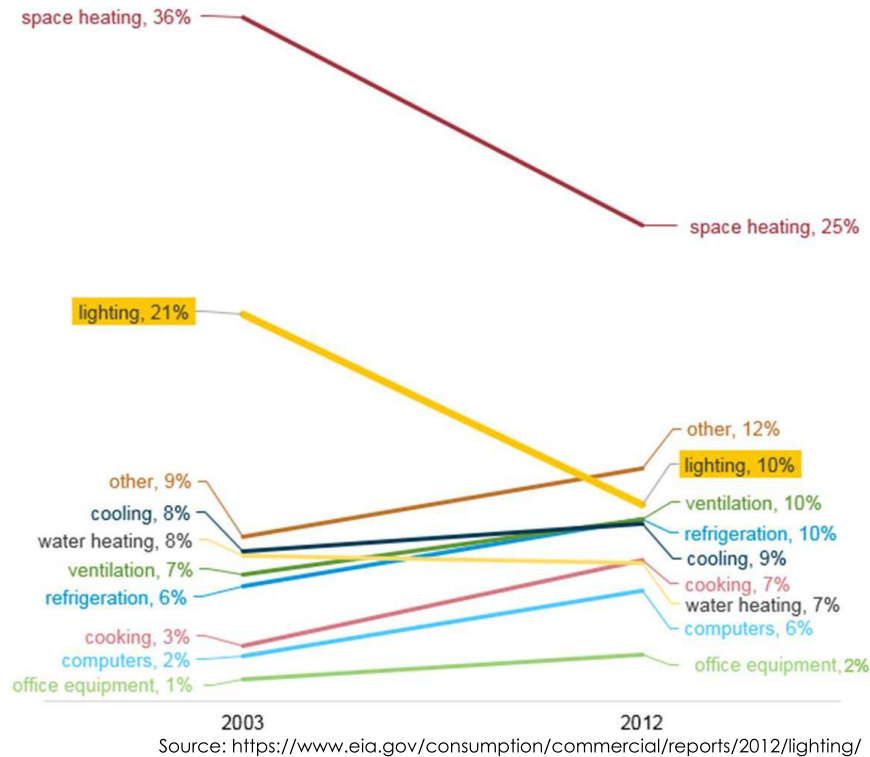


Figure 11-1 Lighting in commercial building sector as percentage of total energy consumption has decreased over time.

electrical engineers, can enhance the overall energy and the environmental performance of buildings. This chapter provides insight into the latest technologies or practices at the time of publication, but given the rapidly changing lighting landscape, this chapter should just be used as a guideline. Because California is a notable example of stringent energy codes (Title 24 Part 6), the reader is advised to look at the California Energy Design Resources pages on lighting, with the website reference listed at the end of this chapter.

The lighting industry has made great strides in energy efficiency in the last several decades and continues to undergo a major shift with the advent of solid-state LED technology. In general, a lighting designer should perform a detailed life-cycle cost analysis to ensure the investment makes sense. A few other recommendations for energy-efficient lighting design include the following:

- Spacing measurements for lighting design are taken from the plan-view center of the luminaire. Luminaires should be mounted at least one-third of the indicated mounting distance away from any ceiling-high partition.
- To allow integration with daylighting, luminaires in rows should ideally be parallel to windowed walls so that controls can be used to step lamps on or off based on the amount of daylight penetration into the room.
- The luminaire type needs to be carefully considered to provide visual acuity for the intended task, visual comfort, glare control, efficacy (lumen/watt output), and total system efficiency for any particular space type. The proper specification of lighting equipment is necessary to optimize lighting quality and minimize energy use.

The following luminaire types have cost effective energy alternatives and, therefore, should be avoided:

- Luminaires using Edison base (standard screw-in) sockets or halogen lamps using any sockets rated over 150 W
- Luminaires designed for incandescent or halogen low-voltage lamps exceeding 75 W
- Track lighting systems using any kind of incandescent or halogen
- Line-voltage monopoints allowing the later installation of incandescent or halogen track luminaires.

This chapter is not intended to be comprehensive summary of the lighting industry but rather to provide a straightforward and instructive approach to basic sustainable lighting design. Professional lighting design assistance may be needed to reach optimum performance in complex spaces and for special conditions.

In all cases, the reader should be certain to review the subsequent sections on other aspects of lighting for detailed information on product specifications and additional energy-saving alternatives.

A Word About LEDs

The lighting industry has made significant improvements in lamp and ballast technology over the last few decades. Recent lighting innovations continue to permit quality lighting even at greatly reduced power levels and with less waste heat generation. Proper specification of lighting equipment is an important part of actualizing these results. The adoption of solid-state LED lighting has allowed this shift.

LEDs have many great features. The energy savings of LEDs exceeds the rival compact fluorescent lamps (CFLs) that had been the standard high-efficiency lighting fixture until recently, and LED lighting efficiency continues to improve. They are a great option for hard-to-access areas where a 50,000+ hour lifetime (for the

better-quality fixtures) means the fixture or lamp does not need to be changed for years.

LEDs can provide good color rendering and pleasing light, but this varies by the LED manufacturer.

Another great feature of LEDs that is often overlooked is that they produce immediate light output. The sluggish start of a CFL may cause you to think the lamp is out, or someone may trip over something in the middle of the room before the light comes up, whereas LEDs eliminate this problem.

Lastly, LEDs are a more sustainable light source that does not have any harmful materials such as mercury (that require special recycling) and adds a relatively small amount of waste heat into the space, that would contribute to the air-conditioning cooling load.

A summary of the key advantages for LED lighting is shown below.

- Energy savings (up to 150 lumens/watt and improving)
 - 20W LED or less can replace a 100W incandescent
- Reduced maintenance costs
 - 50,000+ hour lifetime
- Appealing color temperature
 - 2700 K to 6500 K and beyond
- More accurate color rendering
 - 90 Color Rendering Index (CRI) or higher is available
- Immediate light output
- No UV/IR radiation
- No mercury, no lead
- Controllable and dimmable

The reader is encouraged to use LEDs over other light sources whenever possible.

Lighting Power Density Determination Using ASHRAE Standards

IgCC/189.1 (ICC 2021) specifies reductions in the LPD values given in ANSI/ASHRAE/IES Standard 90.1-2019. These lower LPD values are encouraged to become the basis of design for high-performance buildings. Both of the following methods are acceptable to use to determine the allowable LPD: the *building area method* or the *space-by-space method* can be used to comply with this standard. Examples are given below for both methods for an office building.

The allowable LPD values specified in ANSI/ASHRAE/IES Standard 90.1 have been lowered in the past several versions of the Standard to reflect lighting technology (and cost) changes. For example, under the building area method, the allowable Standard 90.1 LPD for an office building was listed as 0.90 W/ft² (9.65 W/m²) in the 2010 version of the Standard, dropping to 0.82 W/ft² (8.8 W/m²) in 2013, then to 0.79 W/ft² (8.5 W/m²) in 2016, and 0.64 W/ft² (6.9 W/m²) in 2019. The building

area method sets the maximum total wattage for installed lighting based on the total floor area. The LPD is then multiplied by the gross (interior) area of the building to arrive at the maximum allowable installed lighting wattage for the building. The Standard 90.1 values are code minimum, while IgCC/189.1 uses the Standard 90.1 LPDs but has made aggressive lower modifications for increased energy savings. Table 11-1 shows a comparison of LPDs from both Standard 90.1 and IgCC/189.1.

Application of the space-by-space method for determining LPD values in an office building is done for each different space type. Typical spaces found in office buildings were assumed for this example. A hardwired lighting system for a high-performance green building would be installed with the lighting power density (LPD) requirements shown in the last column of Table 11-1. The area of each space is multiplied by the LPD for that space to determine the maximum connected (hard-wired) lighting wattage. For example, for an open office area of 400 ft² (37.2 m²), the maximum wattage for lighting would be 400 ft² × 0.55 W/ft² = 220 W (37.2 m² × 5.92 W/m² = 220 W).

Additional lighting, such as that hardwired to a furniture system, may be acceptable but should not be specified in a space unless a more complete analysis and design are undertaken. These systems need to be carefully coordinated with the permanent lighting systems of the building. An exception is portable plug-in lamps and manufacturer-installed luminaires on modular furniture, overhead cabinets, bins, or shelves.

The total amount of installed lighting is only part of the picture. Additional requirements regarding lighting control are discussed in the “Lighting Controls” section of this chapter. A thorough review of appropriate LPD requirements for all types of buildings can be done by considering both of the latest versions of IgCC/189.1 and ANSI/ASHRAE/IES Standard 90.1.

Specific Space Type Application Notes

Always check required illuminance levels using IES guidelines and LPD restrictions using Standards 90.1 and 189.1 or other applicable standards or codes to ensure both code compliance as well as following green design practices.

Open Offices. For general illumination in spaces with ceilings that are 9 ft (2.7 m) or higher, consider suspended lighting systems supplemented by task lights. Use high-performance luminaires.

Private Offices. Where ceiling heights allow, suspended LED lighting should be a first consideration for private offices, although recessed troffers can also be used. Task lights can also be integrated where appropriate.

Executive Offices, Board, and Conference Rooms. Executive offices can be designed similarly to private offices. If desired, a premium approach using LED downlights, wall washers, and/or accent lights can be used, but care should be taken not to exceed the required LPD.

**Table 11-1: LPD Values for Office Building Example
(Space-by-Space Method)**

Type of Area	Connected LPD Limit per Std. 90.1-2019		Percent Reduction of LPD per Std 189.1-2020	Connected LPD Limit	
	(W/ft ²)	(W/m ²)		(W/ft ²)	(W/m ²)
Private Office Areas ($< 250 \text{ ft}^2$ [23 m^2])	0.74	7.96	9.5%	0.67	7.21
Open Office Areas	0.61	6.56	9.8%	0.55	5.91
Restrooms	0.63	6.78	9.5%	0.57	6.14
Conference/Meeting/ Multipurpose Areas	0.97	10.44	9.3%	0.88	9.47
Lobby (general)	0.84	9.04	9.5%	0.76	8.18
Elevator Lobby	0.65	7.00	9.2%	0.59	6.35
Hallways and Corridors	0.41	4.41	9.8%	0.37	3.98
Lounge/ Recreation Area	0.59	6.35	25.4%	0.44	4.47
Mechanical and Electrical Rooms	0.43	4.63	9.3%	0.39	4.20
Stairwell	0.49	5.27	8.2%	0.45	4.84

Classrooms. Ideally, classroom lighting should be designed using direct/indirect lighting systems using high-efficiency LED-based fixtures. Care needs to be taken to ensure that all desks are evenly illuminated.

Corridors. Typically, corridors strategies include LED sconces, downlights, ceiling-mounted or close-to-ceiling decorative diffuse fixtures, or similar equipment. LED lamps will provide opportunities for changing lighting color as well as having the highest efficacy. Note that these luminaires may be connected to a generator and/or equipped with emergency battery backup when needed as an alternative to less attractive “bug eye” type emergency lighting.

High-Bay Spaces. Industrial, grocery, and retail space without ceilings or with very high ceilings (usually 15 ft [4.6 m] and above) need special lighting fixtures. For mounting heights up to 20 to 25 ft (6.1 to 7.6 m), first consider LED or fluorescent industrial luminaires with T5 lamps.

For mounting heights above 25 ft (7.6 m), consider T-5HO high-bay luminaires. High-wattage metal halide should be reserved for very high mounting (above 50 ft [15.2 m]) and for special applications (e.g., sports lighting).

Other Applications. The following luminaire types are generally recommended for these areas:

- *Artwork, bulletin/display surfaces, etc.:* use LED wall washers or low-voltage monopoint LED lights. Make sure to pay attention to the color rendition index (CRI) of the specific lamps when illuminating art work. A higher CRI will render colors better.
- *Utility spaces (e.g., cable and equipment rooms):* use LED strip lights or surface luminaires.
- *Lobby spaces, cafeterias, and other public spaces:* use appropriate selections from among these luminaires as much as possible.

LIGHT CONVEYORS (TUBULAR DAYLIGHTING DEVICES)

Light conveyors use a specialized technique whereby light from a source is transmitted some distance from the source to illuminate spaces, either along its length or some distance away. Some devices gather light and transmit it down a fiber-optic tube bundle to light an area at a distance; with sensors and lamps in the room it serves to seamlessly ensure constant illuminance. The source can be either natural light or an artificial source. More details on light conveyors are provided in GreenTip #11-1.

DYNAMIC GLAZING AND AUTOMATED WINDOW SHADES

Daylight coming in through skylights and windows can be too much of a good thing and should be managed so that it does not cause disruptive solar glare or too much solar heat gain into the space. There are static ways to help manage daylight, such as using manual window shades, permanent projects (i.e., overhangs), or light shelves that direct daylight upward to the ceiling, allowing non-glary diffuse daylight to reflect down to the occupants. However, these static ways have limitations that are overcome with active or dynamic glazing or shading solutions, such as electrochromic glass or automated window shades. These dynamic options automatically adjust the window tinting/shading throughout the day to allow optimal effective daylight to enter the space and block harsh direct-beam daylight from entering. More details on dynamic glazing and automated window shades are provided in GreenTip #11-2.

LIGHTING CONTROLS

General

While all modern energy codes require automatic shutoff controls for commercial buildings, implementing automatic controls in all building projects is a sound money- and energy-saving idea. There are two ways to reduce lighting energy use through controls:

- Turn lights off when not needed (which reduces hours).
- Reduce lighting power to minimum need (which reduces kilowatts).

With very few exceptions, each interior space enclosed by ceiling-high partitions must have a separate manual switching or dimming device to allow occupants to turn lighting off. Some form of an automated off control (e.g., occupancy-sensing, time-based scheduling, or other) is required to meet the latest codes. In addition, automatic daylight dimming for lights in daylit zones to further reduce energy usage is required. One of the most progressive new lighting-related energy code provisions we see in the *International Energy Conservation Code*® (*IECC*®) (ICC 2018) (soon to be added to ASHRAE Standard 90.1-2022 and California Title 24-2022) is the addition of partial-off or full-off via occupancy sensors in lighting zones in open offices. To better understand this, think of an open-concept office space with two lighting zones. Imagine the last occupant leaves the first zone, but people remain in the second zone. The lighting in the now empty first zone needs to dim or shut off entirely in the vacant zone. Then, after all the people leave the second zone of the open office, all the lights in the open office must shut off. This provides more granular control of the lighting in a space, saving more energy. To comply with code requirements and ensure maximum energy savings, specify as many lighting control strategies (discussed in the “Control Strategies” section) as possible. Figure 11-2 provides the mandatory minimum lighting control requirements for each interior space per ASHRAE Standard 90.1, which will also comply with *IECC* 2021 requirements since *IECC* uses Standard 90.1-2019 as an alternate compliance path.

Control Strategies

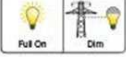
Below are some key energy-saving lighting control strategies that should be considered for your projects. The first five strategies are basic strategies, while the others are more advanced. The Online Resources section at the end of this chapter lists sources for control strategies that should be developed and employed.

Applicability

The controls mentioned in the previous section are applicable to most commercial, institutional, and industrial buildings. Use common sense in special spaces, keeping in mind safety and security. Never switch path-of-egress lighting systems except with properly designed emergency transfer controls.

Pro

- There is low to moderate cost for most space types.
- There is virtually no maintenance.
- These controls will generally lower energy use.

Strategy	Potential Savings
 Scheduling provides pre-programmed changes in light levels based on time of day.	10–20% Lighting*
 Occupancy/vacancy sensing turns lights on when occupants are in a space and off when they vacate the space.	20–60% Lighting*
 High-end trim/tuning sets the maximum light level based on customer requirements in each space.	10–30% Lighting*
 Daylight harvesting dims electric lights when daylight is available to light the space.	25–60% Lighting*
 Personal dimming control gives occupants the ability to set the light level.	10–20% Lighting*
 Controllable window shading adjusts shades to reduce glare and solar heat gain.	10–20% Cooling*
 Demand response automatically reduces lighting loads as required to improve critical load stability.	30–50% Peak Lighting*
 Plug load control automatically turns off loads after occupants leave a space.	15–50% Non-Electronic*
 HVAC integration controls heating, ventilation, and air conditioning systems through contact closure, or BACnet protocol.	5–15% HVAC*

*Go to Lutron.com/References for more information

Source: Lutron Electronics Co., Inc.

Figure 11-2 Energy-saving control strategies.

Con

- If controls are not properly commissioned, unacceptable results may occur until they are fixed.
- Poorly installed and/or commissioned controls negatively affect system performance.
- Substitutions and value engineering can cause bad results.

DAYLIGHT HARVESTING

General Description

Most buildings are designed to have some type of natural light that is transmitted through windows and/or skylights. The majority of commercial, indus-

trial, and institutional buildings have windows and, in some cases, skylights, tubular daylighting devices, clerestories, or more extensive fenestration systems. *Daylight harvesting*, or *daylighting*, is a lighting control strategy that can be used in many situations to not only reduce energy consumption for the lighting but also to improve the overall indoor environmental quality for the occupants.

From an energy perspective, the optimal use of daylight is to reduce the load of the electric lighting system by dimming or switching off luminaires when natural light provides ample illuminance for the tasks performed in the space. It is important to note that the incoming light is only usable if it is controlled to reduce glare and illuminates a space in a way that is comfortable to the occupant (including the consideration of thermal comfort). This process of adjusting electric lighting in the presence of daylight, known as daylight harvesting (see Figures 11-3 and 11-4), is discussed in this section because of its significant energy-saving potential. When done properly, using continuous daylight dimmable light fixtures instead of stepped dimming or switched light fixtures, occupants do not notice the electric light changes as the electric light gradually adjusts based on the available daylight in the space. Fixtures that abruptly switch lighting in steps based on daylight may cause disruption to the occupants. Plus, continuously daylight dimmable lighting saves more energy because daylight dimmable fixtures constantly adjust lighting levels based on the daylight in the space, whereas switched or stepped fixtures do not adjust until a certain daylight threshold is reached, then they abruptly change the lighting level. So, the preferred method is to use daylight dimmable lighting fixtures.

Predicting daylight harvesting savings is a complicated process that involves a comprehensive understanding of the site, building orientation, weather conditions, materials, and system integration. There are some added capital costs for daylight harvesting elements, such as dimmable LED drivers (now typically standard with most LED luminaires) and photoelectric controls (also known as daylight responsive controls). It is important to justify these costs by accurately predicting the potential energy savings of daylight harvesting techniques. However, when the challenges of daylighting are appropriately addressed, significant energy savings are possible. In fact, the latest building energy codes are well aware of the potential for energy savings from daylight harvesting, so they have mandatory requirements for a minimum amount of daylight and lighting in daylight zones or areas (see Figure 11-4) to be controlled with daylight responsive controls. Studies have shown that providing daylight responsive controls for spaces that use more than 75 watts of lighting power in total for all the daylight zones in the space is cost-effective (CEC 2021).

From a lighting design perspective, daylight can be treated similarly to any other light source, so it can be used to compose lighting design solutions that take illumi-



Source: The New York Times Company
(https://facades.lbl.gov/newyorktimes/nyt_post-occupancy.html)

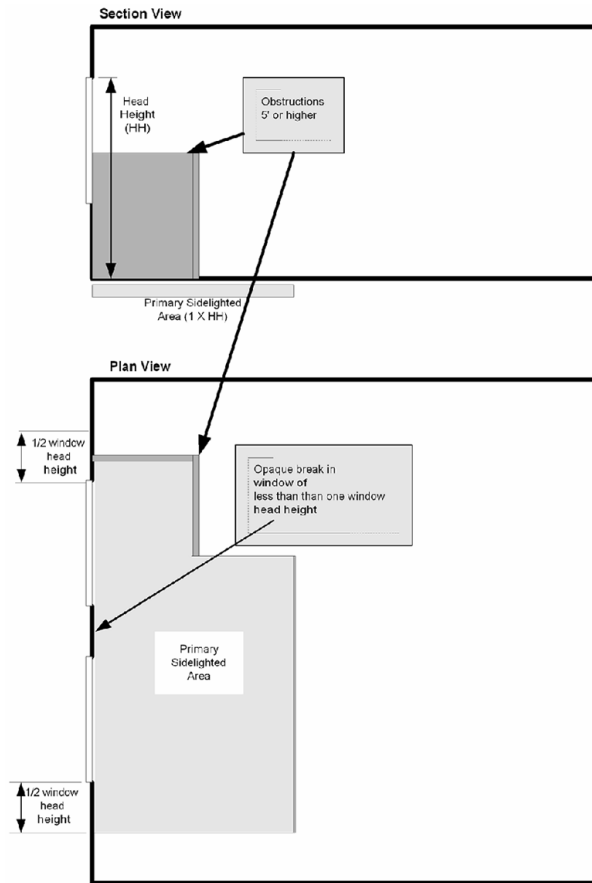
Figure 11-3 Interior view of the Times Building five years after occupancy. The overhead lighting is dimmed in response to available daylight, while the automated shades are adjusted to control for glare and direct sun.

nance, luminance, contrast, color rendition, and other lighting design elements into consideration. However, the lighting designer is challenged to deal with the fact that the light source varies daily and throughout the year. The designer can use blinds, shades, curtains, moveable shutters, light shelves, light conveyors, and other mechanical forms of attenuation and shielding to control daylight.

It is possible to simulate the performance of daylight to determine the amount and, to a certain extent, the quality of available daylight under varying conditions of the season, time of day, and weather. However, this is exhaustive analytical work of a highly specialized nature, and it is recommended that appropriate experts perform such studies. In the meantime, some buildings can benefit tremendously from some simple daylight-harvesting considerations.

Basic Toplighting

Basic toplighting typically involves using simple skylights or tubular daylighting devices in the roof. This is not to say that other toplighting configurations (e.g., the clerestory, roof monitor, or sawtooth roof) are not viable options; indeed, they often have advantages over horizontal skylights. There are many architectural elements,



Source: ASHRAE/IES Standard 90.1-2019

Figure 11-4 Example of daylight harvesting application.

including structure, waterproofing, and other details, that should be considered when exploring the appropriateness of skylights. When used in a manner similar to light fixtures and laid out to provide uniform illumination, toplights are an acceptable way to illuminate single-story, large spaces, or the top floor of a multistory building. Toplighting is best when a number of smaller skylights are used, in much the same way effective lighting systems have many light fixtures rather than one larger light source in the middle of the room. Skylights should be diffuse or prismatic rather than clear to avoid harsh glare from direct sunlight. When layouts adhere to these guidelines, skylights generally do not have to incorporate mechanical or electronic light control louvers because the optimum size of the skylight is

chosen for passive daylighting (i.e., typically, there are no active or moving elements needed to regulate the amount of interior light). If installed in an area requiring the ability to “black out” or darken the space (e.g., for showing movies or videoconferencing), some type of shading should be provided along with controls.

IgCC/189.1 and Standard 90.1-2019 require (in the prescriptive compliance path) a minimum amount of toplighting for buildings of three stories or less having a large enclosed space of 2500 ft² (232 m²) located “directly under a roof with finished heights greater than 15 ft (4 m).” Section 8.4.1 of IgCC/189.1 and Section 5.5.4.2.3 of ASHRAE/IES Standard 90.1 detail the minimum amount of toplighting required.

To determine the optimum size of skylights, one can download a program called SkyCalc. This program, which is optimized for California and the northwestern region of the United States, can be applied (with appropriate care) anywhere in North America. It takes into account location, utility rates, and other basic data, and yields recommended skylight area.

Note that the ideal amount of fenestrated roof is generally about 5%, but designers should always review governing standards and codes. All too often, architects, although well-intentioned, design skylights that are too big. Ideally, the optimized solution between light availability and overall energy use can be achieved.

When/Where Applicable

Daylight harvesting is best suited for skin-load-dominated (SLD) structures, especially single-story or narrow, multistory buildings. It is also an effective strategy for the top story of an internal-load-dominated (ILD) building. In structures where merchandise is sold, it has been found that sales increase for products displayed under skylights. Therefore, large-volume, single-story structures often used for big-box retail stores can still benefit from daylighting, because vertical glazing would be ineffective in bringing light to the deep interior.

Buildings serving several functions can benefit from daylighting, including the following types of buildings:

- Gyms
- Industrial work spaces
- Big box retail stores
- Grocery stores
- Exhibition halls
- Storage
- Warehouses
- Office buildings (if skin load dominated)
- Classrooms

It is essential to use automatic lighting controls programmed to dim or extinguish electric luminaires to efficiently integrate daylighting. Without them, the energy savings will not be realized. (See the later section on Lighting Controls.)

Pros of Daylighting

- Daylight harvesting offers significantly reduced energy consumption (exceeding 60%) and reduced HVAC load (as long as solar gains do not outweigh electric lighting reductions).
- Daylight extends the electric lighting maintenance cycle (lamps can last two to three times as long in calendar years with proper selection of fluorescent lamp/ballast combinations).
- Daylight has been shown to lead to improved human factors and increased enjoyment of space.
- Merchandise daylit under skylights sells at a faster rate.
- Daylight assists in maintaining proper circadian rhythm, which is especially important to sufferers of seasonal affective disorder (SAD)

Cons of Daylighting

- Sunlight is intermittent and variable.
- Daylight harvesting requires intensive architectural, structural, and lighting design coordination.
- There is a potential for glare and, therefore, glare control devices are often required.
- The user must be educated on the proper use and maintenance of the components.
- There is no assurance that the design will meet exact project lighting requirements.
- There can be higher construction costs and higher maintenance.
- There is a risk of poor design or installation workmanship, which can result in roof leaks.
- Daylighting may not be suitable for uncommon room shapes, sizes, and/or finishes.
- There is net decreased roof insulation when skylights are installed.
- Even when using high-performance glazing, there will be significantly larger heat loss than that lost through a solid insulated wall in winter. Additionally, occupants in close proximity to glazing during colder periods may experience discomfort.
- Heat gain may occur at undesirable times.

LIGHTING COST CONSIDERATIONS

Luminaires/Light Sources

The systems described above are generally low-to-moderate cost lighting systems. On average, they also use low-maintenance luminaires. The combination of low first cost, low maintenance, and low energy use leads to lighting choices that are among the most economical available.

Users should consider life-cycle costs when evaluating the use of LEDs. Although high in first cost, LED lamps have significantly higher efficacies and longer life, which can offset first cost in the course of the life cycle. Note, however, that LEDs installed in areas where they will overheat will experience shorter life.

Luminaire level lighting controls (LLCs) are another cost-effective option. LLCs are dimmable luminaires with embedded daylight and occupancy sensors. They also provide an alternative compliance path for the *IECC* 2018 and 2021 energy codes when every luminaire on the project is an LLC. While there is a premium price for LLCs, there is no additional installation for the daylight and occupancy controls since they are part of the fixture. LLCs can provide additional energy savings with separate granular control of every fixture (i.e., each fixture would have independent daylight and occupancy control) instead of controlling a group of fixtures together. However, LLCs may not make sense for every space as the location of the luminaires may not always be the best location for the sensors.

Daylight Harvesting

Daylight harvesting is a potentially complex undertaking in which the first cost of lighting remains the same, the cost of lighting controls increases, and the added cost of skylights and/or structural changes/complications are also incurred. To be cost-effective, this needs to be offset by a combination of HVAC energy savings, lighting energy savings, HVAC system first-cost reduction, and perhaps savings from utility incentives or tax credits. Expect daylight-harvesting systems to yield a four- to five-year simple payback with a utility incentive, six to eight years or more without.

Controls

The lighting control systems described previously are generally of low to moderate cost. Some are scalable from a room to a floor to the whole building or campus. Depending on the system features, building, and occupants, savings can range from modest to considerable. Using wireless networked lighting controls systems—many of which are designed with code compliance in mind—is more cost-effective,

as little or no control wiring is needed for the installation. They provide an easy way to achieve code compliance. Building owners and facility managers should consider simple, scalable wireless lighting control systems, which offer a variety of benefits, including simple design, faster installation, more programming options, and analytic capabilities. Look for manufactures that provide code design tools and strong service organizations to keep your projects on schedule and on budget. A good resource for lighting controls information and education is the Lighting Controls Association (listed in the References and Resources section).

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ASHRAE GreenTip #11-1

Light Conveyors (Tubular Daylighting Devices)

GENERAL DESCRIPTION

A light conveyor is a pipe or duct with reflective sides that transmits artificial or natural light along its length. There are three types of such light-directing devices:

1. a plastic square or round duct with curves or bends that transmits light along its length,
2. a relatively straight tube with an opaque, highly reflective interior coating that transmits daylight or high-intensity electric light to an interior space, and
3. a bundle of multiple fiber-optic tubes that transmit light from the outside (horizontally or vertically) to the interior.

The first type is a square duct or round pipe made of plastic. Based on how the inside of the duct or pipe is cut and treated, light entering one end of the pipe is reflected off these configurations (similar to how light is refracted through a prism) and transmitted through the pipe. The reflected light continues to travel down the pipe and out the other end. Because some light is absorbed and escapes along the length of the pipe (i.e., it is lost), the maximum distance that light can be piped into a building is generally about 90 ft (27.4 m). There are a few installations where sun-tracking mirrors concentrate and direct natural light into a light pipe. In most applications, however, a high-intensity electric light is used as the light source. Having the electric light separate from the space where the light is delivered isolates the heat, noise, and electromagnetic field of the light source from building occupants. In addition, the placement of the light source in a maintenance room separate from building occupants simplifies the replacement of the light source.

The second type of light-directing device is a straight tube with a highly reflective interior coating. The device is mounted on a building roof and has a clear plastic dome at the top end of the tube and a translucent plastic diffusing dome at the bottom end. The tube is typically 12 to 16 in. (300 to 400 mm) in diameter. Natural light enters the top dome, is reflected down the tube, and is then diffused throughout the building interior. The

light output is limited by the amount of daylight falling on the exterior dome.

The third type of tubular daylighting device uses fiber optics technology to transmit light into interior zones of a building. The most complex designs incorporate sensors, controls, and LED lamps to maintain relatively constant light output.

WHEN/WHERE IT'S APPLICABLE

Light-conveyor systems are best suited to building applications where there is a need to isolate electric lights from the interior space (e.g., operating rooms or theaters) or where electric light replacement is difficult (for example, above swimming pools or in roadway tunnels). For the latter reflective-tube system, each device can light only a small area (10 ft² [1 m²]) and is best suited to small interior spaces with access to the roof, such as interior bathrooms and hallways.

PRO

- A light conveyor transports natural light into building interiors.
- The first type of light conveyor isolates the electric light source from the lighted space.
- The first type of light conveyor reduces lighting glare.
- It lowers lighting maintenance costs.

CON

- A light conveyor may have greater capital (first) cost than traditional electric lighting.
- The tube type may increase roof heat loss.
- The tube type runs the risk of poor installation, resulting in leaks.
- The effectiveness may not be worth the additional cost.

KEY ELEMENTS OF COST

Because of the specialized nature of these techniques, it is difficult to address specific cost elements. As an alternative to conventional electric lighting techniques, it could add to or reduce the overall cost of a lighting system—and the energy costs required—depending on specific project conditions. A designer should not incorporate any such system without thoroughly investigating its

benefits and applicability and should preferably observe such a system in actual use.

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ASHRAE GreenTip #11-2

Dynamic Glazing or Automated Window Shading

GENERAL DESCRIPTION

Dynamic glazing or automated window shading is *fenestration*, defined as by ASHRAE Standard 90.1 as *an assembly, including the frame, in the building envelope that allows light to pass* (ASHRAE 2019). Fenestration assemblies include, but are not limited to, windows, plastic panels, clerestories, roof monitors, skylights, glass blocks, and doors where more than one-half of the door area is glazed) systems that adapt based on sky conditions to optimize daylight for energy savings and comfort. The terms *dynamic* and *automated* are used here to differentiate these active fenestration systems from static ones like fixed overhangs or light shelves. Dynamic glazing/automated window shading is capable of better performance than static fenestration systems.

Dynamic glazing is primarily thought of as windows that can automatically darken/brighten or become tinted/untinted based on climate parameters (e.g., using temperature-sensitive thermochromic [TC] coatings or with an electric signal as done with electrochromic [EC] glass). Automated window shading systems are essentially window attachments (e.g., interior roller shades) that automatically open or close based on the sky conditions. These fenestration systems automatically let in effective (non-glary sunlight) and block harsh direct sunlight (glary sunlight) when appropriate. Thus, they help to minimize solar heat gain when heat is unwanted (i.e., during the cooling season), add solar heat when wanted (i.e., during the heating season), and lessen solar glare while still providing occupants access to daylight and views.

The dynamic/automatic nature allows them to operate effectively every day, as many studies have shown that occupants don't take an active role in adjusting shades/windows. Typically when manual shades are used, the first time there is a glare situation, occupants will close the shades but will not open them after the solar glare is gone, thereby negating energy savings from daylight harvesting using daylight-responsive lighting controls. Moreover, dynamic glazing/automated window shading operates differently on each



Image courtesy of Lutron Electronics Co., Inc.

Figure 11-5 Example of automatic shading system for windows.

façade. For instance, on the eastern façade, automated window shades are closed in the morning to block direct beam sunlight while open on the western façade. Throughout the day, the shades automatically open gradually on the east façade and close gradually on the western one to best let in the optimal amount of daylight and block the solar glare automatically.

WHEN/WHERE IT'S APPLICABLE

Dynamic glazing/automated window shading is applicable to most buildings that have a lot of windows, especially ones with a window-to-wall ratio higher than 30%.

PRO

- Active dynamic glazing and automated window shading can be operated to address seasonal variations in solar and temperature

conditions, unlike static overhangs, for example, which behave the same way in September as in March, even though March is still typically heating season and September is often a cooling month.

- Can be operated to reject diffuse sunlight as well as direct sunlight, unlike static overhangs, which usually reject direct sunlight.
- Provides access to nonglary effective daylight, unlike fixed static options like overhangs, which can reduce useful daylight contributions.
- Views outside can still be maintained even when dynamic glazing/automated window shades are deployed (depending on the fabrics used).
- Maximizes energy savings from daylight harvesting.
- Helps achieve points in energy and indoor environmental quality categories in LEED and other green building rating systems. To obtain points in green building rating systems, the designer should incorporate these systems in energy and daylight modeling (often done for LEED projects).

CON

- First cost can be higher than fixed overhangs or other static options.
- Requires a control system.

KEY ELEMENTS OF COST

Because of the specialized nature of these systems, it is difficult to address specific cost elements. As a general rule of thumb, dynamic glazing tends to have more upfront costs than automated window shading, but the costs are coming down as the technology matures. Note if the project already uses a networked lighting control system that can also control window shades, the cost added from upgrading from manual window shading to automated ones is minimized. Even though upfront costs with the automated control systems are higher, these will allow for increased energy efficiency and occupant thermal comfort.

SOURCES OF FURTHER INFORMATION

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- LBNL. 2019. Intelligent Dynamic Facades. Berkeley, CA: Lawrence Berkeley National Laboratory. <https://windows.lbl.gov/intelligent-dynamic-facades>.
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CHAPTER TWELVE

WATER EFFICIENCY

Water efficiency and conservation continue to become critical factors in green-building design. In 2015, total withdrawals for public supply (water delivered for domestic, commercial, and industrial use) amounted to 39.2 billion gallons (148 million m³) per day (Dieter et al. 2018). Between 1985 and 2005, total water use increased by less than 3%, while water use in the buildings sector increased by 27% (DOE 2012). Water use in buildings accounts for a little over 2% of the total water consumption in the US, however, and the good news is that water use in one of the most water intensive-building types (inpatient healthcare) has steadily decreased with newer constructed facilities (EIA 2017). Efficient building products and operational practices provide opportunities to save significant amounts of water. The reduction in energy use through efficiency measures, the desire for lower operating costs, and the expectation of increased government regulation and standards are expected to drive further adoption of water-efficient products and methods.

The areas of focus for this *GreenGuide* chapter are cooling tower systems, water heating, plumbing design, landscape irrigation, and water recovery and reuse systems. Stormwater management with low impact design (LID) is covered in Chapter 7. Typical water use varies by building type, which significantly impacts the best approach to save water. In one typical commercial building with a water-cooled chiller, the HVAC system can account for approximately one-third of water consumption, whereas a similar building with an air-cooled solution may have little to no HVAC water use. Similarly, irrigation may be a heavy user or not present at all. Figure 12-1 shows the rough breakdown of water use within commercial buildings.

Plumbing systems are normally not considered within the purview of the HVAC&R designer's expertise. Nevertheless, designers, in practice, must work closely to put together functional building mechanical systems. Indeed, the designing firm for the HVAC and plumbing systems is frequently one and the same. For detailed design guidelines and information on these systems, please refer to the American Society of Plumbing Engineers (ASPE).

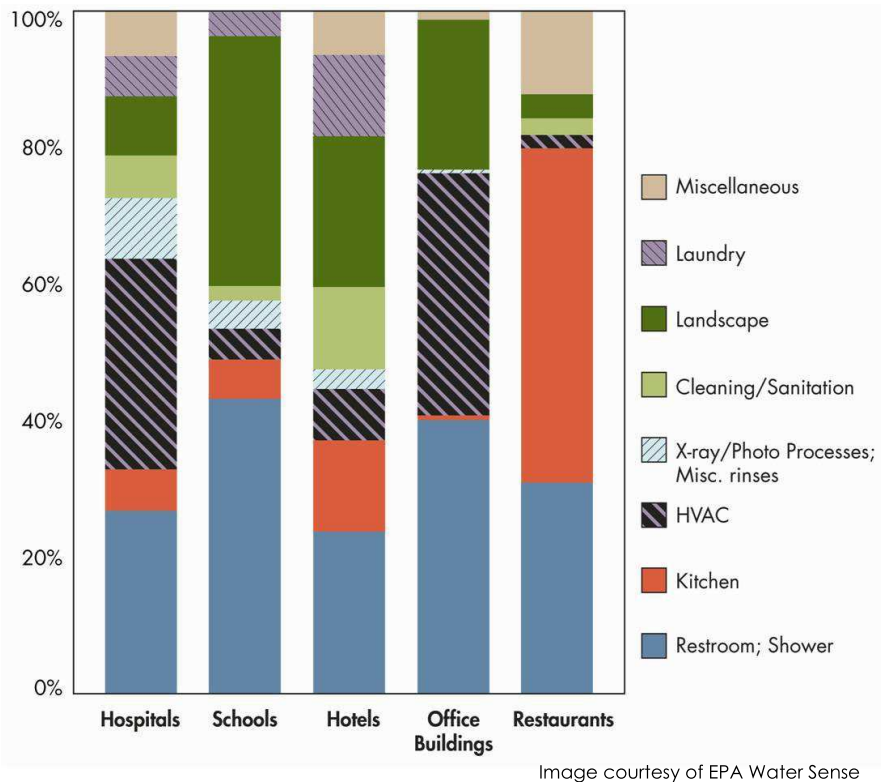


Figure 12-1 Water uses in commercial buildings.

Recently, ASHRAE partnered with the American Water Works Association (AWWA), U.S. Green Building Council (USGBC), and ASPE to develop a new proposed standard titled Standard 191P, *Standard for the Efficient Use of Water in Building, Site and Mechanical Systems*.

In green-building design, the practitioners of each design discipline need to be familiar with what the other disciplines may bring to an effective green design. This holds true as well with plumbing design and landscape design. The editors of this guide have chosen to include a discussion of some key aspects of plumbing design that impact green design as well as landscape design, including several ASHRAE GreenTips. Several of these GreenTips may have an impact in other areas as well. For instance, point-of-use hot-water heaters (ASHRAE GreenTip #12) not only save heating energy and distribution energy, but they also often result in the use of less water.

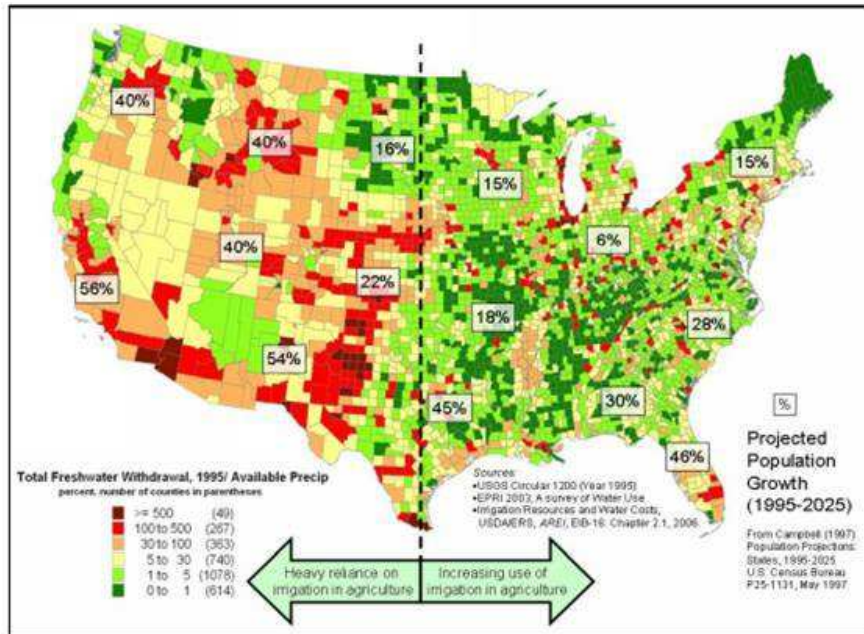


Image courtesy of Universities Council on Water Resources
Journal of Contemporary Water Research and Ed/Sandia National Laboratories

Figure 12-2 United States water availability map.

WATER-ENERGY NEXUS

The continued security and economic health of the global population depends on a sustainable supply of both water and energy. These two critical resources are inextricably linked. A nation's ability to continue providing both clean and affordable energy and water is being seriously challenged by myriad issues, including limited resources and increased demands from a burgeoning global population.

According to the World Health Organization, approximately 785 million people lack even a basic drinking-water service (WHO 2017). The amount of water in its various forms on the planet is finite. Moreover, the amount of freshwater of a quality suitable for the purposes for which it may be used is not uniformly distributed. For instance, 21% of the world's freshwater is in the US Great Lakes, while elsewhere, it is often nonexistent or in meager supply (EPA 2019). The distribution of water relative to regional population growth is also not always the most uniform, as is the case for the US (see Figure 12-2). In short, it is becoming increasingly difficult to provide for the adequate and equitable distribution of the world's water supply to those who need it. In arid coastal regions such as California, it may be

necessary to supplement water supplies with desalination as long as sufficient renewable energy capacity is provided to meet demand. Specific energy consumption of desalinating seawater with energy recovery boosted reverse osmosis is typically about 4 kWh/m³ (15 Watt-h/gallon) (Schunke et al. 2020), plus the work of pumping through pipelines to consumers. While similarly sunny and with a long coastline, Florida has lower-cost water sources available that need less treatment as compared to desalination, such as rainwater harvesting and cooling coil condensate.

Energy production requires a reliable, abundant, and predictable source of water. The largest use of water in the United States, at 41% of total water withdrawals, is for thermoelectric energy production, requiring 133 billion gallons (503 million m³) of water per day in 2015 (Dieter et al. 2018). Although much of the water used by thermoelectric power plants using once-through cooling systems is returned to waterways, it is done so at a higher temperature leading to a greater evaporation rate. On the other side, the water use cycle involves considerable energy expenditures; energy is needed to extract, treat, and transport potable water great distances and to collect and treat wastewater. For reference, estimates of water-related energy use range from 4% to 19% of US electricity use (Copeland 2017). Replacement of thermal power generation with wind farms substantially reduces the water demand associated with electricity, while solar thermal plants may be no better (Wu and Chen 2017).

It is estimated that the US requires 12% of the nation's public water supply for domestic, commercial, and industrial purposes (Dieter et al. 2018), and residential and commercial buildings require 39% of its energy consumption (EIA 2020). Clearly, water is a precious resource, essential at every building site. In areas where the water supply is not plentiful, an engineer focusing on green design should take into consideration the total water consumption in addition to the energy required to operate the building or facility. For example, when considering a cooling plant, a life-cycle analysis should be performed to compare an air-cooled chilled-water plant to a water-cooled chilled-water plant. Several factors, such as climate, load profile, utility rates, and availability (to name a few), will impact the total cost of ownership and the environmental impact of a cooling plant. While many of the measures to protect and preserve the world's freshwater supplies are beyond the design engineer's purview, there are many simple steps related to building sites that can be taken as part of a green design effort.

COOLING TOWER SYSTEMS

Cooling towers represent one significant but largely invisible source of water use in commercial buildings. One university estimated that roughly 20% of the total water consumption on their campus was in cooling tower makeup water alone. The following section details cooling tower operations, particularly as they affect green-building design and water efficiency.

Cooling towers are commonly used in larger-scale building systems, and they consume water through evaporation, drift, and blowdown losses. Cooling towers may be the single largest consumer of potable water in a building, depending on load, operating strategy, and location.

Cooling towers are energy-efficient devices for removing heat from water through evaporation and can do so close to the ambient wet-bulb temperature. The wet-bulb temperature is always lower than the dry-bulb; thus, water cooling allows for more efficient condenser operation (as much as a 50% energy savings) than air cooling at peak temperatures. However, cooling towers use a significant amount of water, as defined in the Evaporation, Drift, and Blowdown sections that follow. In addition to evaporation, some recirculated water must be bled from the system to prevent soluble and semisoluble minerals from reaching too high a concentration causing scale to build up. The water may also become corrosive and/or have biological growth posing durability and safety concerns. This bleed or blowdown is usually drained to the sanitary plumbing system and ends up being treated further downstream at a sewage waste treatment plant. It is possible to maximize both the energy and the water efficiency of the cooling tower system by appropriately addressing splash-out and spill issues, limiting microbiological activity, treating the water with chemical-free systems, and using filtration systems with low water usage for the blowdown requirement.

For more information, consult Chapter 40 in the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2020a).

Evaporation

Evaporation is a cooling tower system's primary component of net water consumption. To reject 1 ton-h (3.52 kWh) from a cooling tower through evaporation requires 1.5 gal (5.68 L) of water based on the latent heat of vaporization. This value is not fixed and is a function of cooling tower water temperature, but it does not vary greatly at typical operating temperatures.

It should be noted that one ton-h of cooling does not yield one ton-h of heat rejection. The chiller's efficiency must be included in the calculation as the heat gain from consuming electrical energy in the chiller compressor is added to the heat rejection. A 1000-ton (3514 kW) ASHRAE/IES Standard 90.1-compliant chiller with a coefficient of performance (COP) of 6.1 would reject 1164 tons (4094 kW) of heat to a cooling tower. Chiller COPs can vary between three and eight depending on the technology applied and the chilled water and condenser water temperatures but typically operate between five and seven. Therefore, as chiller efficiency improves, less water needs to be evaporated.

Drift

To promote efficient heat transfer through evaporation, cooling towers force intimate contact between outdoor air and warm water.

Small water droplets entrained and carried out with the air passing through the tower are called *drift*. Drift is always present when operating a cooling tower. Because drift is generated by small droplets of the cooling tower water, it contains all the dissolved minerals, microbes, and water treatment chemicals in the tower water. Drift is a source of PM₁₀ emissions (i.e., particulate matter that is less than 10 µm in diameter) and, since it can contain biological growth suspended in the water, it is a suspected vector in *Legionella* transmission.

Drift is usually reported as a percentage of the recirculating water flow rate, though it is more accurately described in terms of the parts per million (ppm) of the air passing through the tower. Tower designs may use drift eliminators to capture virtually all this entrained water. A typical value of drift for high-efficiency eliminator performance in modern cooling towers is 0.001 to 0.005% of the recirculating water rate, a quarter of the water volume without a drift eliminator.

It should further be noted that since drift is liquid water being aspirated from the cooling tower, it is simply one component of tower blowdown. Because of this, the drift rate has no impact on total water consumption since the amount of drift will result in a commensurate reduction in blowdown. Assuming tight controls on blowdown with accurate measurement, the water treater will see a difference between measured blowdown and makeup water along with calculated evaporation. With proper design, the quantity of drift should be so small it is often dropped from the cooling tower calculations.

Blowdown

The cycle of concentration (CoC), the ratio of the concentration of dissolved solids in the blowdown water compared to the makeup water, is a measure used to compare the blowdown performance of a cooling tower system. CoC values may range from 2.0 to approximately 25.0; however, most systems operate between 2.5 and 3.5. The chart shown in Figure 12-3 demonstrates the relationship between evaporation and blowdown.

The CoC value achieved by a cooling tower system is a function of makeup water quality and treatment strategy. Water quality varies greatly throughout the US and worldwide; certain locations struggle to achieve 2.5 CoC, while others easily achieve 6 CoC or more. A CoC calculation method is included in IgCC/189.1 to estimate performance. A local water treatment professional should be consulted to determine a realistically achievable level that balances water consumption, chemicals use, and cooling tower material considerations.

Water Consumption of Typical Cooling Tower

Applying Figure 12-3 is relatively straightforward to establish an approximate water consumption of a cooling tower. First, determine the cooling load (tons) plus the average efficiency of the chiller of the building and the number of equivalent full load hours (EFLH). Add the cooling load plus the chiller efficiency to estimate

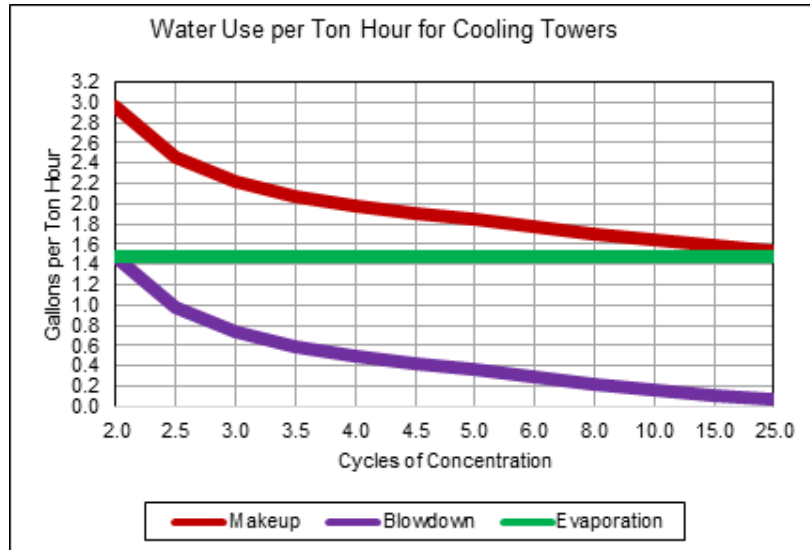


Image courtesy of H.W. Hoffman and Associates

Figure 12-3 Correlation of blowdown and cycles of concentration (CoC).

the quantity of heat rejected to the cooling tower. For example, a 1000-ton chiller with a COP of 5 would have about 200 tons of additional load from the chiller motor added to the condenser loop. Therefore, 1200 tons are rejected to the condenser loop. Then, multiply the heat rejection load and the EFLH values to determine a heat rejection energy value in ton-h.

Next, a CoC value should be determined. This can be calculated using the IgCC/189.1 method, which requires knowing makeup water quality values or surveying nearby buildings that include cooling towers to determine what their systems are achieving. In absence of any data, a safe estimate is 3 CoCs; however, as previously stated, this value can have a large range depending on incoming water quality and treatment strategy.

Building on the example of the 1000-ton chiller rejecting 1200 tons of heat to the tower and assuming 2000 EFLH for a year, the chiller will reject 2,400,000 ton-h of heat. Assuming 1.5 gal/ton-h of evaporation and 0.75 gallons/ton-h of blowdown results in 5,400,000 gallons of water use per year. Only the blowdown portion of the water is sent to the sanitary drain or about 1,800,000 gallons per year.

This same analysis can be completed in a more granular way if the cooling load frequency can be increased. Hourly energy models may also be used to calculate cooling tower consumption if a model is available.

Green Choices—Water Treatment

The water in the evaporative cooling loop must be treated to minimize biological growth, scaling, and corrosion. Minimizing biological growth is particularly important to protect people who may come in contact with contaminated water droplets in the vicinity of cooling towers, e.g., to prevent Legionnaires' Disease. Typically, a combination of biocides, corrosion inhibitors, and scale inhibitors are added to the system.

Corrosion inhibitors are usually phosphate- or nitrogen-based (e.g., fertilizers) or molybdenum- or zinc-based (e.g., heavy metals). These inhibitors are more effective when added in combinations. These materials have low vapor pressure and are not used by the system. The inhibitors simply need to remain in the solution at the proper concentration to maintain a protective film on the metal components. Their only loss is through bleed and drift.

Most scaling inhibition is done by polymer-based chemicals, organic phosphorous compounds (e.g., phosphonates), or by acid addition. The acid reacts with the alkalinity in the water to release CO_2 and is consumed. The polymer and phosphonate scale inhibitors, on the other hand, remain in the solution to delay scaling; their major loss is through bleed and drift. Some polymers are designed to be easily broken down by bacteria in the environment, while others are not.

Many biocides are available. A typical system will use an oxidizing biocide (e.g., bromine or chlorine) maintained at a constant level and slug feed a nonoxidizing biocide once a week. Chlorine and bromine have a high vapor pressure in water. Much of the chlorine and bromine added to the tower is stripped from the water into the air and a small quantity reacts with organics in the tower. Drift and bleed will contain all the nonoxidizing biocides small quantity of oxidizing biocides, and the reaction products of the biocides.

There are additional ways to treat the system with fewer negative impacts on the environment. Besides being rapidly stripped into the air, chlorine and bromine may react with organic molecules to produce very hazardous products. Other oxidizing biocides (e.g., hydrogen peroxide), on the other hand, do not have this issue. Further chemical additions can be added only when needed if continuous monitoring of the cooling system is in place. This technique can yield equivalent performance with fewer added chemicals. For reference, the U.S. Environmental Protection Agency (EPA) website on green chemistry (<https://www.epa.gov/greenchemistry>) contains criteria on how to evaluate the life-cycle environmental impact of a particular chemical.

Nonchemical water treatment has the potential to be a powerful method for water treatment. By not adding chemicals to the cooling tower water system, there are substantially reduced levels of toxic chemicals stored and handled on site, a reduced risk from spills or leaks of cooling tower water, the bleed water will be better to send to the local publicly owned treatment works (POTW), and any concern associated with

drift will be reduced. Additionally, instead of being sent to the POTW, bleed water could be used on site for irrigation or other needs where potable water is not required. There are several nonchemical technologies available; however, their successful use depends on the water chemistry, operating procedures, and degree of pollution of the specific system. Examples include those that use ozone, UV, pulsed electric fields, mechanical agitation, ultrasound, and hydrodynamic cavitation. Each of these technologies has developed a widespread following.

ASHRAE has conducted several research projects that investigated water treatment options and their effectiveness. For example, the effectiveness of scale prevention of some of these nonchemical water treatment technologies was assessed in ASHRAE Research Project RP-1155 (Cho et al. 2003). Others, such as ASHRAE Research Project RP-1361 (Vidic et al. 2010) raised questions regarding the overall efficacy of alternative methods. Technologies for water treatment continue to be developed and the reader is encouraged to investigate thoroughly any option chosen and evaluate all the trade-offs. ASHRAE published Standard 188, *Legionellosis: Risk Management for Building Water Systems*, which provides additional requirements for treating cooling tower water (ASHRAE 2018).

Green Choices—Tower Design and Selection

All cooling tower designs are efficient at removing heat from water through evaporation; however, not all designs perform as well environmentally. Some tower designs are more prone to splashout, spills, drift, and algae growth than others. Splashout involves tower water splashing from the tower and often happens when circulating tower water with the fans off while there are strong winds. Cross-flow towers are more prone to this issue since, in the no-fan condition, some water will fall outside of the fill.

Spills from the cold-water basin can occur when all the water in the piping drains into the basin at shutdown and overflows. Attention to proper water levels will prevent this. Some tower designs use hot-water basins or spray header pipes to distribute water at the top of the tower. The hot-water basin design can overflow if the nozzles clog; however, a spray header pipe never overflows.

Algae can contribute to microbial growth. Control requires harsher chemical treatment than typical biological control and thus are particularly problematic. Algae are plants and need sunlight to grow. Therefore, tower designs that are light-tight rather than open eliminates algae as an issue in cooling towers.

The amount of drift varies extensively in tower design. Some tower designs have very little drift, and the less the drift from a tower, the lower the amount of water containing minerals, water treatment chemicals, and microbes that will be released into the surrounding environment.

Green Choices—Filtration for Water Cooled Systems

A critical consideration with respect to green operation of water-cooled systems is to design, install, and maintain a filtration system capable of continually removing visible solids (40 μm and larger) from the water-cooled system. Keeping the system free from dirt, corrosion by-products, and scale maintains optimal heat transfer efficiency and reduces under-deposit corrosion. Filtration systems that use centrifugal action and require no media or moving parts have the advantage of reduced maintenance, no disposal of used media, better water efficiency, and offer minimal or zero liquid loss.

The filtration system and sweeper piping should be able to provide adequate pressure and flow (constant 20 psi at the nozzles, 1 gpm/ft² [138 kPa at the nozzles, 40.8 L/min per m²]) to remove visible solids from the water and provide for efficient handling of the solids. It is not necessary to remove particles smaller than 40 μm , because the extra energy and water loss to achieve this level of filtration for a water-cooled system is wasteful.

Green Choices—Operation and Maintenance

An often-overlooked method to minimize environmental impact is maintenance. Cooling towers operate outdoors under changing conditions. Wind damage to inlet air louvers, excessive airborne contamination, clogging of water distribution nozzles, and mechanical problems can best be prevented and quickly corrected with periodic inspections and maintenance.

Green Choices—Nonpotable Water

Cooling towers do not require potable water to operate, but it is the most common approach as it's relatively simple compared to using nonpotable water. There are a variety of nonpotable water sources that may be suitable for cooling tower operation, such as gray water, cooling coil condensate, roof rainwater, and reject process water, to name a few. Note that reject process water quality should be carefully investigated prior to use, but depending on the application, it may prove suitable. The volume of water available for each source depends on the project location and building program. Further, local codes must be consulted as not all jurisdictions allow nonpotable water capture and reuse. The nonpotable water pipe should always be purple in color to ensure that water lines fit for human consumption are not crossed with nonpotable water lines. Many operators also dye the water purple to show that it's only for nonpotable applications.

Water entering a cooling tower must be treated regardless of its source; so the water quality from alternate sources should be tested periodically to ensure reliable operation.

Municipal nonpotable water systems are gaining popularity. These sources offer lower-cost water for end-uses such as cooling towers. Again, check the quality of

the municipal nonpotable water to ensure that the quality is suitable for cooling tower operations. Refer to the Water Recovery and Reuse section in this chapter for more information.

DOMESTIC WATER HEATING

Efficiently producing and delivering domestic hot water (DHW) is an important consideration for reducing water waste in building fixtures, as occupants often wait for hot water when using fixtures. Water heating is the second largest consumer of site energy in US residences, at 19% (1745 trillion Btu [511 million kWh]) (EIA 2018). An important energy-reducing technique is using water heaters with higher uniform energy factors (UEFs). The UEF is a measure of efficiency as defined by US regulations on residential and commercial water heaters (DOE 2014). Gas and electric storage water heaters are currently the dominant technology in the water heater market. In recent decades, advanced water heaters have been developed that achieve UEFs beyond those dictated by the minimum efficiency standard, in part facilitated by the EPA's ENERGY STAR[®] program launched in 2009. Such technologies include tankless water heaters, electric heat pump water heaters, condensing gas water heaters, and direct-contact water heaters, among others.

Further, minimizing hot-water distribution heat losses is an effective measure to save both water-heating energy and water. For example, field studies have estimated that up to 30% of water is wasted while residential occupants wait for hot water to arrive at showers (Lutz 2012). Mitigation measures include insulating exposed hot-water pipe and reducing pipe lengths between the source of hot water and end-uses. GreenTip #12-1 discusses the use of point-of-use water heaters for addressing the latter measure.

PLUMBING

Water-Conserving Plumbing Fixtures

Water conservation strategies save building owners money when it comes to both consumption and demand charges. Further, municipal water and wastewater treatment plants save on operating and capital costs for new facilities. As a rule, water conservation strategies can yield significant cost savings when properly applied.

The minimum water usage standards were established by the Energy Policy Act of 1992 (EPACT) for typical fixture types. These values would be used to calculate the baseline water consumption on a LEED project. ANSI/ASHRAE/USGBC/IES Standard 189.1 requires more efficient fixtures in the design, equivalent to the levels set under the US Environmental Protection Agency's WaterSense program (<https://epa.gov/watersense/>). A good comparison of the various water efficiency requirements has been published by the Alliance for Water Efficiency and included in the references list at the end of the chapter.

Applicable state and local codes should be checked prior to design, as they have approved fixture lists; some code officials have not approved the waterless urinal and low-flush toilet technologies. Waterless urinals and low-flow lavatory fixtures can have a rapid payback period. Toilet technology continues to evolve rapidly, so be sure to obtain test data and references before specifying. Some units work very well, while others perform marginally.

Options that should be considered in the design of water-conserving systems include the following:

- High efficiency (WaterSense compliant or equivalent) toilets
- Lavatory faucets with flow restrictors
- Low-flow kitchen faucets
- Domestic dishwashers that use 10 gal/cycle (38 L/cycle) or less
- Commercial dishwashers (conveyor type) that use 120 gal/h (455 L/h)
- Waterless urinals

A comparison of water consumption for a typical office building using the baseline Energy Policy Act (EPAct) specifications compared to the more efficient WaterSense program values is given in the Digging Deeper sidebar titled “Example Calculation to Compute a Baseline Predicted Water Consumption for a Building” at the end of this chapter.

LANDSCAPE IRRIGATION

Irrigation may be the largest water consumer in many building types depending on the type of plants selected, climate, and amount of irrigated space. Plant selection, irrigation technology, and controls are the most common approaches to reducing landscape water consumption. Through proper plant, technology, control selection, and the use of nonpotable water, it is possible to achieve zero potable water consumption for irrigation. Additional resources are available from the American Society of Landscape Architects (<https://asla.org>). Landscape irrigation may be prioritized as an essential use of water (e.g., if the amenity provided by shade trees is considered essential). See the Trees and Design Action Group (<https://tdag.org.uk>).

Plant Selection

Although many types of plants will grow in a particular environment, it is best to apply xeriscaping, i.e., the selection of native and adaptive plant species appropriate for the project location that will not require irrigation once they are established.

Technology

There are many technologies for applying water to the landscape, including sprinklers and drip irrigation systems. Sprinklers are the most common type and

have a variety of efficiency levels. Sprinkler technologies are inherently inefficient as the water is sprayed into the atmosphere, where a fraction of it is evaporated. The amount of water evaporated varies per technology but can be as high as 60%. Compare equipment and determine a payback for using more efficient equipment.

An alternative to sprinklers is drip irrigation, where a distribution system of pipes is buried under the irrigated landscape to directly apply water to the plants rather than spraying water in the air. Drip irrigation systems should achieve evaporation rates of less than 10%.

If rainwater can be harvested legally, it is recommended to use it as the source for irrigation. Most local regulations require that it not be administered through sprinklers but through drip irrigation methods. Refer to the Rain Harvesting section for additional information.

Controls

A large variety of controls are available on the market that manages the amount of water in the soil through moisture sensing and/or preventing the operation of the irrigation system prior, during, or after rainfall. These control systems may save upwards of 25% as compared to manual- or timer-based operation. When timer-based controls are used, favor operations in the evening or at night when temperatures are lowest and solar radiation is minimal to minimize evaporation.

Furthermore, overwatering is a major concern and can consume 20% more water without any appreciable differences in landscape aesthetics. Controls should be field-adjustable, allowing the operator to experiment with water quantities to minimize water consumption while maintaining the desired aesthetic.

Nonpotable Water

Irrigation systems don't require potable water to operate. There are a variety of nonpotable water sources that may be suitable for irrigation such as gray water, cooling coil condensate, roof rainwater, and reject process water. Refer to the Green Choices—Nonpotable Water subsection in the Cooling Tower Systems section in this chapter for more information.

Water treatment for irrigation primarily includes a modest level of filtration to avoid clogging pumps. Some nonpotable water sources may be unsuitable for irrigation if they are heavily contaminated or disallowed by codes and regulations. Each source should be tested periodically to avoid killing off desired vegetation.

The technology used to irrigate also impacts the level of treatment required. Drip irrigation systems typically require the least amount of treatment as the water is not sprayed into the air, a major *Legionella* concern. Local regulations should be consulted prior to selecting an irrigation technology. If there is a choice of technology, a life-cycle cost analysis should be completed comparing drip irrigation with minimal treatment versus traditional spray rotor solutions requiring more treatment when nonpotable water is applied.

WATER RECOVERY AND REUSE

Condensate Collection

For HVAC&R engineers looking for water recovery and reuse opportunities, condensate collection should be considered on most projects. Factors that determine whether condensate collection should be considered include location (i.e., whether building is in a more humid climate), building type (particularly relating to amount of outdoor air required), the size, number and accessibility of air handlers that condition outdoor air, and location of potential uses for the condensate. Location determines both the potential to collect a significant amount of condensate as well as the value of the water to the local community.

ANSI/ASHRAE/USGBC/IES Standard 189.1 requires that condensate collection be done on all air-conditioning units with a cooling capacity greater than 65,000 Btu/h (19 kW) and in regions where the ambient mean coincident wet-bulb temperature at 1% design cooling conditions is 72°F (22°C) or greater.

Building or space occupancy type determines the amount of outdoor air required, and thus, the amount of moisture in the incoming air. As the air passes over cold cooling coils, if the coil surface temperature is less than the dew point of the airstream passing by, then the potential exists for water condensation on the coils. (See the How Much Condensate Water Will Collect at Design Conditions? Digging Deeper sidebar.) Water that condenses on the coils will collect and drop to the drain pan below. The actual amount of water collected depends on parameters such as the absolute humidity level, total airflow, and coil bypass ratio. A major source of the moisture being condensed is from outdoor air brought in through outdoor air intakes or through infiltration exchange with the outdoors. A building or space that requires a lot of outdoor air on an ongoing basis (e.g., a laboratory) is an ideal candidate for condensate collection. Dedicated outdoor air systems (DOAS) are also prime candidates for consideration. More information about condensate collection can be found in GreenTip #12-2.

Rainwater Harvesting

Rainwater collection, or rainwater harvesting, is one of the oldest systems of supplying clean water to communities. Modern, decentralized rainwater harvesting involves the capturing runoff water from building roofs or other surfaces that can be reserved for later use. Depending on the application, rainwater can provide for all or part of a site's indoor and irrigation uses, reducing the burden on potable water supplies.

Systems can be as basic as a rain barrel under a downspout or as complex as a filtered and pumped mechanism providing landscape irrigation, cooling tower makeup, and/or building waste conveyance. Rainwater systems are generally composed of five or fewer basic components: a catchment area, a means of conveyance

from the catchment, storage (optional), water treatment (optional), and distribution to the end-use.

1. The *catchment* area can be any impermeable area from which water can be harvested. Typically, this is the roof, but paved areas (e.g., patios, entries, and parking lots) may also be considered. Roofing materials that are metal-, clay-, or concrete-based are preferable for roofs planned for rainwater harvesting compared to those with potential contaminants, such as asphalt or those with lead-containing materials. Similarly, care should be given when considering a parking lot for catchment due to oils and residues that can be present.
2. *Conveyance* to the storage will be gravity-fed, like any stormwater piping system. The only difference is that the rainwater is now being diverted for reuse purposes.
3. Residential systems may, and commercial systems will, require a means of *storage*. Cisterns can be located outside the building (e.g., above-grade or buried) or placed on the lower levels of the building. The storage tank should have an overflow device piped to the storm system and a potable water makeup if the end-use need is ever greater than the harvested volume.
4. Depending on the catchment source and the end-use, the level of *treatment* will vary. For simple site irrigation, filtration can be achieved through a series of graded screens and paper filters. If the water is to be used for waste conveyance, an additional sand filter may be appropriate. Parking lot catchments may require an oil separator. The local code authority will likely decide acceptable water standards, and, in turn, filtration and chemical polishing will be a dictated parameter, not a design choice.
5. *Distribution* can be via gravity or pump depending on the proximity of the storage tank and the end use.

If the building design is to include a gray-water system, condensate collection, or landscape irrigation and space for storage can be found, rainwater harvesting is a simple addition to those systems.

When a desire exists to limit potable water demand and use, depending on the end-use requirement and the anticipated annual rainfall in a region, harvesting can be provided as a standalone system or to augment a conventional makeup water system. Sites with significant precipitation volumes may determine that reusing these volumes is more cost-effective than creating stormwater systems or on-site treatment facilities.

Rainwater harvesting is most attractive where municipal water supply is either nonexistent or unreliable, hence its popularity in rural regions and developing countries.

States and provinces around the world have established various degrees of regulation for rainwater harvesting with regard to protecting public health and/or

adopted a view that the resource is common property. Excessive discharge of stormwater from impervious surfaces is also regulated, so harvesting and on-site storage are encouraged in many jurisdictions. Some jurisdictions consider rainwater harvesting to be a private property right. In rural areas, rainwater may be the only feasible source of potable water, particularly where groundwater is unsuitable or not included within property rights. Reading all local regulations and public health guidelines is a prerequisite to any scheme. State or university extension services may be prepared to assist in particular community settings. The following discussion is focused on harvesting rainwater from roof surfaces stored for nonpotable uses, such as toilet flushing and subsurface irrigation. Subject to local regulations, water used for sprinkler irrigation or evaporative condensers could be used in sign-posted, restricted access areas.

The monthly minimum, maximum, average, and standard deviation of rainfall is given in *ASHRAE Handbook—Fundamentals* climate data for thousands of locations around the world (ASHRAE 2021). In the face of changing climate, various chapters in the 2021 edition of *ASHRAE Handbook—Fundamentals* make reference to the same “Example City” for the historic period of 1990–2014. Example City had an extreme monthly minimum of only 2 mm (0.1 in.) during one October during the quarter century of observations. This example indicates that makeup supplies could occasionally be necessary if there is insufficient on-site storage capacity or if local public health guidelines preclude banking stormwater for extended periods of drought. Autonomous rainwater harvesting system design requires analysis of the daily precipitation demand balance over several years. See the How Much of Demand can be Met by Rainwater Harvesting? Digging Deeper sidebar for an example of daily rainwater supply-demand-storage calculation.

Specialist designers can be engaged to determine if there is potential to meet demand and how much on-site storage is required. First, there needs to be an audit of demand indoors and outdoors. Second, precipitation must be assessed at the project site and clean collection surface area. Storage capacity may not be as much as first calculated to balance supply and demand. In this case, imported water may be necessary during drought by tanker truck if a pipeline is unavailable. Overflow disposal is also an important aspect of design.

The local health code authority has jurisdiction, potentially making a particular site infeasible due to backflow prevention requirements, special separators, or additional treatment.

For additional information on rainwater harvesting, the American Rainwater Catchment Systems Association (<https://www.arcsa.org/>) offers online training courses, and the International Code Council and the Canadian Standards Association published CSA B805-18/ICC 805-2018—*Rainwater Harvesting Systems* (ICC 2018).

Fire Flow Testing Catch and Reuse

Potable water is used to test fire sprinklers and hydrants and is normally discharged into stormwater. Australian communities and fire protection contractors have recently been developing methods to capture and recycle this water resource for nonpotable uses (Aldag 2020). Capturing the waste from fire pump tests involves large tanker trucks or temporary raised ponds. Hydrant flushing companies can provide truck-mounted systems where discharge is piped through a series of tanks and filters and reintroduced into a dedicated fire main system if there is backflow-prevented isolation from potable mains. Sprinkler system test water is not potable but may be usefully diverted for irrigation or other gray water systems.

Gray Water Systems

Gray water is wastewater from lavatories, showers, bathtubs, and sinks that is not used for food preparation. Gray water is further distinguished from blackwater, which is wastewater from toilets and sinks that contains organic or toxic matter. Local health code departments have regulations that specifically define the two kinds of waste streams in their respective jurisdictions.

A gray water system reduces a building's potable water use, reducing demand on the municipal water supply and lowering costs associated with water. It reduces a building's overall wastewater generation, thus becoming less taxing on the existing sewage systems.

Where allowed by local code, separate blackwater and gray water waste collection systems can be installed. The blackwater system would be treated as a typical waste stream and piped to the water treatment system or local sewer district. However, the gray water would be recycled by collecting, storing (optional), then distributing it via a dedicated piping system to toilets, landscape irrigation, or any other function that does not require potable water.

Typically, for a commercial gray water system (e.g., for toilet flushing in a hotel), a means of short-term, on-site storage, or, more appropriately, a surge tank, is required. Gray water can only be held for a short period of time before it naturally becomes blackwater. Often some treatment of the graywater is done, such as with a bleach solution or other means, to prolong storage time. The surge tank would be provided with an overflow to the blackwater waste system and a potable makeup line for when the end-use need exceeds stored capacity.

Distribution would be accomplished via a pressurized piping system requiring pumps and some low level of filtration. Usually, there is a requirement for the gray water system to be a supplemental system. Therefore, systems will still need to be connected to the municipal or localized well service.

Plumbing codes require that a colorant be added to graywater used within buildings, such as for toilet flushing, to help distinguish it as nonpotable water.

Careful consideration should be given before pursuing a gray water system. While a gray water system can be applied in any facility that has a nonpotable water demand and a usable waste stream, the additional piping and energy required to provide and operate such a system may outweigh any benefits. Such a system is best applied where the ratio of demand for nonpotable water to potable water is relatively high and consistent, as in restaurants, laundries, and hotels.

Some facilities have a more reliable gray water volume than others. For example, a school would have substantially less gray water in the summer months. This may not be a problem if the gray water was being used for flushing, since it can be assumed that toilet use would vary with occupancy. However, it would be detrimental if gray water were being used for landscape irrigation.

There is negative public perception of gray water reuse and health concerns regarding ingestion of nonpotable water. The local health code authority has jurisdiction, potentially making a particular site infeasible due to that authority's definition of blackwater versus gray water.

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www.epa.gov/greenchemistry/.

US Environmental Protection Agency, WaterSense Program.
www.epa.gov/watersense/.

US Green Building Council
www.usgbc.org.

US Geological Survey
www.usgs.gov.

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Digging Deeper

EXAMPLE CALCULATION TO COMPUTE A BASELINE PREDICTED WATER CONSUMPTION FOR A BUILDING

Often, the design project team may want or need to compute the estimated water consumption of a building and compare that to some baseline level of performance. For example, this type of comparison is necessary for a building project working to demonstrate the minimum prerequisite water efficiency for a LEED project and to determine water savings credit points. This procedure involves estimating the water consumption using flow rate or usage rate values specified for the baseline performance in the LEED program description. These baseline levels correspond generally to the 1992 EPACT values listed in Table 12-2, with one exception for residential faucets.

It is fairly easy to determine the values to use for both the baseline level and the proposed building fixture flow or usage rates; these are taken from the table listed in the corresponding LEED program description and the specifications for the building project. Total water consumption is estimated based on occupancy expectations and thus requires some estimates or assumptions on occupancy levels and patterns.

This is because it is the number of people in a building, not necessarily the number of fixtures in the building, that determines how much water is consumed.

4 00:22:05 +0000 by University of Toronto User.

One common method for determining water consumption is to base it on the number of full-time occupants in the building on daily basis. For this example, consider an office building that contains space for 100 employees, with a 50/50 breakdown of males and females. We assume that 10% of the employees are not at this office on any given normal workday, that this facility has 14 outside visitors a day (7 male, 7 female), and that each visitor stays an average of two hours per visit. On weekends and holidays, also assume that on average 5% of the employees are in the office for a total of four hours for each person each day, with no visitors. Basing the full-time occupancy estimate on an 8 h workday, the full-time equivalent occupancy of this building therefore is estimated as follows.

Weekdays

$$FTE_{male} = \frac{100 - 10}{2} \times \frac{8}{8} + \frac{14}{2} \times \frac{2}{8} = 46.75 \approx 47 \text{ people}$$

Because we have assumed an equal distribution of males and females, this is also the female FTE for weekdays. In this example, we are also rounding up the population to a whole number for each case.

Weekends, holidays

$$FTE_{male} = FTE_{female} = \frac{5}{2} \times \frac{4}{8} = 2.5 \approx 3 \text{ people}$$

Next, an assumption is needed for how many times per day each occupant uses the facilities. We will assume that each person visits them three times during each full, 8 h day. During each visit we assume that the males use the water closet once and a urinal twice. For each visit, regardless of gender, we assume that the lavatory sink is used a total of 15 s. We will also assume that this building contains a break room with a sink where the water is run a total of 30 min per day on weekdays and 5 min per day on weekends and holidays.

We now have all the information needed to compute an estimate of the water consumption, which is illustrated in the following tables.

Digging Deeper

Weekdays:						
Fixture Type	No. Occupants or Devices	Flow/ Flush Rate	Units	Daily Use per Person	Duration, min	Daily Water Volume, gal (L)
W.C. Female	47	1.6 (6.1)	gpf (Lpf)	3		226 (854)
W.C. Male	47	1.6 (6.1)	gpf (Lpf)	1		75 (284)
Urinal	47	1 (3.8)	gpf (Lpf)	2		94 (356)
Lavatory Faucet	94	0.5 (0.03)	gpm (L/s)	3	0.25	35 (133)
Kitchen Sink	1	2.2 (0.14)	gpm (L/s)		30	66 (250)
Weekends, holidays:						
These give an estimated total water consumption of 496 gal (1878 L) per day during each weekday and 38 gal (144 L) on weekends and holidays.						
The final step in the calculation is to apply this to the number of days per year for each day type, which gives us an estimated total annual water consumption of 133,010 gal (503,498 L) per year.						
Fixture Type	No. Occupants or Devices	Rate	Units	Daily Use per Person	Duration, min	Daily Water Volume, gal (L)
W.C. Female	3	1.6 (6.1)	gpf (Lpf)	3		14 (53)
W.C. Male	3	1.6 (6.1)	gpf (Lpf)	1		5 (18)
Urinal	3	1 (3.8)	gpf (Lpf)	2		6 (23)
Lavatory Faucet	6	0.5 (0.03)	gpm (L/s)	3	0.25	2 (9)
Kitchen Sink	1	2.2 (0.14)	gpm (L/s)		5	11 (42)

A similar procedure would be conducted for estimating the water consumption in the proposed building design that includes water conservation features. Note that these numbers provide an estimate for the amount of potable water used for the restroom and breakroom sink usage only. It does not include water use for other processes, such as a cooling tower, which would need to be factored in depending on the particular building situation. If alternative sources of water were used to supplement, for example, the toilet flushing, then this would have to be factored into the water use per fixture, based on specific information for that project.

Day Type	No. Days per Year	Daily Use, gal (L)	Total, gal (L)
Weekday	260	496 (1878)	119,808 (455,780)
Weekend	105	38 (146)	4037(15,283)
Total			133,010 (503,498)

Online

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- US Geological Survey www.usgs.gov.
- US Green Building Council www.usgbc.org.

Digging Deeper

ASHRAE GreenTip #12-1

Point-of-Use Domestic Hot-Water Heaters

GENERAL DESCRIPTION

As implied by the title, point-of-use domestic hot-water heaters provide small quantities of hot water at the point of use, without tie-in to a central hot water source. A cold-water line from a central source must still be connected as well as the energy source for heating the water, which could be electricity or gas.

There is some variation in types. Typically, the device may be truly instantaneous (e.g., lavatories), or it may have a small amount of storage capacity. With the instantaneous type, the heating source is sized such that it can heat a normal-use flow of water up to the desired hot-water temperature (e.g., 120°F [49°C]). When a small tank (usually 3 to 10 gal [11 to 38 L]) is incorporated in the device, an electric heating coil can be built into the tank and can be sized somewhat smaller because of the small amount of stored water available. The device is usually installed under the counter of the sink or bank of sinks. Slightly larger-sized units are available that can provide instantaneous heating for a residential house without requiring a storage tank and its associated thermal losses.

A similar type of device boosts the water supply (which is cold water) up to near boiling temperature (about 190°F [88°C]). This is typically used, for example, to make a cup of coffee or tea without having to brew it separately in a coffeepot or teapot.

WHEN/WHERE IT'S APPLICABLE

These devices are applicable wherever there is a need for a hot-water supply that is low in quantity and relatively infrequently used and is excessively inconvenient or costly to run a hot-water line (with perhaps a recirculation line as well) from a central hot-water source. Typically, these are installed in lavatories or washrooms that are isolated or remote, or both. However, they can be used in any situation where there is a hot-water need but where it would be too inconvenient and costly to tie in to a central source. (There must, of course, be a source of incoming water and a source of electricity.)

PRO

- A point-of-use device is a simple and direct way to provide small amounts of domestic hot water per use.
- Long pipe runs—and, in some cases, a central hot-water heating source—can be avoided.
- Energy is saved by avoiding heat loss from hot-water pipes and, if not needed, from a central water heater.
- In most cases, where applicable, it has a lower first cost.
- It is convenient—especially as a source of 190°F to 210°F (88°C to 99°C) water supply.
- When installed in multiple locations, central equipment failure does not knock out all user locations.
- It may save floor space in the central equipment room if no central heater is required.
- Water is saved by not having to run the faucet until the water warms up.

CON

- This is a more expensive source of heating energy (though cost may be trivial if usage is low and may be exceeded by heat losses saved from a central heating method).
- Water impurities can cause caking and premature failure of electrical heating coils.
- It cannot handle changed demand for large hot-water quantities or too-frequent use.
- Maintenance is less convenient (when required), since it is not centralized.
- A temperature and pressure relief valve and floor drain may be required by some code jurisdictions.

KEY ELEMENTS OF COST

The following provides a possible breakdown of the various cost elements that might differentiate a point-of-use domestic hot-water heater from a conventional one and an indication of whether the net incremental cost for the system is likely to be lower (L), higher (H),

or the same (S). This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process. The listings below may also provide some assistance in identifying the cost elements involved.

First Cost

- Point-of-use water-heater equipment H
- Domestic hot-water piping to central source (including insulation thereof) L
- Central water heater (if not required) and associated fuel and flue gas connections L
- Electrical connection H
- Temperature and pressure relief valve and floor drain (when required by code jurisdiction) H

Recurring Cost

- Energy to heat water to appropriate temperatures H
- Energy lost from piping not installed L
- Maintenance/repairs, including replacement H

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ASHRAE GreenTip #12-2

Air-Handling Unit (AHU) Condensate Capture and Reuse

GENERAL DESCRIPTION

As air passes over cold cooling coils in an AHU, if the coil surface temperature is less than the dew point of the airstream passing by, then the potential exists for water condensation on the coils. Water that condenses on the coils will collect and drop to the drain pan below. In conventional building systems, this water typically drains, unused, to the sewer system or elsewhere, but in some situations it can be worthwhile to capture and reuse it.

Condensate collection can either be designed into new construction or retrofitted into existing buildings. While the former is preferable (due to lower costs and fewer complications), the latter presents the highest potential, since existing buildings comprise about 98% of the building stock.

The best end use for the collected water will depend on the particular circumstances of the location. In a building with its own chiller and cooling tower, the most logical choice is to route collected condensate to the cooling tower sump to reduce the need to use freshwater for makeup. In most cases, peak condensate production will occur at the same times as peak makeup water demands, creating an elegant synergy. This is also the simplest retrofit, involving reasonably inexpensive equipment and piping; water can be routed directly to the tower with no need for treatment.

Condensate collection can also be integrated with a rainwater collection system, a scheme often referred to as *rainwater plus*. This will usually involve a storage tank or cistern and can require considerably more expense and engineering than using the condensate in a cooling tower. Depending on the intended use (e.g., irrigation, ornamental fountains, or other internal uses including toilet flushing), different amounts of further treatment will be required. In all cases, local building codes must be followed.

WHEN/WHERE IT'S APPLICABLE

Factors that determine whether condensate collection should be considered include location (e.g., climate), building type (particularly relating to amount of outdoor air required), the size, number, and accessibility of air handlers that condition outdoor air, location of potential uses for the condensate, etc. Location determines both the potential to collect a significant amount of condensate and the value of the water to the local community. In periods of drought, the actual value of a unit of water to the local society and economy may be worth much more than the rate currently paid to the local utility.

A building or space that requires a lot of outdoor air on an ongoing basis (e.g., laboratories) is an ideal candidate for condensate collection. Other obvious candidates include spaces with indoor water features, natatoriums, gymnasiums, or locker rooms. DOAS units are also prime candidates for consideration, since they are typically designed for optimal latent load removal.

Using typical meteorological year data, assumptions about the air-handling system, and the following equation, it is possible to estimate the amount of condensate that can be collected annually in a particular location.

Condensate collection is required by IgCC/189.1 for air-conditioning units that are above a certain cooling capacity and in more humid climates (ICC 2021).

LESSONS LEARNED

Attention must be paid to the cleanliness of the water and the system components. For example, any external condensate collection pan should be covered to prevent foreign particles from getting into the system. The potential is also there for biological growth and contamination, so UV may be desired in the AHU to keep the collection pan clean or an alternate treatment method after collection. Also, there may be an increase in corrosion potential in the cooling tower loop, if that is where the condensate is sent.

Sweating on the outside of the condensate piping can be an issue, particularly in semiconditioned mechanical rooms, so all lines (as well as perhaps the collection basin itself) should be insulated. If the condensate line is tied into rain downspouts, you may want to consider running a smaller pipe or tube inside of the downspout for

the condensate to avoid moisture buildup on the outside downspout surface.

The dimensions of the U-trap in the existing condensate drain pipe between the AHU and the floor drain should be maintained when connecting the drain pipe to the external collection pan. It is also highly recommended that a condensate flow meter be installed and that it be located to facilitate easy reading. The additional cost of the meter is worthwhile because of the good feedback on functionality and the education potential it provides. It's also a good way to verify water and cost savings.

During the COVID-19 pandemic, HVAC systems received attention as never before, including an interest in cooling coil condensate as it was generated at the AHU, where contaminated air might be present. At the time of this publication, no link between cooling coil condensate and COVID-19 transmission has been identified. However, the investigation has sparked a larger discussion around potential water contamination within poorly maintained AHUs. The EPA started the Water Reuse Action Plan (WRAP), which, among many other things related to water reuse, investigates cooling coil condensate water quality.

PRO

- If condensate is routed to a cooling tower, demand for makeup water will reduce and so will the need for treatment chemicals. Blowdown frequency should decrease, and sewer costs could be reduced with appropriate metering. Use in cooling towers is especially favorable as condensate generation rate is directly proportional to cooling tower demand.
- Cooling coil condensate routed to a cooling tower will provide residual free cooling for condenser water due to its reduced temperature leaving the cooling coil.
- Incorporating condensate collection into a rainwater collection and storage system can reduce the cistern size requirement by providing a supplemental water source during long periods between rain events.

CON

- Complications arise when dealing with district cooling systems with satellite chillers, because it is possible to produce condensate in an AHU while the chiller and cooling tower (for that particular building) are idle. This leads to the risk that treatment chemicals in the sump will be diluted and needlessly washed away via the overflow drain.
- In general, less-efficient systems have higher condensate production potential. Enthalpy wheels, for example, will greatly improve system efficiency but will dramatically reduce condensate production. A building with 100% outdoor air supply that is overpressurized will produce more condensate but will consume more energy. Energy efficiency should always take precedence over water production.

KEY ELEMENTS OF COST

The following capital cost issues list the various cost elements associated with either building condensate collection into new construction or retrofitting an existing building. This assessment is only a perception of what might be likely, but it obviously may not be correct in all situations. There is no substitute for a detailed cost analysis as part of the design process.

Pipe. Depending on the distance between the AHU and the end use, and whether a storage tank is involved, the material and labor costs of the pipe installation are likely to be the most expensive part of the system. For new construction the additional cost should be minimal, since a condensate drain pipe would need to be furnished, regardless of the end use.

Storage. If condensate is to be stored for later use, a cistern or storage tank can represent a considerable part of the system cost. Additional costs will be incurred for system design (i.e., tank sizing) and tank site selection and installation. Finally, treatment of stored water prior to end use, if necessary, will add equipment, design, and maintenance costs.

Metering. A totalizing meter is a relatively inexpensive but important component of a condensate collection system. Once in

place, a condensate meter will help verify payback on the investment in the system.

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HOW MUCH CONDENSATE WATER WILL COLLECT AT DESIGN CONDITIONS?

For simplicity, consider the process of a unit conditioning 100% outdoor air (where the unit is a dedicated outdoor air system). The psychrometric chart represents a path of outdoor air as it passes across the cooling coil for the 0.4% cooling design condition in Athens, Georgia. Assuming a supply air condition of 55°F (12.8°C) and 85% relative humidity (wet-bulb temperature = 52.5°F [11.4°C]), the humidity ratio changes across the coil from 0.0141 to 0.0078 lb/lb_{air} (kg/kg_{air}). The difference in absolute humidity ω between the incoming outdoor air and supply air leaving the unit represents the amount of condensation that occurs. Thus, for every lb (kg) of air supplied by the unit, 0.0141 – 0.0078 or 0.0063 lb (0.00286 kg) of water are condensed.

The total amount of condensate expected is determined by the equation below:

$$\text{Condensate} = \text{Airflow} \times \text{Density} \times 60 \frac{\text{min}}{\text{h}} (\text{I-P}) \text{ or } 3600 \frac{\text{s}}{\text{h}} (\text{SI}) \times \Delta\omega$$

Assuming 1000 cfm (472 L/s) of outdoor air is being conditioned, the total amount of condensate expected would be the following:

$$\begin{aligned} \text{Condensate} &= 1000 \frac{\text{ft}^3}{\text{min}} \times \frac{\text{lb}}{13.133 \text{ ft}^3} \times 60 \frac{\text{min}}{\text{h}} \times (0.0141 - 0.0078) \frac{\text{lb}_{\text{water}}}{\text{lb}_{\text{dry air}}} \quad (\text{I-P}) \\ &= 28.8 \frac{\text{lb}}{\text{h}} \end{aligned}$$

$$\begin{aligned} \text{Condensate} &= 0.472 \frac{\text{m}^3}{\text{s}} \times \frac{\text{kg}}{0.820 \text{ m}^3} \times 3600 \frac{\text{s}}{\text{h}} \times (0.0141 - 0.0078) \frac{\text{kg}_{\text{water}}}{\text{kg}_{\text{dry air}}} \quad (\text{SI}) \\ &= 13.05 \frac{\text{kg}}{\text{h}} \end{aligned}$$

This is approximately 3.5 gal (13.1 L)/h at the cooling design condition.

Similar calculations can be run for any locality, and the result can vary widely depending on the climate. For example, when the calculation is run for other representative cities the condensate yields are as follows:

- Boston, MA (90.8°F [32.6°C] dry-bulb/73.3°F [22.8°C] mean coincident wet-bulb [MCWB] temperature)
= 3.2 gal (12.1 L)/h
- Sacramento, CA (100.4°F [37.9°C] dry-bulb/70.7°F [21.4°C] MCWB)
= 0.8 gal (3.1 L)/h

- Denver, CO (94.3°F [34.5°C] dry-bulb/60.3°F [15.6°C] MCWB)
= no condensate collected

Interestingly, the total annual rainfall is only a partial indicator of how much condensate might be collected, as shown in Table 12-2. The two comparative eastern and western US cities have similar rainfall totals, but they vary significantly in terms of the total amount of condensate collection potential.

What to Do with Collected Water

The best end use for the collected water will depend on the particular circumstances of the location. In many locations the primary use of city water is for makeup water in cooling towers. Therefore, it may be the most logical choice to collected condensate to its cooling tower sump. In most cases, peak condensate production will occur at the same times as peak makeup water demands, creating an elegant feedback loop. This is also the simplest retrofit, involving reasonably inexpensive equipment and piping; water can be routed directly to the tower with no need for treatment. Complications arise when dealing with district cooling systems with satellite chillers, because it is possible to produce condensate in an air-handling unit while the chiller and cooling tower for that particular building are idle. While it is no tragedy that condensate sent to the cooling tower will simply overflow to the sewer (where it would have gone prior to retrofit), there is the risk that treatment chemicals in the sump will be diluted and needlessly washed away. In this scenario, care should be taken to prioritize condensate retrofits in buildings with baseline chiller plants.

Table 12-1: Annual Condensate Collection Compared to Total Annual Rainfall

	Annual Condensate for Continuous Outdoor Air, gal/cfm (L/L/s)	Average Annual Rainfall, in. (m)
Athens, GA	12.5 (100.4)	47.8 (1.21)
Boston, MA	4.5 (36.1)	42.5 (1.08)
Sacramento, CA	1.3 (10.4)	17.9 (0.45)
Denver, CO	0.5 (4)	15.4 (0.39)

Digging Deeper

Digging Deeper

Condensate collection can also be integrated into a rainwater collection system, a scheme often referred to as *rainwater plus*. This will usually involve a storage tank or cistern and can require considerably more expense and engineering than using the condensate in a cooling tower. Depending on the intended use (e.g., for irrigation, fountains, toilet flushing, or potable water), different amounts of further treatment will be required. In all cases, local building codes must be followed.

Digging Deeper

HOW MUCH OF DEMAND CAN BE MET BY RAINWATER HARVESTING?

Simulations with different combinations of roof catchment areas, storage capacities, and demands can be assessed at any location where daily rainfall data is available. For the present, consider a building in an example city in Georgia, USA, with an impervious roof area of 100 m² roof (1076 ft²) and a nonpotable demand of 200 L/d (26 gal/d).

After establishing the water demand, the supply-storage-demand problem can be iteratively experimented with an Excel spreadsheet if local daily rainfall data is available to cover many decades. An example is provided for a simple rainwater harvesting example notionally in Atlanta, Georgia (33.64°N latitude, 84.43°W longitude), which is referred to as “Example City, GA, USA” in Chapter 14, “Climatic Design Information” of *ASHRAE Handbook—Fundamentals* with the bogus ID WMO777777/WBAN99999 identifier to indicate that it is unchanged from the 2017 edition of *ASHRAE Handbook—Fundamentals* Atlanta Hartsfield-Jackson with actual ID WMO 722190/WBAN13874. An I-P or SI version of this spreadsheet can be downloaded from Peterson (2022) in the “Sources of Further Information” section. The period of observations 1990–2014 stated in the 2017 and 2021 *Handbook* datasheets are with respect to temperature, humidity, wind, pressure, and solar radiation but not precipitation data. Within the US, the best source of rainfall data is found in National Oceanic and Atmospheric Administration’s (NOAA) Daily Observations Data Map (<https://www.ncei.noaa.gov/maps/daily/>). There are several different datasets available, but for this discussion, we are using the Global Historical Climatology Network (GHCN) to illustrate one possible spreadsheet form you could construct.

Station	Name	Date	PRCP
USW00013874	ATLANTA HARTSFIELD JACKSON INTERNATIONAL AIRPORT, GA US	01/01/1930	0
USW00013874	ATLANTA HARTSFIELD JACKSON INTERNATIONAL AIRPORT, GA US	02/01/1930	1.05
USW00013874	ATLANTA HARTSFIELD JACKSON INTERNATIONAL AIRPORT, GA US	03/01/1930	0

Station	Name	Date	PRCP	Cache, L	Makeup, L/d	Overflow, L/d
USW00013874	ATLANTA HARTSFIELD JACKSON INTERNATIONAL AIRPORT, GA US	1/1/1930	0	0	0	0

Digging Deeper

In this case, select GHCN and enter the coordinates so you can zoom out to select station “GHCND:USW00013874.” Then select “custom GHCN Daily CSV” with the earliest possible date range (1930-01-01 through yesterday) and select only precipitation “PRCP.”

Open your GHCN order with precipitation data (“PRCP”) in a spreadsheet. It will be four columns wide and thousands of rows long. The first four rows are shown to explain that if there were, for example, 100,000 rows below the starting date, it would be a record of 273 years of daily rainfall records, which precedes the earliest station ITE00100554 in Milan, Italy, which has been reporting daily since 1763 with a few gaps. Be aware that start dates prior to 01/01/1900 will not be recognized in Microsoft Excel spreadsheets as a number readable in date formats that specify the day, month, and year of record. The second column will be used to provide input and output parameters in your analysis of the date and precipitation records in the third and fourth columns, as well as running accounts of a rainwater harvesting system to occupy the fifth, sixth, and seventh columns titled “Cache (L),” “Makeup (L/d),” and “Overflow (L/d),” respectively.

Next, enter the following information into the fourth through thirty-sixth rows of the first two columns (Cells A4:B36). See Table 12-2.

Most important are the four input parameters highlighted in Table 12-2: The 12th row should be marked “mm/PRCP” with a value of 10 at Cell B12 to convert the fourth column to mm of precipitation. For this example, the 17th row should be marked “Area (m²)” with 100 in Cell B17, and the 22nd row should be titled “Demand (L/s)” with 200 entered in Cell B22. “Capacity (L)” is adjusted in Cell B26 with an initial value of 1000 (to last five days without rain). These values are referred to by formulas you need to enter and copy down the columns to the right of the PRCP column for an equal number of rows.

The daily accounting of storage inventory discussed below is an approximate calculation that uses the previous day’s overflow or makeup to avoid circular references. The initial condition of “Cache (L)” is entered in Cell E2 as zero in Figure 12-4, followed in Cell E3 by Equation 1 daily balance taken from the previous day’s sum of Cache and Makeup, less Overflow adding Equation 2 current daily rainwater harvest, less the daily demand. Copy downward from cell E3’s script = E2+F2–G2+\$B\$14*\$B\$19*D3–\$B\$24. Except for the first day of records, the stored Cache on a given date is calculated from the Cache on the previous day, plus makeup on the previous day, minus Overflow on the previous day, plus Harvest on the given date, minus Demand on the given date.

Table 12-2: Replace Succeeding Repetitions under STATION and NAME Columns (Cells A3:B36)

Write Descriptive Text (in the First Column)	Values and Equations Go in the Second Column	Equations Start with Equal Sign (in Second Column)
(Dates after year 1899 as positive integers)		
Last Date	44230	=MAX(C:C)
First Date	10959	=MIN(C:C)
Years	91.1	=COUNT(C:C)/365.25
m/d/yyyy Date Format, Last Date	2/3/2021	=MAX(C:C) &Format Cells ... Custom
Alternatively ... ddd d mmm yyyy	Wed 3 Feb 2021	=MAX(C:C) &Format Cells ... Custom
Factor to Convert PRCP to Units of mm (10 or 25.4?)	(input)	
mm/PRCP	10	
Maximum mm/d	66.8	=MAX(D:D)*\$B\$11
Average mm/d	1.35	=AVERAGE(D:D)*\$B\$11
Roof Over Tank	(input)	
Area (m ²)	100	
Maximum Catch (L/d)	6680	=B12*B16
Average Catch (L/d)	135	=B13*B16
Specification of need	(input)	
Demand (L/d)	200	
Tank Sized by Days Demand Persists without Rain	(input)	
Days Autonomy = capacity/daily_demand	5	
Capacity (L)	1000	=B21*B24
Check Outputs	(performance)	
% Harvested	67%	=(1-(SUM(F:F)/(COUNT(F:F)*\$B\$21)))
% Imports	33%	=SUM(F:F)/(COUNT(F:F)*\$B\$21)
Makeup L/year	23,949	=SUM(F:F)/(COUNT(C:C)/365.25)
Minimum in Cache (L)	0	=MIN(E:E)
Average in Cache (L)	1433	=AVERAGE(E:E)
Average % Full	14%	=B32/B25
Maximum Poured over the Cache (L)	12,860	=MAX(E:E)
Overflow L/year	188	=SUM(G:G)/(COUNT(C:C)/365.25)

Digging Deeper

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$$\text{Except for the first day: } \text{Cache}_d = \frac{\text{Cache}_{d-1} + \text{makeup}_{d-1}}{-\text{Overflow}_{d-1} + \text{Harvest}_d - \text{Demand}} \quad (1)$$

$$\text{Everyday: } \text{Harvest}_d = \text{PRCP}_d \times (\text{mm}/\text{PRCP}) \times \text{Area} \quad (2)$$

$$\text{If } \text{Cache}_d < \text{Demand}, \text{ then } \text{Makeup}_d = \text{Demand} - \text{Cache}_d \quad (3)$$

$$\text{If } \text{Cache}_d > \text{Capacity}, \text{ then } \text{Overflow}_d = \text{Cache}_d - \text{Capacity} \quad (4)$$

Makeup is automatically activated when the level in the cache drops below one day's demand allowance. The equation is implemented in the spreadsheet Cell F2 as Makeup (L/d) =IF(E2<\$B\$24,\$B\$24-E2,0)

Overflows are registered on days when the daily balance in the cache (Equation 1) is greater than storage capacity, and Equation 4 is implemented in spreadsheet Cell G2 as Overflow (L/d) =IF(E2>\$B\$28,E2-\$B\$28,0).

Copy cells E3, F2, and G2 containing equations down as far as the latest record of DATE and PRCP.

Note that daily supply (L/d) is the product of mm rainfall in mm and the square meters of effective catchment area in m². You may want to discount the area to account for various losses, but you need to be very careful what units of daily rainfall were provided in the fourth column. Read the documentation URL in NOAA's data delivery email to establish that PRCP = Precipitation (tenths of mm), but please be aware that other sources may report inches or tenths of inches. In this particular example, the daily rainwater harvest is one-tenth of the product of PRCP and square meters of the effective catchment area.

Cell B29 in Figure 12-4 reports (1-(SUM(Makeup)/(COUNT(Makeup)×Demand))) as the percentage of demand supplied by the rainwater harvesting system, because the numeric format was set as a percentage, otherwise it would have been a decimal value. In Figure 12-4, the result is that 47% of 200 L/d demand could have been supplied from a 1000 liter tank under a 100 m² roof. Doubling both the tank and catchment area would have resulted in 76% satisfaction of demand. If demand were reduced to 150 L/d, there would still have been times of drought when water imports would be required. One hundred percent autonomy could have been achieved with an extended 200 m² roof area by cutting demand to 100 L/d, as long as the storage capacity was increased to 4000 liters. There are an infinite range of partial and complete solutions to pursue for the rainwater harvesting, storage, and demand problem, as long as rainfall records are available. There is a potential for a shift of climatic patterns, and so it

=E2+F2-G2+\$B\$12*\$B\$17*D3-\$B\$22						
A	B	C	D	E	F	G
STATION	NAME	DATE	PRCP	Cache (L)	Makeup (L/d)	Overflow (L/d)
USW00013874	ATLANTA HARTS	1/1/1930	0	0	200	0
replace A3:B36 with the following equations						
(Dates after year 1899 as positive integers)						
MAX(C:C) = last date	44230	1/2/1930	1.05	G2+	0	50
MIN(C:C) = first date	10959	1/3/1930	0	800	0	0
COUNT(C:C)/365.25 = years	91.1	1/4/1930	0	600	0	0
m/d/yyyy date format ... MAX(C:C) = last date	2/3/2021	1/5/1930	0	400	0	0
alternatively ... ddd d mmm yyyy	Wed 3 Feb 2021	1/6/1930	0	200	0	0
Factor to convert PRCP to units of mm (10 or 25.4?)	(input)	1/7/1930	0	0	200	0
mm/PRCP	10	1/8/1930	0	0	200	0
MAX(D:D)*\$B\$11 = maximum mm/d	66.8	1/9/1930	0	0	200	0
AVERAGE(D:D)*\$B\$11 = average mm/d	1.35	1/10/1930	0	0	200	0
roof over tank	(input)	1/11/1930	0	0	200	0
Area (m²)	100	1/12/1930	0	0	200	0
B12*B16 = max Catch (L/d)	6,680	1/13/1930	0	0	200	0
B13*B16 = aver Catch (L/d)	135	1/14/1930	0.44	440	0	0
Specification of need	(input)	1/15/1930	0.51	750	0	0
Demand (L/d)	200	1/16/1930	0	550	0	0
Tank sized by days demand persists without rain	(input)	1/17/1930	0.01	360	0	0
days autonomy = capacity/daily_demand	5	1/18/1930	0.26	420	0	0
B21*B24 = Capacity (L)	1,000	1/19/1930	0	220	0	0
check outputs	(performance)	1/20/1930	0	20	180	0
(1-(SUM(F:F)/(COUNT(F:F)*\$B\$21))) = % harvested	47%	1/21/1930	0.54	540	0	0
SUM(F:F)/(COUNT(F:F)*\$B\$21) = % imports	53%	1/22/1930	0.17	510	0	0
SUM(F:F)/(COUNT(C:C)/365.25) = makeup L/year	38,552	1/23/1930	0	310	0	0
MIN(E:E) = minimum in Cache (L)	0	1/24/1930	0	110	90	0
AVERAGE(E:E) = average in Cache (L)	298	1/25/1930	0	0	200	0
B32/B25 = average % full	30%	1/26/1930	0	0	200	0
MAX(E:E) = maximum poured over the Cache (L)	7,480	1/27/1930	0.13	130	70	0
SUM(G:G)/(COUNT(C:C)/365.25) = overflow L/year	14,791	1/28/1930	1.06	1060	0	60
Remove repetitions of STATION & NAME (saved above)		1/29/1930	1.14	1940	0	940
		1/30/1930	0.01	810	0	0
		1/31/1930	0	610	0	0
		2/1/1930	0	410	0	0
		2/2/1930	0	210	0	0
		2/3/1930	0.01	20	180	0
		2/4/1930	0.54	540	0	0
		2/5/1930	0	340	0	0

Figure 12-4 Example City GHCN daily precipitation amended according to Table 12-2.

is essential to have a risk management plan to both impose restrictions on demand and source water imports.

SOURCES OF FURTHER INFORMATION

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Digging Deeper

CHAPTER THIRTEEN

SMART BUILDING SYSTEMS

Our society has entered the age of Big Data and the Internet of Things (IoT). Using smart devices and the ever-expanding wireless networks, we are intimately connected to the world in which we operate. Portable access to information also allows us to make informed decisions more quickly and accurately than in previous decades.

Building operations and maintenance are also being transformed by this connectivity. For example, at the device level, smart thermostats are capable of remote adjustment and monitoring via any number of graphical interfaces (smartphone, tablets, computers, and so on) and IP-addressable HVAC equipment such as rooftop units, facilitating remote troubleshooting and control. These examples show how building systems infrastructure is leveraging technology to improve control, comfort, and maintenance efficiency. At a building- or portfolio-scale, open architecture controls and cloud-based software platforms now facilitate integration, aggregation, and analysis of building data and control across systems. At the electric grid scale, a growing number of buildings are integrated into and operating as a dynamic part of the smart electric grid through on-site renewable energy, thermal and/or battery storage, and participation in demand response (DR) programs. The built environment is rapidly evolving from closed, stand-alone systems to those that are interconnected and accessible globally.

Smart buildings are unique among the broader building stock in that they take advantage of data, communication, and controls to optimize building performance by continually turning data into information and knowledge and ultimately into action. This chapter highlights components and strategies often used in smart building systems and is divided into nine sections as follows:

- **Integrated building automation systems:** A smart approach to operations and maintenance integrates building infrastructure systems into a common operations interface, facilitates data visualization and sharing across systems, and serves as a repository of maintenance information and procedures.

- **Controls system design:** A clear definition with respect to design intent and system functionality provides the contractor, commissioning authority, and facilities staff a roadmap for installing, configuring, and operating the building.
- **Automated fault detection and diagnosis:** To maximize ongoing building operational performance, automated fault detection and diagnosis (AFDD) serves as a database overlay designed to uncover, report, characterize, and often correct system faults.
- **Smart hardware:** Hardware in smart buildings often possess intelligence to diagnose defective devices and recalibrate and/or fix those devices.
- **Occupant-centric control:** Through the use of smart applications and graphical user interfaces, building occupants can both directly control and solicit feedback from buildings, a process critical to ongoing optimization.
- **Energy and water efficiency in smart buildings:** Through both stand-alone and integrated systems strategies, smart controls have the capability of significant reductions in building energy and water usage in a typical commercial building.
- **Indoor environmental quality in smart buildings:** In most commercial buildings, controls play a crucial role in monitoring and regulating space temperature, humidity, ventilation, acoustics, and light levels.
- **Smart building control system commissioning:** Commissioning occurs from design through postoccupancy and helps ensure that control systems—both stand-alone and interconnected—are installed and configured correctly.
- **Building-electric grid interaction:** The interaction of a smart building with the coming smart grid. With smart grid technologies being deployed by utilities worldwide, as well as the rise in the use of renewable wind and solar resources, demand response programs directed at commercial, industrial, and residential buildings are increasingly being piloted and implemented.

INTEGRATED BUILDING AUTOMATION SYSTEMS

Building operation is a systematic process comprehensively influenced by building technology, cultural context, occupant interactions with building equipment and systems, and social equity, among other factors. Consistent throughout these factors are building occupants and their energy-impacting behavior, representing a strong influence on building operations. The occupants' and operators' expectations of comfort and/or satisfaction in the built environment are often a driver for building controls.

The integration of building systems data, communication capabilities, and intelligent controls provides a framework from which to operate a more efficient, higher-performing building. A smart building systems approach to facilities management and control aggregates monitoring and control into a common system. This system provides easy access to, and the visualization of operational data and system feedback that allows building operators to better understand the building's dynamics. With knowledge and actionable information in hand and monitored on a

real-time basis, building staff can make informed decisions on how to efficiently position, operate, maintain, and optimize their assets over time.

The heart of a smart building system is an open architecture or integrated systems approach to building management that allows the dynamic features of the modern building such as information technology (IT), lighting and lighting controls, shading controls, mechanical/HVAC, plumbing, power/power monitoring, security, and audio-visual to integrate to a common front-end. As specified in the commercial buildings Master-Format Division 25 for Integrated Automation, (CSI 2016) this front end serves as both the:

- Single point of operations, controls and maintenance information for the building's dynamic systems.
- Data aggregation, analytics, visualization, and reporting platform for sustainable operation and maintenance.

Recognizing that the building operators generally are key in supporting the long-term operational performance of the building, a key part of ensuring smart buildings operate as intended is sufficiently educating them on the types of available data, and the appropriate use of this data and corresponding controls, feedback loops, and tools to more intelligently control and troubleshoot building system operations. Ultimately, this also includes defining the building owner's project requirements (OPR) (see Chapter 5, Commissioning, for more information). With the OPR in hand, a collaborative, performance-based process facilitates the design and specification of systems and components and the careful evaluation and selection of integration contractors aligned to deliver an optimal outcome.

However, a well-intentioned design devoid of proper functionality, utilization, and regular maintenance by appropriately trained building operators will never maximize its value (which applies to any building, not just a "smart building.") Coordinating, specifying, and commissioning the connectivity, installation, and integration of otherwise disparate systems becomes critical to the utility of a smart building system. This cohesive process is generally led by a dedicated, multidisciplinary team. In addition to coordinating the design effort related to systems integration, the smart building systems team specifies the system's metering, monitoring, training, and ongoing commissioning requirements. Defining these components helps ensure that the owner has easily-accessible tools to drive operations and optimization.

Control System Design

Lack of clarity with respect to design and/or control intent for building systems oftentimes results in suboptimal building performance. To ensure the contractor, commissioning authority, and ultimately the building operators understand how the building systems should function, the following control-related elements should be

included in the contract documents. While most of this section focuses on controls for HVAC systems, the process described can and should be applied when developing controls designs for other systems within a smart building (e.g., lighting). This list of items is not comprehensive, but it provides an idea of the type of issues that should be considered and addressed.

Provide Detailed Control Descriptions. One of the most prevalent reasons control systems fail to perform as intended is that insufficient forethought is given to the sequence of operation prior to the contractor programming setup. The designers, and later, the control contractor's programmer often do not think through the sequence of operations and consider how it will (or will not) function during all possible modes and scenarios of weather, loads, staging, and interactions. This issue can be mitigated through the following:

- Ensure the designer provides flow diagrams of the major controlled systems, showing interfaces and control authorities between local and central control.
- Ensure the designer includes detailed sequences of operation, including a brief system narrative, points list, alarms, what initially starts equipment, staging, failure and standby functions, power outage response and reset requirements, interlocks to other systems, control authorities with local (packaged) controls, trending requirements, and energy efficiency strategies with given set points.
- Develop a graphical test simulation of the control program(s) to ensure the mechanical equipment sequences on and off as load increases and decreases, according to the sequences of operation.

Match Control Strategies to Operator Capabilities. If the building operators do not understand the features or sequences sufficiently, and there is not a qualified controls technician maintaining the system, the advanced features or sequences that were originally programmed during commissioning will likely be overridden or disabled. Designers and design reviewers should make sure the complexity of control schemes matches the expected level of technical expertise of the building operators. They should also be clear regarding these expectations in communications with the building owner or manager who oversees the hiring and management of the building operators. It is critical that operator training be conducted on a regular basis, including during initial commissioning and in a timely manner, including follow-up sessions as needed.

Strategies Relying on Sensors Requiring Ongoing Maintenance. Where smart hardware is not used, control sensor and loop recalibrations are a necessary function for maintaining high-performing systems. The OPR document should define the operator training and skillsets needed to maintain the system functioning at the designed efficiency. Major control strategies that depend on sensors that are known to drift and/or require regular maintenance should be avoided, or, if specified or required, the necessary training and recalibration programs must be institu-

tionalized into the building maintenance culture. For example, consider the case of a chiller staging sequence using supply and return temperatures and flowmeter(s). These sensors may drift over time, and typical accepted error ranges in these types of sensors will yield inaccurate load calculations that may disrupt proper staging. This strategy can result in high overall efficiency, but to achieve this high level of efficiency, this requires a regular calibration and maintenance checks to maintain this high efficiency.

Requirements for System Architecture Rationale. It is important to ensure that, in the requirements for the controls submittal, the controls contractor is mandated to provide calculations and rationale for the number and layout of the primary (peer-to-peer) and local (application-specific) controllers in relation to the total number of points and other network traffic. It should also be required that the contractor describe how many points can be reasonably trended simultaneously without appreciably affecting point value refresh rates, and describe the impacts on network speed that alternative layouts would have (or alternatively provide insight into the network requirements needed to operate the desired system architecture).

The building automation system (BAS) performance requirements should be defined in the contract documents (i.e., specifications such as those set forth in ASHRAE Guideline 13-2015, *Specifying Direct Digital Control Systems* [ASHRAE 2014]). The performance requirements are defined during the predesign phase and should be contained in the OPR document in accordance with ANSI/ASHRAE/IES Standard 202-2018.

Requirements for Clear Control Sequences. Ensure that the requirements for the controls submittals in the specifications include statements requiring the following:

- A brief overview narrative of the system, generally describing its purpose, components, and function (i.e., the design intent for the controls)
- All interactions with other systems
- Detailed delineation of interaction between any localized controls and the BAS, listing what points only the BAS monitors and what BAS points are control points and are thus adjustable
- Start-up, warm-up, cooldown, occupied, and unoccupied operating modes, plus power failure recovery and alarm sequences
- Capacity control sequences and equipment staging
- Initial and recommended values for all adjustable settings, set points, and parameters that are typically set or adjusted by building operators, as well as any other control settings, fixed values, delays, and so on, that will be useful during testing and ongoing operating the equipment
- Rough zone analysis requirements to assure reset strategies are effective
- Energy mapping requirements to help operators understand building efficiency
- System override capabilities and requirements

- Description of building isolation areas for off-hours operation
- Front-end graphics requirements including summary screens by system type, zone, and plant

To facilitate review and referencing in testing procedures, all sequences should be written in short statements, each corresponding to a number for easy reference.

Requirements for Clear Control Drawings. The specifications must ensure the control drawing submittal requirements include at least the following:

- The control drawings must contain graphic schematic depictions of all systems showing each component (e.g., valves, dampers, actuators, coils, filters, fans, pumps, speed controllers, piping, ducting, etc.), each monitored or control point and sensor, and all interlocks to other equipment. Drawings may include fan and pump flow rates as well as horsepower.
- The schematics should include the system and component layout of any equipment that the control system monitors, enables, or controls, even if the equipment is primarily controlled by packaged controls.
- A full points list should be provided, including point abbreviation key, point type, system point with which it is associated, point description, units, panel ID, and field device.
- Network architecture drawing should include all controllers, workstations, printers, and other devices in a riser format and including protocols and speeds for all trunks. Include the network buses with the bus speeds.
- Sketches of all graphics screens for review and approval must be included.

Include Commissioning Engagement in Design Fees. In estimating the fees for the design process, owners and the design team should include sufficient allowance for these parties to be fully engaged in the commissioning process during design. This includes responding to design review comments and incorporating commissioning requirements into the project specifications.

AUTOMATED FAULT DETECTION AND DIAGNOSIS

Three factors that are critical to sustaining the efficiency level of a new building are (1) a well-designed measurement and verification (M&V) process, (2) implementing a commissioning program that will evaluate the function of all key systems and equipment regularly, and (3) strong building operator training on the control system functions (see previous section, Match Control Strategies to Operator Capabilities). The first two factors allow building operators to monitor performance regularly and intervene when problems are detected. The control system is essential in implementing a strong M&V process. Good training can help ensure that all capabilities of the control system, including those related to M&V, are used to their full potential over the lifetime of the building. The technologies for fault detection and

diagnosis (FDD) were developed to aid building operators in maintaining an improved level of efficiency before these evolved into the more advanced field of automated fault detection and diagnosis (AFDD). FDD is a nonsoftware-driven means of detecting and correcting operational faults. This method often uses in-field or handheld equipment that maintenance personnel can use on site to assess equipment performance under different conditions.

The objective of automated fault detection and diagnosis (AFDD) is the early detection and correction of system faults and inefficiencies. In this two-step process, first, the fault in equipment operation is detected. Second, the actual cause of the fault is isolated (and potentially recommended maintenance or solution method). Enabling this practice is monitoring and metering infrastructure that continuously trends available data across building systems. This data is used with algorithms ranging in complexity to process and interpret the collected data. At the equipment level, this data originates from a set or subset of sensor readings taken from sensors installed on the HVAC equipment and its components. These can include variables such as temperature, pressure, humidity level, energy and/or power use, or other related values. At the building level, this may also include data such as indoor and outdoor temperatures, smart meters, and other data enabled through the growing sensing and communication capabilities of wireless sensors and IoT. This measured data is combined with known information on the equipment, system, and/or building characteristics. AFDD software then analyzes the combined data set using a host of rules and algorithms and flags instances of non-conformance. These instances are typically prioritized based on another set of rules and/or evaluated by building operations staff to determine the underlying cause and appropriate corrective action.

AFDD methods may be divided into three main categories, including (1) qualitative model-based methods, (2) quantitative model-based methods, and (3) process-history-based methods. The two model-based methods (1 and 2) use *a priori* knowledge to identify actual operational data and model result predictions. Qualitative methods trigger a fault when measured data violate a set of rules describing the proper operation of a building, system, or equipment. These rules are determined based on expert knowledge, process history data, and/or quantitative models. Quantitative methods use a mathematical model based on the underlying physical relationship and characteristics of the equipment, system, or building performance, which is then compared to the actual performance, triggering a fault when the actual and predicted values do not match. The data-based methods (3) use limited to no knowledge of the physical system being analyzed, focusing on data previously collected to train the systems. This approach typically uses statistics-based black box methods, or grey-box models where the model parameters are based on physical principles, to relate measured input sensor data, measured output data, and/or predicted data, triggering a fault if the relationship between these values is violated. Compared to the first two methods, this method requires less knowledge

of the building, system, and/or equipment characteristics but also requires a significant amount of historical data to use as training data to develop the input/output sensor relationships that are comprehensive enough to cover a large range of operational conditions. This is important for this method as these methods typically do not extrapolate well outside the bounds of the training data.

AFDD can be implemented for building equipment in many different ways. The first most basic way is through embedded AFDD developed by the manufacturer and specific to a piece of equipment. This method includes equipment-specific values and algorithms that cannot be applied elsewhere. AFDD can also be implemented using non-manufacturer-specific methods that can be added to existing equipment through a standalone or online software as a service (SaaS) or a cloud-based model. Similar to the embedded FDD, this provides continuous monitoring and feedback on the performance of a piece of equipment using a set of sophisticated algorithms and expert rules. These bottom-up methods focus on specific pieces of equipment. Conversely, top-down methods are also used, which focus on detecting the presence of a fault using building- or system-level data rather than equipment-level data.

AFDD methods have been applied to all types of equipment through significant research efforts in recent years, including air handlers, packaged units, VAV terminal units, boilers, chillers, and economizers. Common HVAC&R faults can include stuck or leaking valves or air dampers, actuator failures, leaky ducts, clogged air filters, incorrect sensor calibrations, low refrigerant, and restricted airflow. They can also be used in a broader sense to identify system faults such as equipment not operating in accordance with the specified schedule and/or associated design parameters.

Moving forward, IoT has a strong potential to further improve the current AFDD methods by providing more data, which can better inform AFDD algorithms. This enables smarter building operations that can more quickly identify issues and alert building operators so they can work to resolve them. More IoT devices continue to be connected at a rapidly expanding rate, while at the same time, sensors are becoming smaller, lower-cost, more reliable, and more readily available. These will allow more data to be included in control and maintenance decisions. Improved security and standard protocols for communications are currently under development, mostly due to mounting concerns about cybersecurity as our systems rely more heavily on data, communication, and connectivity. These IoT devices, such as networks of low-cost sensors, result in more data that can be combined to improve building operations feedback. Similarly, portable handheld devices, such as smartphones can provide additional data feeds to AFDD, potentially at low to no cost. Data fusion methods have been proposed that use large amounts of data that come from many different types of sensors that alone would not be sufficient, but because of the insights that can be determined from multiple different overlapping types of sensors (e.g., occupant presence from a low-cost infrared (IR) camera and a low-

cost CO₂ sensor), enabling a check of accuracy of the input data into AFDD and improved performance and reliability of the resulting output from these methods.

SMART HARDWARE

Smart operation of buildings depends on quality input data from a range of sensors and information collected about a building and its systems, as discussed in previous sections of this chapter. However, if the sensors that are relied upon for intelligent operation are providing inaccurate information, this can have a negative impact on the building performance. Typically, sensors need calibrating every few years, depending on the manufacturer, sensor quality, sensor type, and how they are used. The types of sensor technologies currently used today for the collection of common building system operations must generally be checked every 1 to 3 years. High-level control algorithms could potentially add a weighting to the sensor inputs, based on an assigned reliability for that data. In recent years, particularly with the growth and commercialization of a broad range of IoT solutions for a range of markets, modern sensors and sensor systems have become more “plug-and-play” solutions that require minimal setup to use. Information that was previously required from a manufacturer, such as calibration coefficients to ensure the correct interpretation of a sensor output signal, are now more commonly integrated into the sensors themselves. This makes for a more user-friendly set of sensors that are easier to install and used by a wide variety of end users and technical skill levels. However, it also reduces awareness of the needs for calibration and the limitations of these sensors by end users, who may or may not be aware of calibration methods. Therefore, smart hardware with improved accuracy and reliability for longer periods of time is of interest to the building community who continuously rely on the values of the sensor outputs. The accurate calibration of sensors is also of interest to the manufacturers of the sensors themselves to ensure a level of accuracy for their sensors at a low cost.

In an effort to improve sensor reliability and reduce frequent maintenance needs, new sensors are being developed that self-calibrate. While complete self-calibration is impossible, a strong reduction in the amount of calibration effort needed is possible, enabling longer time periods between manual calibration and/or replacement of sensors. This can be accomplished in a number of ways, many of which involve the use of multiple sensors. Methods include co-integration of other sensors that enable self-calibration through methods such as:

- **cross-sensitivity compensation**, which uses two sensors, including a main sensor that is sensitive to the property being measured and also an interfering quantity from the second sensor. Assuming the sensitivity of the sensor to the interference is consistent over time, this can be used to correct the value of the property being measured by the main sensor.

- **differential sensing**, which includes two identical sensors that measure the same value but with the opposite signs, where the error can be compensated for by taking the difference between the outputs.
- **background calibration**, which involves the comparison of the output values of two different types of sensors that measure the same parameter, enabling compensation for their differences. Another method related to this could include using a current signal when a value can be known or deduced, such as CO₂ levels during an unoccupied period and the assumed value then.
- **co-integration of actuators to generate a calibration signal**, which is used to compare the sensor's output to a reference output, which then is used to correct the sensor's output.

In the future, from an IoT perspective, the number of sensors and actuator and their networking capabilities will significantly increase. This requires advancements in software capabilities to make more smart decisions than the current BAS in use today. It also requires such software to better prioritize the issues identified from the BAS and sensors to support the most efficient use of the building operators' time. To achieve this, the BAS should follow open protocols to integrate information from different buildings easily.

OCCUPANT-BASED CONTROLS

Human perceptions of thermal and visual comfort vary considerably among individuals. For this reason, a design principle to consider is that building occupants, the primary users of most buildings, should be given some level of control over their thermal and visual environments. Some definitions for smart buildings emphasize that “smartness” is achieved through the balancing of the ability of the occupants to control their environment and the ability of the building systems to manage their energy consumption efficiently (Buckman et al. 2014). Room thermostats, operable windows, dimming switches, and adjustable blinds are all connected building systems that can be automated but also can provide the ability for occupants to adjust these systems manually if the environmental conditions do not fit their personal level of comfort. Intelligently integrating considerations for these manually operable controls into the BAS can contribute significantly toward optimizing both IEQ and energy efficiency. In addition, other efforts in recent years have focused on the development and use of personal comfort devices, which allow an occupant to adjust their near-person environmental conditions with systems that only adjust the environmental conditions directly adjacent to the person.

Among the main driving factors of building performance, occupant behavior plays a key role (Hong et al. 2016, Yan et al. 2015). This, in part, is because of the controls adjusted by the occupant(s) to achieve comfort and satisfaction in the built environment. In addition, items used by occupants, such as computers and other

electronics, consume energy and thus are correlated with the occupants' preferences, behaviors, and presence in buildings.

Occupant behavior is also a key factor in evaluating various technologies for building design and retrofit efforts. Many case studies demonstrate that occupant behavior greatly influences the adaptability and implementation of a building technology. Correctly understanding the interactions between occupant behavior and building technologies is critical to improving building design and operations. Different occupant behavior needs different technical solutions, and different technical solutions may affect or change occupant behavior in buildings. Occupant-based controls addressing the occupants' needs and building efficiency would be a more effective solution since it can lower the manual intervention on control of different systems. A variation on this approach is when the building control system can provide information to the occupants, for example, when operable windows can be opened for overall thermal conditioning efficiency.

Most current building control systems use static and homogeneous human profiles, ignoring diverse and dynamic human comfort needs and the diverse and varied occupancy schedules and activities that can occur. This can lead to energy waste and human dissatisfaction in buildings. Smart buildings challenge this convention through the collection of operations data and transfer of information and control, in the least part, to building occupants. This occurs through smart devices, operations dashboards, and occupant-comfort-centric controls, which have opened a pathway for improved occupant satisfaction and building operational efficiency.

One such smart control strategy is the integrated-building-human-cyber systems technology (Figure 13-1), which integrates wireless sensing, data collection, analytics, machine learning of human behavior, and comfort feedback to manage energy end uses in buildings optimally.

ENERGY AND WATER EFFICIENCY IN SMART BUILDINGS

Smart buildings can help achieve energy and water efficiency through their controls and ability to continuously monitor their interior environment and the building systems that service it. In occupied buildings, energy efficiency is achieved by reducing the amount of energy required to provide occupants with an indoor environment that supports productivity with the appropriate lighting, thermal comfort, and ventilation people needed to carry out their tasks effectively. In modern buildings, control systems operate lights, chilled- or hot-water plants, ventilation, space temperature and humidity control, plumbing systems, electrical systems, life-safety systems, and other building systems. These control systems, informed by a broad range of sensors to monitor the state of indoor environment and building systems, can assist in conserving resources through the scheduling, staging, modulation, and optimization of equipment to meet the needs of the occupants and systems that they are designed to serve.

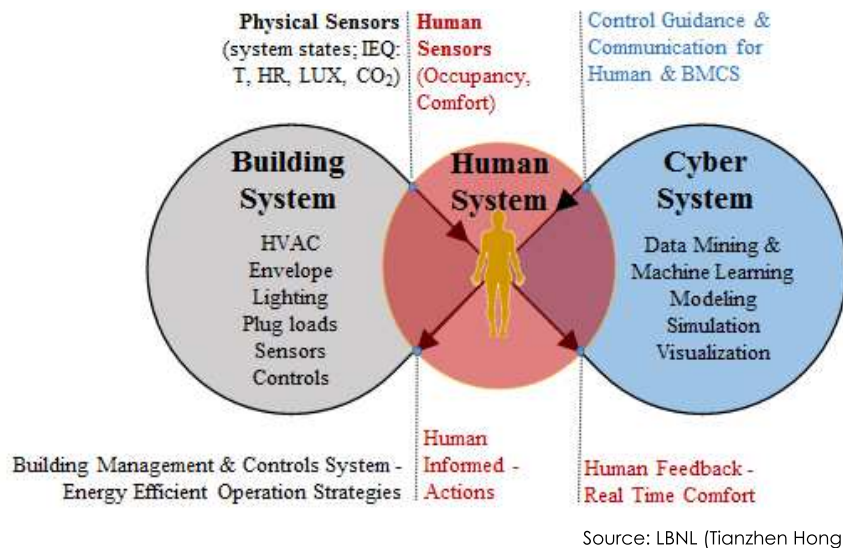


Figure 13-1 Integrated building-human-cyber systems.

The potential for energy and water savings through proper design, installation and operation of building automation systems is significant. Energy efficiency can be achieved through a variety of methods as discussed in ANSI/ASHRAE/IES Standard 90.1-2019 and/or ANSI/ASHRAE/USGBC/ IES 189.1-2020. The following are a number of recommendations on how building and system controls can be used to support high-performance, sustainable design

- Reduction of equipment runtime. Examples include scheduled control of lighting and HVAC systems inside buildings and photoelectric controls for site (exterior) lighting.
- Daylight harvesting control with dimming or stepped lighting in spaces with access to natural light.
- Static pressure reset of fans (and/or pumps) with variable-frequency drives (VFDs).
- Resetting temperature set points for chilled and condenser water supply, hot-water temperature, and/or coil discharge air temperature.
- Variable-speed control of pumps, fans, and compressors. This is another common method employed for cooling systems.
- Demand-controlled ventilation. Modulation of system and zone ventilation air-flow rates based on occupancy or occupancy level.

Beyond energy, smart buildings can support building water efficiency in three main areas: landscape irrigation, leak detection and overall usage monitoring, and cooling tower makeup. Additionally, controls can be used to regulate and monitor on-site wastewater treatment plants where those systems are in place. Chapter 12, “Water Efficiency,” of this guide provides additional details on efficient and sustainable water system design, operation, and maintenance.

Integrating landscape irrigation controls into the smart controls system provides a number of advantages. Among these are the ability to adjust schedules and set points from a single location, the ability to perform remote diagnostics, and the ability to track system performance and water use. Integrating water meters enables continuous measurement of water consumption. Water consumption data can be analyzed during unoccupied periods to determine whether leaks are present in the water distribution system. The judicious placement of submeters can allow building maintenance staff to identify the system or location in which the leak or leaks are present. Continuous water meter data can also be used to identify processes and areas of high water use and guide post-construction water conservation efforts.

Smart irrigation controllers using embedded sensors in the ground can make a significant contribution to reducing the annual water use of a building. Note that this is a requirement for landscaping irrigation in ANSI/ASHRAE/USGBC/IES Standard 189.1-2020, *Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings* [ASHRAE 2020]). The simplest irrigation controls are based on time clocks that open valves for a set duration, for a set number of periods per week. Unless the duration and frequency of watering is adjusted throughout the irrigation season, the use of time clock controllers often results in excessive water use. To automatically address seasonally varying irrigation requirements, some time clock controllers allow for 365 day programming.

An improvement on the time clock controller is to add moisture sensors, which can enable the system to bypass a watering period (if ground moisture levels are above a set point). Still more sophisticated controllers can gather data about local weather conditions—either directly via sensors, indirectly via a remote weather station, or by direct input from a remote weather station—and use that data to adjust the amount of water delivered to the landscape.

Regarding cooling tower makeup, Chapter 12, “Water Efficiency,” covers HVAC water use reduction in detail. Installing controls to continuously monitor condenser water quality in the interest of reducing the frequency of chemical treatment and cooling tower blowdown can reduce potable water consumption. Independently submetering cooling tower make-up water and blowdown should also be considered as a means to reduce sanitary/sewer bills.

Finally, some advanced green buildings feature on-site water and wastewater treatment plants. Such plants generally include pumps, fans, and sensors to monitor characteristics of the treated water (e.g., dissolved oxygen levels and total suspended solids). Depending on the goals and complexity of the water treatment

plant, an industrial supervisory control and data acquisition system may be necessary to ensure maximization of throughput, efficient energy use, and code compliance.

INDOOR ENVIRONMENTAL QUALITY IN SMART BUILDINGS

Factors regulated by building control systems that impact indoor environmental quality (IEQ) include operative temperature, relative humidity, outdoor airflow rates, and light levels. The first two factors are addressed in ANSI/ASHRAE Standard 55, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2020), the third factor is addressed in ANSI/ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2022), and the fourth factor is addressed in Chapter 10 of the IES Lighting Handbook (IES 2011). Chapter 8 (Indoor Environmental Quality) of this guide discusses the design and implementation of each of these factors.

Thermal Comfort

ASHRAE Standard 55 specifies thermal comfort for mechanically conditioned buildings based on occupant activity level, clothing level, air temperature, mean radiant temperature, air velocity, and relative humidity. One of the most common controls to all types of buildings is the thermostat, which adjusts the dry-bulb temperature of a space, therefore adjusting this comfort condition. Thermostats modulate the HVAC system operation to meet the desired temperature within a generally narrow deadband range above or below this set point. While they are less common than thermostats and temperature sensors, stand-alone humidistats and humidity sensors can be used to control room humidity levels. ASHRAE Standard 55 specifies a maximum humidity ratio of 0.012 for thermal comfort. The standard does not specify a minimum humidity ratio for thermal comfort (although it did in earlier versions) but nonthermal comfort factors (e.g., skin drying) may be used to establish such a minimum. Thermal comfort is important when considering the use of sophisticated controls, including occupant-based controls. As building are increasingly automated using smart building systems and controls, it is paramount that thermal comfort be monitored and considered in design and control decisions, as well as ongoing operations.

Air Quality and Ventilation

Procedures for determining minimum outdoor airflow rates are described in ASHRAE Standard 62.1. Building controls play a critical role in ensuring minimum outdoor airflow rates are achieved in three areas: VAV system control, mixed-mode ventilation systems, and dynamic reset of outdoor air intake flows.

It is difficult to ensure minimum outdoor airflow rates are met by VAV systems over the entire range of operating conditions in the absence of controls and associated sensor systems designed, installed, and maintained specifically for that

purpose. In recent years, there have been significant efforts to more intelligently monitor and control commercial building ventilation systems through demand-controlled ventilation (DCV). This automatically adjusts the ventilation rate provided to a space in response to changes in occupancy. Typically, this is accomplished through the use of CO₂ sensor systems. Ideally, these are installed in occupiable spaces, although the sensor location may sometimes be selected within the return air. When the CO₂ levels rise, this indicates greater occupancy and thus a greater need for outdoor air per ASHRAE Standard 62.1. There is also a range of other types of sensor systems in development that, instead of measuring CO₂, use data fusion techniques to count the number of people in a space.

The controls utilized to adjust ventilation based on occupancy can be accomplished in several ways. One method is to measure the supply airflow rate and CO₂ concentrations and adjust the outdoor air intake on a continuous basis based on these input values. Another potential method is measuring the outdoor air intake flow. Control systems based on CO₂ levels, as well as those that measure outdoor air intake flow, all have their potential errors and design difficulties. In addition, like any measurement device, maintenance, including calibration, must be done as recommended by the manufacturer to ensure the accuracy of that information. Based on this information, the BAS can determine if the outdoor airflow rate is sufficient and can adjust the mixed-air dampers accordingly. The preferred method of controlling the outdoor air intake flow rate is to control the static pressure in the mixing plenum. This will indirectly control the needed variations in outdoor airflow. If This control routine can be further improved if airflows are also measured at each VAV box. As described in ASHRAE Standard 62.1, zone air distribution effectiveness can change when the temperature of the supply air changes. Therefore, it may be necessary for the control system to reset the minimum outdoor airflow after a seasonal switchover of supply air temperature.

Mixed-mode ventilation refers to the combination of mechanical ventilation and operable windows that provide natural ventilation. During some times of the year, if the windows are sized, located, and operated (by automatic control) properly, it is not necessary to provide mechanical ventilation when the windows are open. Perhaps the most straightforward way to control mixed-mode ventilation systems is to use the output of a window switch to shut down the terminal unit (e.g., the VAV box) when the window is open. This is most applicable for single-occupant zones or areas with a relatively small number of occupants. When the occupants decide that it is preferable to shut the window, the mechanical HVAC system is brought back online. It may be necessary to install an alarm or override based on space temperature, wind annoyance, wet weather, or to provide freeze protection.

Lighting Levels

The BAS can maintain desired light levels by either adjusting electric light output or controlling the amount of daylight entering the building. One or more photo-

cells may be used to measure the light level in the occupied space and the output used to brighten or dim electric lights. Photocell output may be used to switch between multiple light levels, raise or lower window shading devices, or adjust louvers to keep daylighting at comfortable levels and minimize glare. Equations that calculate the sun position angle for various wall or roof orientations can be input into the BAS and used to vary the tilt angle of window blinds, to minimize glare and maximize daylighting. Some technologies also allow for the use of occupancy sensors to control lighting levels, in addition to the monitoring of illuminance and glare. Chapter 11, “Lighting Systems,” provides insight into designing and operating lighting and lighting controls for efficiency and visual comfort.

SMART BUILDING CONTROL SYSTEM COMMISSIONING

Improper control systems operation can lead to 15% to 30% excess energy consumption in commercial buildings (Katipamula and Brambley 2005a, 2005b). As defined in Chapter 4, the commissioning process serves as a first and ongoing means of ensuring that building systems operate as intended. Coupled with AFDD, an ongoing commissioning program provides early fault detection, diagnosis, and correction. The commissioning process is defined in ASHRAE Standard 202-2018 as follows:

A quality focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements.

The full process from project planning through occupancy and operations is explained in ASHRAE Standard 202-2018 and in Chapter 43 of the *ASHRAE Handbook—HVAC Applications* (ASHRAE 2019b). Additional information relative to design reviews and commissioning for designers and commissioning providers can be found on the Energy Design Resources website (www.energydesignresources.com/publication/gd/).

This section covers salient elements of applying the commissioning process to controls in new construction and will focus on what the commissioning provider can do during the design phase to facilitate a successful commissioning program. For commissioning of existing buildings, the reader is referred to sources of information, such as U.S. Green Building Council's (USGBC) LEED program for Existing Buildings (see References and Resources section at the end of the chapter for website).

Conduct and Participate in Design Reviews

During the design reviews, the commissioning provider should see that the control-related elements are included in the contract documents. The section called “Detailing the Design of a Control System” provides a list of items that should appear in the contract documents that should be reviewed by the commissioning provider.

Specify a Systems Manual

Ensure that the commissioning scope for the commissioning provider, contractor, and designer includes a systems manual that, among other things, includes the following:

- Narratives explaining all energy-efficiency features and strategies
- Set point and parameter table that indicates the impacts of changing the values
- Recalibration and retesting frequency table
- Suggested smart alerts in the control system to send alerts on malfunctioning sensors and actuators
- List of standard trend logs to view to verify proper performance

The building operators also need to be trained on the systems manual and its contents in order to properly operate and maintain the system.

BUILDING-ELECTRIC GRID INTERACTION

The electrical grid has become increasingly “smart” in recent years. This modernization of the electric grid includes the addition of sensor systems and monitoring equipment to monitor grid operations in real-time, including supply, consumption, and transmission. In addition, the buildout of monitoring, communication, and control infrastructure by utilities and operators increasingly supports two-way communication between utilities and their customers.

Electric utilities and other interested stakeholders continue to develop, pilot test, and implement the tools and procedures for smart grid applications. However, there is a growing need and push for developing hardware and software that will allow smart buildings to interact smoothly with the smart grid. Research has demonstrated that information gathering, modeling, and more intelligent controls can help reduce energy consumption within individual buildings. Beyond this, the interactions between buildings and the smart grid require a new and more complex integration of information gathering, decision, and control. To support reliable and sustainable electric grid operations, there is strong potential for the use of integrated demand-side management (DSM), the goal of which is to modify consumer demand for electricity through various methods. This includes the integration of energy efficiency, demand response, energy storage, and distributed generation, among others. Technology innovations, standards, and policies are helping to push

toward the automated control of different electricity end-use loads for interacting with a smart grid.

The different types of demand response (DR) programs that are currently available can be broadly classified into price-based and incentive-based programs. In price-based programs, such as time of use, critical peak pricing, or real time pricing, customers voluntarily change their electricity consumption based on varying price of electricity. Incentive-based programs provides monetary incentives to customers for their participation, enabling the utility adjust loads when most needed, such as through the use of direct load control (DLC) switches on HVAC systems or the use of a smart thermostat to automatically adjust set points during DR events. In terms of automation, manual DR uses manual turning off of different equipment or changing set point of thermostat, while automated DR does so automatically using a BAS, advanced metering infrastructure (AMI), or other means. Automation helps improve the DR performance by allowing more repeatable and reliable response compared to DR.

The Open Automated Demand Response (OpenADR) Standard has helped to pave the way for building energy management and automation systems to communicate with electric utility providers and implement demand response measures. The development of the OpenADR Standard during the past decade was the result of national research labs and companies, with Lawrence Berkeley National Laboratory (LBNL) providing a significant, early role. The OpenADR Alliance was formed to support the development and deployment of commercial demand response through adoption of the OpenADR Standard. Commercialized products are now beginning to enter the market that support DR programs to be implemented in commercial buildings. This area will continue to grow in importance in society and with green buildings in particular. More information on OpenADR can be found in the OpenADR primer (OpenADR Alliance).

In terms of load types used to support grid-interactive efficient buildings, the opportunities in the commercial and industrial (C&I) sector, including HVAC systems (air handlers, chillers, chilled-water systems, and CHP) and lighting systems. Overall, in the commercial sector, research suggests that HVAC load provide the greatest opportunity for DR when used with water or ice thermal storage, which stores thermal energy during off-peak hours and then releases that energy during peak hours to provide conditioning to the buildings, although many other options for DR exist. To motivate the increased participation in DSM programs, various incentive programs exist, providing rebates for efficient and/or DR-enabled lighting, HVAC, air compressors and variable-speed drive motors. Small to midsize business' (SMB) participation in energy-efficiency programs is lower than large C&I customers, in part from the lack of dedicated workforce focused on energy issues. However, the participation of the SMBs is increasing from the efforts of the utilities company.

The way smart buildings interact with the smart grid will see even more rapid changes in the coming years as technology advancements and distributed energy resources will modify traditional demand response value streams. The result will be the need for a multitude of demand response strategies to take form, including what can be defined as shape, shift, shed, and shimmy. These strategies are beginning to take form by the integration of demand response into wholesale markets where it can be dispatched consistent with locational marginal prices, the use of demand response aggregators by utility programs to deliver tailored options that work for customers with unique needs, utility tariff restructuring, and offering incentives based on relative locational value (LBNL 2015).

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OpenADR Primer

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U.S. Green Building Council

www.usgbc.org.

CHAPTER FOURTEEN

RESIDENTIAL APPLICATIONS

A residence is a person's home. For many people, the image of home is a house where the person lives or where they lived as a child. Many people live in homes where the building is shared by other people or families such that more than one residence is part of the structure. This is known as a multifamily residence. Multifamily residences have a variety of building styles, including low-rise and high-rise levels. The size and height of the building make these more applicable to commercial building architectural and construction practices and codes. But there is a fundamental difference between a residence and a commercial space. A residence is where a person lives; that is, eats, sleeps, bathes, relaxes, and raises a family. It is a focus on the living, and the quality of living, that sets apart a residential space from a commercial space and, therefore, a residential building from a commercial building.

For the most part, the individual living spaces of multifamily residences act like and are treated like the living space of a single-family residence. There is much in common with the faculty and utility of all different types of living space with respect to shelter, comfort, health, privacy, and security. The common aspects of residences are discussed in this chapter.

While the living spaces of different types of residences are roughly similar, the buildings can be vastly different with respect to climate, structure, construction, and climate control.

Residential buildings should provide for the utility needs of the residents. At the same time, it is the desire of society to have buildings that minimize the number of natural resources needed to operate. Homes are constructed using combinations of natural and engineered materials to provide structure, insulation, barriers, and protection from the elements. Other materials provide utility for the home in the form of lighting, plumbing, appliances for cooking and storing food, appliances for heating and cooling, and appliances for work and leisure activities. In a nutshell, for residences to provide their utility and function, they are consumers of resources. Energy and water are the most notable resources consumed by residential buildings after construction is complete. The residential structure

also expels waste as either soiled liquid, solid waste, or exhaust fumes from combustion processes. Many other forms of emissions, such as offgassing, must be dealt with in residential buildings for the consideration of occupant health. Processes to resolve these unwelcome exhaust products require the use of additional energy or water resources.

ENERGY USE: RESIDENTIAL BUILDING SECTOR

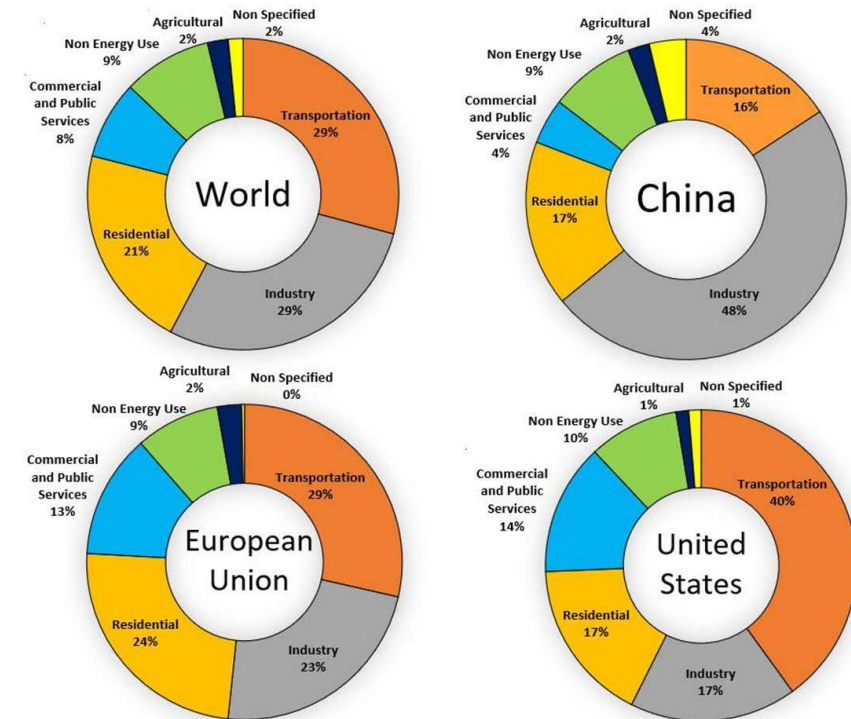
The residential sector is responsible for 20% of all final energy consumption in the United States and accounted for almost 54% of the final energy used by all buildings in 2019 (EIA 2019). Similarly, residential buildings dominate the European building stock, representing about 26% of the final energy consumption in the European Union and 65% of the energy used by the buildings sector (Eurostat 2020). Similar data are observed in other parts of the world (Figure 14-1). From economic, environmental, and energy security perspectives, a sector that consumes one-fifth of all the energy used in most countries and more than half of all energy used by buildings around the world demands significant attention.

According to US Census data, there are more than 135 million dwellings in the United States; similar European data indicate 216 million dwelling units in Europe. The projection is that by 2030 this number will grow to about 141 million in the United States and 241 million in the European Union. Given that number is increasing, efficiency must increase as well. More than 74% of all existing homes in the United States were constructed before 1989 and the widespread adoption of model energy codes governing their construction. Similarly, about 68% of European residential buildings were constructed before the 1980s, when energy building regulations were very limited. By almost any measure, most of these homes are likely underinsulated, have poorly performing fenestration, have significant envelope air leakage, need upgrades to all HVAC&R components and delivery systems, and contain outdated and inefficient lighting systems when compared to today's basic energy code minimums. In addition, these homes should be treated as systems that provide good indoor environmental quality for people. These needs define the significant opportunity for energy, carbon, and peak power savings within the residential sector.

STANDARDS

ANSI/ASHRAE Standard 55—Thermal Environmental Conditions for Human Occupancy

ASHRAE/IES Standard 55-2022 specifies conditions for acceptable thermal environments and is intended for the design, operation, and commissioning of buildings and other occupied spaces. The 2022 edition of Standard 55 includes three compliance methods: a graphic method for simple situations, an analytical method for more general cases, and a method that uses elevated air speed to provide



Source: <https://www.iea.org/data-and-statistics/?country=USA&fuel=Energy%20consumption&indicator=TFCShareBySector>

Figure 14-1 Final energy use breakdown in the world, the European Union, China, and the United States. Mtoe: Million tonnes of oil equivalent (1 Mtoe = 39.683 MBtu = 41.868 GJ = 11,630 kWh).

comfort. The Standard has a separate method for determining acceptable thermal conditions in occupant-controlled naturally conditioned spaces.

ANSI/ASHRAE Standard 90.2—Energy Efficient Building Design of Low-Rise Residential Buildings

ANSI/ASHRAE/IES Standard 90.2-2018 establishes minimum whole-building energy performance requirements (design, construction, and verification) for low-rise, energy-efficient residential buildings. The standard applies to the building envelope, heating equipment and systems, air-conditioning equipment and systems, domestic water heating equipment and systems, and provisions for overall building design alternatives and trade-offs. The 2018 revision of Standard 90.2 seeks to deliver residential building energy performance that is at least 50% more efficient

than a building built to standards as defined by the 2006 *International Energy Conservation Code* (IECC). Changes from the 2007 edition of Standard 90.2 include:

- Clarification of which elements of the standard apply to new construction and which apply to additions and alterations
- Guidance on the use of international climate data from ASHRAE Standard 169 for users outside of the US
- Revision of prescriptive envelope performance data tables
- New performance specifications for ground-source heat pumps
- Updates to minimum lighting efficiency provisions for single-family, large single-family, and multifamily homes
- Clarification on pool heater pilot lights, pump motor efficiency, and roof and gutter de-icing systems
- Clarification on compliance verification authority in locations outside of the US
- Revisions to emphasize key building data and reports necessary for compliance determination
- Revision for modeling software requirements
- Updates for lighting modeling requirements
- Clarifications to address multizonal building air-leakage testing procedures
- A new normative appendix that addresses proper installation techniques for critical components of buildings that provide thermal resistance

ANSI/ASHRAE Standard 62.2—Ventilation and IAQ

ANSI/ASHRAE Standard 62.2-2022 (ASHRAE 2022a) defines the minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality in residential buildings. There are three primary sets of requirements that involve dwelling-unit ventilation to dilute contaminants, local exhaust ventilation to reduce contaminants at their source, and source control or contaminants. There are also a number of secondary requirements that focus on the properties of specific items needed to achieve the main objectives of the Standard.

Standard 62.2 applies to spaces intended for human occupancy within single-family houses and multifamily buildings, including manufactured and modular houses. This Standard does not apply to transient housing such as hotels, motels, nursing homes, dormitories, or jails. The Standard considers chemical, physical, and biological contaminants that can affect air quality. It does not address thermal comfort requirements, specific pollutant concentration levels, or certain potential contaminant sources, such as unvented combustion space heaters and contamination from outdoor sources or episodic occupant-controlled events such as painting, smoking, cleaning, or other high-polluting events.

ANSI/ASHRAE Standard 152—Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems

ASHRAE Standard 152-2014 quantifies the delivery efficiency of duct systems, based on factors including location, leakage, and insulation of ductwork. It applies to single-family detached and attached residences with independent thermal systems. The standard provides estimates of the efficiency of thermal distribution systems that may be used in energy consumption or system capacity estimates. Computer simulation tools can be tested according to ASHRAE Standard 140, which also includes certification of residential energy performance analysis tools (ASHRAE 2022b).

The standard also provides thermal distribution system efficiencies for both heating and cooling systems. Thermal distribution system efficiency is calculated for seasonal conditions (for energy consumption) or design conditions (for system sizing). This results in a total of four outputs from the method of test. This standard does not address the effectiveness of the tested system to provide comfort in the conditioned space or to deliver the designed or required airflow to individual rooms within the conditioned space.

A spreadsheet tool developed by Lawrence Berkeley National Laboratory (LBNL) and modified by the National Renewable Energy Laboratory (NREL), assists with the calculation of seasonal distribution system efficiency. A web link reference is given in the references list of this chapter. This calculation is required by the House Simulation Protocols (Wilson et al. 2014) when the simulation tool being used does not allow detailed duct modeling.

ISO 17772-1 and ISO/TR 17772-2

ISO 17772-1:2017, similar to EN16798-1, deals with indoor environmental factors like thermal comfort, indoor air quality (IAQ), and acoustics. It gives recommended values for design and energy calculations of buildings and HVAC systems. It covers both residential and commercial buildings. In Europe, it is a mandated standard used to calculate a building's energy performance for energy certification. The recommended criteria for each parameter are divided into three to four categories to account for differences in expectations and national regulations.

ISO 17772-2:2017, similar to EN 16798-2, is a guideline on how to use ISO 17772-1. It includes several examples of use especially for residential buildings.

International Energy Conservation Code

The *International Energy Conservation Code* (IECC) is a model code regulation addressing the design of energy-efficient building envelopes and installation of energy-efficient mechanical, lighting, and power systems through requirements emphasizing performance (IECC 2021). The code contains separate provisions for

low-rise residential buildings and commercial buildings. The IECC—Residential Provisions establish minimum regulations for energy-efficiency using prescriptive and performance-related provisions, founded on broad-based principles that make possible the use of new materials and new energy-efficient designs. The 2021 edition includes an option for residential buildings using the energy rating index (ERI) path, in addition to the prescriptive and performance paths of previous versions. The target ERI score can be met through a wide range of performance options to demonstrate compliance. The ERI performance path needs to also meet the other mandatory code requirements of the IECC, follow hot-water piping provisions, and comply with the minimum insulation and window envelope performance requirements.

ANSI/ICC 700—Residential Green Building Standard

This voluntary standard was first published in 2009 and serves as an important resource for designers, contractors, developers, and policy makers, and as the industry benchmark for new construction, additions, and alterations of residential projects. The most recent edition of the National Green Building Standard (*ICC 700-2020* NGBS) was developed by the International Code Council (ICC) and the National Association of Home Builders (NAHB) of the United States. The ICC 700-2020 covers sustainable sites, energy efficiency, water efficiency, materials and resource use, indoor environmental quality, operations and maintenance, and building owner education. The NGBS is the only residential green building rating system approved by the American National Standards Institute (ANSI).

The standard contains few minimum criteria but allows the builder or developer great flexibility in selecting green building practices. Projects receive points in each subject area for reaching certain performance or construction goals. There are four green certification levels for homes—bronze, silver, gold, and emerald. Land developments can earn one, two, three, or four stars. Projects require inspection by third-party verifiers at the rough-in stage and upon completion. NAHB provides accreditation for the verifiers as well as the final certification. The NGBS serves as the basis for several US federal, state, and local green building programs, and more than 93,000 US homes have been certified as of 2016.

European Legislation

The EU Directive 2018/844 of the European Parliament and of the Council of May 30, 2018, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency now includes direct requirements for building control systems. All relevant European Union legislation can be accessed at the EUR-Lex link in the References and Resources section at the end of this chapter.

Under the EPBD, the main provisions mandate that: (a) energy performance certificates (EPC) be included in all advertisements for the sale or rent; (b) all new

buildings must be nearly zero energy buildings (nZEB) by December 31, 2020 (public buildings by December 31, 2018); and (c) minimum energy performance requirements must be set at the national level for all new buildings, major building renovations, and for replacing or retrofitting building elements (e.g., heating and cooling systems, roofs, and walls). The Directive defines a nearly zero energy building (nZEB) as a building with very high energy performance. It states that the nearly zero or very low amount of energy required should be covered significantly by energy from renewable sources, including energy from renewable sources produced on-site or nearby. The nZEB requirements are defined at the national level (BPIE 2015). For new residential buildings, most jurisdictions aim to have an annual source of energy use of less than 50 kWh/m^2 (15.8 kBtu/ft^2). In Denmark, it is less than 25 kWh/m^2 (7.9 kBtu/ft^2). The energy must be expressed as primary energy taking into account the type of energy source (wind, solar, fossil fuel, waste, and so on) and the production and distribution from power plants (district heating/cooling). The primary energy factors are regulated at the national level and sometimes used as “political” factors to promote or discourage certain energy sources.

Under EED, there are specific energy savings requirements on existing European buildings, requiring EU member states to establish national plans for renovating their existing building stock. Most of the national building renovation strategies focus on residential buildings. The specific national strategies are part of the National Energy Efficiency Action Plans (NEEAP). They provide an overview of the country’s national building stock, identify key policies that the country intends to use to stimulate renovations, and provide an estimate of the expected energy savings that will result from renovations.

Under the ELR and EED, energy-efficiency regulations focus on specific commercial products that are also used in the residential sector (Bertoldi et al. 2016). Energy labels encourage consumers to purchase more energy-efficient products, leading to lower household energy bills. They refer to energy-using products (EuP), which are products that use, generate, transfer or measure energy. Examples include boilers, air-conditioners, water heaters, water storage, stoves, freezers, pumps, motors, refrigerators and cooking appliances, consumer electronics, and lighting (more information can be found under DG Energy and DG Growth in the References section). These labels also refer to other energy-related products (ErP) that do not use energy (e.g., windows, thermal insulation, showerheads) but have an impact on the energy performance of buildings. All products should meet minimum requirements for energy efficiency or be banned from use. The legislation also covers “packages” of space heating and water heating products (e.g., an air-to-water heat pump, temperature controller, and solar thermal system) or heating boilers coupled with renewables. Noncondensing boilers have been phased out of the market as of the end of 2015.

The impact of ecodesign, energy labeling, ENERGY STAR, and potentially new forthcoming actions is estimated at $4.3 \times 10^9 \text{ GJ}$ ($4.1 \times 10^{15} \text{ Btu}$) savings in 2020,

of which ~52% come from the residential sector (Kemma et al. 2016). Several countries around the world such as the United States, Australia, Brazil, China, and Japan are implementing similar actions, contributing to a converging worldwide regulatory environment.

PERFORMANCE

Building Science

Building science is the application of physics and scientific methods to the design, maintenance, and operations of buildings. As part of the effort to make residential buildings more energy efficient, reducing air leakage in newly built and existing homes fostered concerns for occupant safety and health. As a response to these concerns, during the last three decades, building science methods have become common in analyzing and treating residential structures. Newly developed protocols for combustion safety testing, moisture analysis, and IAQ testing have been published, and instruments for field testing have become common, including digital manometers, blower doors, infrared cameras, and other specialized equipment. These protocols and the common use of testing equipment have also allowed the introduction and widespread practice of performance ratings in both the new and existing sectors of the residential market.

These new methods allow designers and field analysts to verify that a residential building and its HVAC systems perform as intended. In this regard, residential structures are now usually “commissioned” based on the verified performance of each component and the dynamics of the dwelling as a system.

Testing and Quality Assurance

As national residential building codes have evolved over the past decade, testing certain aspects of home construction has become increasingly important. The *International Energy Conservation Code* (IECC) for residences has specified since 2009 that envelope leakage is maintained below specific levels. In 2012, the IECC implemented requirements that residential air distribution systems (ducts and air handlers) meet or exceed specific thresholds of air leakage (see GreenTip #14-1 at the end of this chapter). Additionally, ASHRAE Standard 62.2 effectively requires the testing of envelope leakage to determine the mechanical ventilation requirements for acceptable indoor air quality in homes. These codes and standards specifications for the residential envelope and duct leakage have led to increasing testing in residential construction. Although research-level ASTM standards for performing these types of tests exist, there has been a national effort to provide less time-consuming and less expensive methods of satisfying these recent codes and standards requirements. In 2019, ANSI/RESNET/ICC Standard 380-2019 was promulgated to focus on testing residential envelope leakage, air distribution system leakage, and ventilation fan flow to meet the market demand for more cost-effective test methods.

Significant national efforts to improve installation quality in residential construction have been made. For example, the Air Conditioning Contractors of America (ACCA), an industry association, has developed the HVAC Quality Installation Specification (ANSI/ACCA 5 QI-2015) to specify the installation and verification protocols for residential HVAC systems. The Residential Energy Services Network (RESNET), to ensure that manufacturer's installation requirements are followed, requires its certified practitioners to grade the installation quality of the insulation. These efforts are bolstered by federal programs such as the Environmental Protection Agency's ENERGY STAR New Homes program and the Department of Energy's Zero Energy Ready Homes program, which requires high-quality field installations.

Performance Ratings

Performance ratings for homes are becoming increasingly important in the residential construction marketplace. In the United States, the most widely used voluntary residential performance rating is the Home Energy Rating System (HERS) Index determined in accordance with the provisions of ANSI/RESNET/ICC Standard 301-2019, *Standard for the Calculation and Labeling of the Energy Performance of Low-Rise Residential Buildings using an Energy Rating Index*. The purpose of the HERS Index is to provide homeowners and stakeholders in the home construction, finance, and real estate markets a measure of the energy performance of homes. As of September 2020, approximately 2.9 million US homes have been inspected and received a HERS rating. During 2019, more than 241,000 homes received the HERS rating (Baden 2017).

The HERS Index was incorporated into the 2015 *International Energy Conservation Code* (IECC) as an alternative code compliance mechanism called the Energy Rating Index (ERI). One major distinction between the HERS Index (or the ERI) and prescriptive IECC code compliance is that the HERS Index considers all the energy uses in the home rather than just the code-regulated uses of heating, cooling, hot water, and lighting energy.

A certified HERS Rater performs a home inspection and a series of diagnostic tests (e.g., blower door test, duct leakage test, combustion analysis) to determine, for example, the effectiveness of envelope thermal insulation, the amount and location of air leaks in the building envelope and HVAC distribution ducts, and existing or potential combustion safety issues. An accredited rating software is then used to calculate a rating score on the HERS Index.

The US Department of Energy has also created a performance rating called the Home Energy Score (HES). Rather than a performance rating based on a reference home, HES is based solely on the absolute source energy use of the rated home. The HES rating scale is from 1 to 10, with 10 being the best rating obtainable and 1 being the worst. The home is rated on this scale based on its projected source energy use as compared with the absolute range of home energy use for all homes

within the geographic location of the home. The HES was created primarily for use in existing homes as a simplified mechanism to encourage home energy retrofits. As of October 2020, more than 145,000 HES evaluations have been completed (U.S. Department of Energy, Better Buildings).

Thirty-five US jurisdictions have laws or executive actions mandating energy performance rating. Most of them cover various types of buildings, including commercial, multifamily, and single-family homes. Several other efforts are in place throughout the world. Information on worldwide practices for building energy performance ratings and disclosures and examples of labels and certificates are available from the Institute for Market Transformation website (reference at the end of this chapter).

The European Union introduced mandatory energy labeling requirements for its member states in 2006 under the provisions of the European Directive (EPBD 91/2002/EC) on the energy performance of buildings. All new and existing buildings that undergo major refurbishment should meet minimum energy performance requirements and an energy performance certificate (EPC) is issued for all buildings or building units (e.g., apartment) that are rented out or sold, and they are valid for 10 years. Most of the European member states enforced the process after 2007 primarily issuing EPCs for new residential buildings. Certification of existing buildings and commercial buildings often followed at a later stage. Frontrunners such as Denmark, Germany, the Netherlands, and the United Kingdom have had similar schemes for new residential buildings since the 1980s (e.g., the Standard Assessment Procedure [SAP] in the UK).

Almost all EU member states have implemented an asset rating for new and small existing buildings, and some use operational rating for large complex commercial and public buildings. There are national differences in the qualifications, training, and/or accreditation of experts that perform an energy audit, the calculation tools used for the analysis, and the level of detail of the EPC's content. The EPC always includes a rating with an energy label commonly using a letter scale (e.g., A or A+ for high energy performance to G for low energy performance) and specific recommendations for improving the energy performance existing buildings (Arcipowska et al. 2014). Under the EPBD recast (31/2010/EC) there is more emphasis on the EPC rating disclosure to prospective tenants or buyers at time of lease or sale and the mandate to list the rating during property advertisement in public media. The new challenge is the mandate towards nearly zero energy buildings for all new buildings as of January 2021.

Relevant EU directives like EPBD and EED include direct requirements for building automation. It is explicitly stated that it is important to ensure that measures to improve the energy performance of buildings do not focus only on the building envelope. Terms such as self-regulating devices, smart charging of electric vehicles, digitalization of the energy system, electronic monitoring, and connected buildings appear several times. There is also a demand to make buildings “smart-

ready” and to make their smart readiness measurable and verifiable. This is to be based on the “smart readiness indicator,” a common EU scheme for rating the smart readiness of buildings (https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/smart-readiness-indicator_en).

Several voluntary schemes are also available in Europe. A notable effort is the voluntary Active House label for new and renovated homes supported by the Active House Alliance (Active House 2019). It aims to create healthier, more comfortable lives for occupants while also delivering environmental and climate benefits. Active House offers a holistic approach to building design and performance on the basis of three main principles: energy (e.g., demand, supply, primary energy performance) comfort (e.g., indoor thermal environment, air quality, daylight), and environment (e.g., environmental load, water consumption, sustainable construction), and their subparameters.

Another popular voluntary energy efficiency standard is Passive House (Passivhaus) for new buildings and for home renovations through the EnerPHit Retrofit Plan. It is especially popular in German-speaking European countries and Scandinavia, standardizing the design and construction of low energy buildings, including homes. Emphasis is placed on super insulation mostly suitable for cold climates (e.g., typical U-factors in the range of 0.10 to 0.15 W/m²·K [0.018 to 0.026 Btu/h·ft²·°F]), elimination of thermal bridges, low-e glazings (U-factor less than 0.80 W/m²·K [0.141 Btu/h·ft²·°F]), along with efficient mechanical ventilation (e.g., at least 75% heat recovery).

Similar concepts and labels are also introduced in France (i.e., Bâtiment Basse Consommation—BBC Effinergie label, or low energy building) and Switzerland (e.g., Minergie), which are most popular for residential buildings.

In the UK, the Code for Sustainable Homes (CSH) is an environmental assessment method for rating and certifying the performance of new homes. It was developed along the lines of the well-recognized and used environmental assessment and rating system of Building Research Establishment Environmental Assessment Method (BREEAM®) introduced in the 1990s. CSH addresses wide-ranging environmental and sustainability issues and enables developers, designers and building managers to demonstrate the environmental credentials of their buildings to clients, planners and other parties. The assessment involves the evaluation of the performance of a building in terms of specification, design, construction, and use. The rating is derived from a standard set of performance measures ranging from management processes to ecology that are set against various benchmarks.

Recently, a new rating system (Estidama Pearl Rating System) was introduced in the Emirate of Abu Dhabi that follows a point-based system along the lines of LEED and BREEAM but tailored to the Middle East region. The Pearl Villa Rating System (PVRS) aims to promote the construction of sustainable villas (e.g., large houses containing one dwelling for use by a single household or multifamily buildings with less than three stories) and improve the quality of life. The PVRS encour-

ages water, energy, waste minimization, and local material use and aims to improve supply chains for sustainable and recycled materials and products. The PVRS respects the traditional fareej residential design and supports historical priorities of solar shading, outdoor thermal comfort, and internal privacy.

ARCHITECTURE AND DESIGN

Economy plays a big part in the design of homes. The residence needs to have appeal to be desirable for living, in the same way that it needs to provide comfort for living. Comfort requires balance between indoor thermal conditions—mostly temperature and air quality—to maintain not just adequate healthful living, but thriving, and unnoticeable freshness of the air that does not require extra effort on the part of the occupant to ensure healthy living. This creates a natural economy for the building from the time of construction, during its time of use and necessary upkeep, and in maintaining the inherent value of the property for eventual resale throughout the life of the dwelling. The goal of the architect is to tie all of this together to design appeal into the function in a way that best uses materials and resources to serve the living function of the dwelling, as well as manage its waste output to minimize the impact on the environment.

Several factors influence the appeal of a residential structure, such as location (urban, suburban, or rural), and many others that focus on the look of the structure. Similarly, the geographic location has a major influence on the design with respect to the function of the home: the operation of and maintaining the indoor environment. The living space, by definition, is not empty because of inside living activities and therefore requires mechanical systems to manage the indoor temperature, humidity, and freshness. Typically, outdoor air has better quality than indoor air because indoor pollutants are constantly being added to the environment. Both passive and mechanical systems are crucial elements of home comfort, and it is in these systems that the challenge of minimizing the use of natural resources becomes the art of green building.

New Energy-Consuming Systems

The recent trend in transportation toward electric vehicles is driving an increase in electricity usage. This trend connects the electric vehicle to the residential building for refueling (battery charging).

Materials Use

Generally speaking, residential building construction in North America is different from commercial buildings by the use of timber (wood) products, using both milled dimensional lumber and engineering composite materials, versus the primarily steel-based construction practices used in commercial buildings. Concrete in residential construction is mostly limited to foundations and slab flooring, and as mortar for brick sheathing. As such the principles of construction for stability in the

structure and for tight enclosures apply to residential buildings as well as they do to commercial buildings.

Building construction practices differ in other parts of the world. For example, central and southern European houses are dominated by concrete and masonry construction. The use of materials like stones, bricks, and concrete increase the building's thermal mass (usually contained in walls, floors, roofs) that absorbs, stores, and then releases significant amounts of heat at a later time. More information is available on this topic in Chapter 6. Thermal mass could have a positive effect on the indoor conditions during summer and winter. It regulates the magnitude of indoor temperature swings, reduces peak cooling loads in summer and acts as a thermal barrier in winter. Traditional architecture, especially in southern European countries, has successfully demonstrated these positive effects for passive, naturally ventilated houses. This type of construction practices combined with reduced infiltration high performance windows result in airtight envelope assemblies.

Thermal Performance

The thermal performance of a building can be defined by the amount of energy it needs for heating and cooling to maintain the desired comfort level of the occupants. There are many factors to consider in the thermal performance, including occupancy in the number of people and their activity level, which relates to the internal heat gain in the space. Other factors are the air barrier or envelope; insulation of the envelope including walls, floor, and ceiling; windows in terms of wall surface area; and placement with respect to the sun. There are other factors but these mentioned are the most significant to the home energy performance.

Thermal Air Barrier. Good thermal design practices require a tight barrier against both conductive losses as well as convective losses. In smaller structures such as single family dwellings, the volume of the home is small enough that the dominant thermal control is to reduce the convective or air exchange losses (losses in this sense could include either heat lost or gained to/from the environment). This is accomplished by use of an air barrier. The barrier, typically plastic sheeting or built into the construction board, must enclose the entire structure in a continuously connected or joined fashion. It is necessary that the barrier is designed into the building architecture before construction begins, including the foundation. Improper installation is a common cause of poor air barrier performance.

Measurement of the tightness of the thermal envelope is done by means of a pressure and flow evaluation, such as the blower door test. This test measures the volume of air that passes through a fan used to pressurize (or depressurize) the space (home) to a given pressure differential, typically 50 Pa (0.2 in. w.c.). In the United States, the measured value would be expressed in cubic feet per minute (cfm) or CFM50, and is converted to an air change rate per hour (ACH50) by dividing the measured value by the volume of the space or house and converting minutes

to hours. The ACH50 value is normalized to the building volume, and can be used for comparing buildings of different sizes for compliance to green home standards.

Thermal Insulation. The air change rate defines the convective thermal performance and is a dynamic variable, whereas the conductive thermal performance is a static variant addressed by insulation. There are two major considerations for insulation: the resistance values (R-value) of the insulating layer(s) in walls, floors, and ceilings and reducing losses through bridging. The overall thermal transmittance of the wall assembly, called the U-factor, combines the R-values of the individual components of the wall assembly. Thermal bridging is essentially a thermal bypass to the surrounding insulation layers of the structure. Generally, thermal bridging occurs around structural members of the building. The bridging effect is reduced by using layers of materials. In this regard, using thicker dimensional lumber (for example using 2×6 in. instead of 2×4 in. studs) for framing increases the available insulation level. It is possible to widen the spacing between the studs to reduce the material usage and thermal bridging effect.

Thermal Performance of Windows. Windows provide a different challenge for managing conductive heat gain or loss to the space. Windows are necessary for daylighting, natural ventilation, and the desirable living function of the home. Windows must be designed into the structure to use the natural daylight and winter solar heat gain during daylight hours. Well-designed shading of the windows is necessary to limit the amount of solar gain during summer months. Aside from daylighting and natural ventilation during temperate seasons, windows designed on the north side of the house in the northern hemisphere are mostly used for exterior view, daylighting, and design appeal.

Similar to wall structures, window thermal transmittance (U-factor) of fenestration takes into account heat transfer from conduction and thermal bridging, convection, and longwave infrared radiation in the window design. The solar heat gain coefficient (SHGC) for a window is a ratio of how much incident solar radiant heat is admitted through the glass to the building interior. Ranging from 0 to 1, a lower number equates to lower heat gain by the window. In regions where the cooling load is dominant, it is naturally desirable to minimize solar heat gain. In regions where heating is the dominant load, it becomes desirable to use windows as a way of offsetting the heat demand during the cold seasons. That brings us back to the shading discussion because, even in higher heating load areas, there is need to reduce summer heat gains through use of shading design techniques. In addition, a prudent use of a robust load calculation tool will help to identify the optimal window performance factors (U-factor and SHGC) and avoid costly retrofits or lower effective energy performance.

A third criteria for window performance is air leakage, and this corresponds to the discussion on infiltration in the thermal air barrier section above.

Ground Source Thermal Performance. Basement, cellar, or slab constructions are made of high-mass masonry products for strength and stability against the

forces of the solid soil and hydraulic pressures from the earth. For best performance, insulation and the air barrier must be continuous around the masonry construction as well. The air barrier serves also as a barrier against unwanted soil gas migration as well as prevention of moisture migration through the masonry. Design of the architecture demands careful details of how the barrier continues into the wall, as well as details of where and how continuation barriers are connected. Thermal conduction is minimized by using layers of thermal insulation board. Caution should be exercised to ensure moisture resistance and prevent mold-related deterioration by selecting materials that do not absorb moisture, and have good thermal insulation properties (high R-value).

To the homeowner, there is value in comfort and in reduced energy loads by sealing and insulating masonry walls, especially during the cold season. This building technique reduces cold temperature discomfort for the occupants by improving the interior surface temperatures, especially on walking surfaces. When the occupant feels more comfortable, there is less tendency to overcompensate by adjusting the thermostat to a higher setting. Using the barrier to reduce moisture migration through masonry surfaces reduces need for dehumidification. Using both a thermal barrier (insulation) and air barrier (plastic also serves as a water barrier) improves both comfort and moisture management will thus reduce the energy needs of the home. This is the ultimate goal of thermal performance and energy conservation.

The air barrier tightness introduces other needs related to air freshness for the occupants. Factors affecting the thermal performance of the residence must take into account the following issues:

- Infiltration.
- Moisture—introduced by occupant metabolism, cooking, and cleaning (bathing), as well as by infiltration through walls and concrete.
- Solar—gains or losses are mostly through glazing surfaces (windows).
- Internal heat gains—this includes living activities of basic metabolism, exercise, lighting, cleaning, cooking, and use of electronics and other appliances. Heat gains from lighting are decreasing with the advancement of lighting technology, such as LED lighting, but heat gains from electronic equipment have risen over the past couple of decades.

Indoor Environmental Quality

Indoor environmental quality (IEQ) implies that there is a level of satisfaction to be achieved with respect for the needs of the occupants. The IEQ components are developed and discussed in Chapter 8. Residential buildings have similar needs for IEQ as commercial buildings; however, activities in the home may differ in some ways because the occupant may have more control of their environment than in commercial buildings. The economy of a residence varies by the occupant's ability to afford different improvement factors associated with applying higher levels of



Source: Sherman (2004)

Figure 14-2 Top 10 ways to ensure good indoor air quality at home.

green concepts into the design and construction of the residence. In many jurisdictions, use of legislated building codes reinforces the use of lower-energy applications and higher levels of comfort based on a knowledgeable and health-focused framework of standards such as ASHRAE Standard 62.2 and ISO 17772-1 in applying indoor air quality.

Indoor Air Quality. Chapter 8 of this guide discusses indoor air quality (IAQ) and references other sources for thorough coverage of air quality issues. It applies to residential buildings similarly to other types of buildings. However, in residential buildings, the level of comfort may be more acutely felt because the residents have a longer period of occupancy than with other types of buildings. Pollutants may have a higher concentration indoors than outdoors. To address IAQ is to understand and control common pollutants that can harmfully affect the health of the occupants. Some practical guidance is illustrated in Figure 14-2. A good resource on

best practices for design, construction, and commissioning for professionals concerned with IAQ in buildings is available in the *ASHRAE Indoor Air Quality Guide* (ASHRAE 2009).

The three main steps to control IAQ are as follows:

1. **Eliminate sources of indoor pollutants.** These can include cleaners, animals (pets), amid building materials made with offgassing chemicals, which includes furniture, carpet, and other textiles. Indoor air chemistry is complex because compounds can undergo chemical reactions in the presence of other reactive species and generate more harmful indoor compounds than those involved in the reaction. It is not always possible to eliminate pollutants entirely; for example, managing the offgassing by using sealed storage containers for cleaners is a way of achieving the nearly ideal condition. Natural pollutants such as allergens, dampness and mold, and radon should also be considered.
2. **Ensure proper space ventilation.** Ventilation is designed to minimize lingering effects of pollutants that cannot be eliminated from the space in Step 1. For proper mechanical ventilation, it is necessary to manage moisture and thermal energy so there is no direct loss of energy from the space through the fresh air exchange. Energy recovery ventilators (ERVs) are appliances that facilitate exchange of polluted indoor air with fresh outdoor air. They are designed to transfer the enthalpy (heat and moisture) to the appropriate direction with high level of effectiveness. ERVs require an energy source to move air in two directions as well as any rotating enthalpy transfer media.

Proper natural ventilation strategies, depending on outdoor conditions, should ensure the minimum outdoor air requirements. This may be a challenge in some areas. Exposure may be associated with location, socioeconomic factors, quality of housing, and other factors. For example, high-density urban cities may have residential areas close to traffic emissions. Socially deprived population groups tend to be more exposed to outdoor air pollutants (e.g., living in areas with high traffic) and indoor air pollutants (e.g., fuel poverty and inappropriate use of heating and cooking devices). Caution should be exercised when focusing on air-tightness and lower ventilation rates that may increase chemical and biological pollutant concentrations.

Ventilation in bedrooms is especially important as occupants spend six to eight hours there every day. Bedrooms are often underventilated, negatively impacting sleep quality and the next day's performance.

3. **Filtration of the air.** Filtration requires energy to move air through a porous media that entraps the unwanted materials from the air. Particle filters or air cleaners need proper maintenance.

Illumination. Lighting is necessary for occupant satisfaction and perceived comfort. Where possible, daylighting should be used, provided the pros and cons as

mentioned in Chapter 11 can be managed to provide the utility function and minimize possible discomforts and thermal gains to the home. Electrical lighting that requires planning so that wires and fixtures are managed to prevent sources of air leakage and in preventing thermal bridges where possible. Where it is not possible to add lighting without penetrating the thermal barriers, sealing must be made to prevent infiltration and load gains. Efficient design of lighting is covered in Chapter 11.

Acoustics. Depending on the setting of the home, acoustics can be a significant source of dissatisfaction to IEQ. With a majority of residences being in urban settings, noise issues from traffic, and neighbors are to be accounted for. The thermal barrier discussed in the Thermal Performance section will reduce migration of noise as well as air. Windows are especially important when considering noise reduction. The number of panes of glass, and how well the windows are sealed will affect overall acoustic results. Other common factors for consideration include location of internal mechanical systems and appliances that have rotating or vibrating parts. Isolating these mechanical systems in isolated spaces will reduce noise penetration. Placement of external mechanical equipment such as compressor bearing condenser unit away from high-occupancy rooms, bedrooms, and close proximity to neighbors should be considered as well.

Designing and sizing ducts and registers to keep flow velocity less than 900 and 750 fpm (4.6 and 3.8 m/s), respectively, will have the best results.

Thermal Comfort. For the occupants, thermal comfort is probably the most important parameter. People are very different in their perception of thermal comfort and preferred room temperature. However, in their home, the possibilities for individual adaptation and control are, in most cases, much better than at a workplace or commercial building. In addition to the possibility of opening windows, individual room thermostats and ventilation control are recommended to provide thermal comfort.

Low-Flow Fixtures

Water conservation is a critical aspect of a green home, and many builders are incorporating low-flow fixtures to decrease water use in a home. The EPA's Water Sense Program guides selection of such fixtures. Plumbing design is trending toward a lower amount of water stored in pipes between water heaters and end uses (e.g., home-run manifold plumbing), meaning that less hot water is sent down the drain prior to users entering showers or using hot water in other ways. While the goal of lower water consumption is laudable, there have been discussions about the lower workable limits for such fixtures to maintain the expected service to occupants, the proper functioning of on-site waste systems, and the quality of the water.

Legionnaires' Disease

Legionnaires' disease is a severe, often lethal, form of pneumonia. It is caused by *Legionella pneumophila*, a waterborne pathogen found in natural and manmade water systems. In nature, *Legionella* lives in freshwater and rarely cause illness. In manmade settings, *Legionella* can grow if water is not properly maintained. These manmade water sources become a health problem when small droplets of water that contain the bacteria get into the air and people breathe them in. In general, people do not spread Legionnaires' disease to other people.

Outbreaks are commonly associated with buildings or structures with complex water systems, such as hotels and resorts, long-term care facilities, hospitals, and cruise ships, or when water systems are not properly drained prior to being left dormant for an extended time. The most likely sources of infection include water used for showering, hot tubs, decorative fountains, aerosol-generating humidifiers, and cooling towers. The risk of acquiring Legionnaires' disease from single-family water systems is quite low. Multifamily residential buildings usually have relatively simple, individual water systems that are much less likely to harbor *Legionella* bacteria.

The greatest risk is posed to those individuals who may be susceptible to respiratory diseases. For example, elderly cigarette smokers, those with chronic lung disease, or those with immune status deficiencies (transplant recipients).

Building characteristics that present a risk include

- Water temperature in storage tanks or distribution piping between 75°F and 120°F (24°C and 49°C) is conducive to bacterial growth. An elevated hot-water temperature (about 130°F [55°C]) can minimize the chance that *Legionella* will exist and amplify in a water heater and the hot-water points of distribution. Consideration should be given to the risk of scalding to small children and impaired adults if the water temperature is distributed at this high temperature.
- Lack of disinfection chemicals in the water that would have controlled bacterial amplification. This can occur when the water is stagnated in the building due to low or nonoccupancy or interruptions in water service.
- Stagnant or exceptionally low-flow fixtures and cisterns.

MAINTENANCE

A key aspect of the sustainability performance of any home is maintenance. While it is inevitable that equipment will eventually reach its end of life, steps can be taken to minimize performance degradation. Table 14-1 lists examples of tasks that should be carried out to maintain a green residence. Consult manufacturer's instructions for specific approaches and the frequency of these maintenance tasks. Keep in mind that some tasks are most appropriately carried out by industry professionals rather than the homeowner.

Table 14-1: Sample Tasks for Maintaining a Green Residence

Residential System	Task
Envelope	• Recaulk or reapply weather stripping on failing seals • Repair holes or gaps to minimize water damage risk • Repair faulty roof components to minimize water damage risk
HVAC	• Change filters on space cooling and heating systems • Change filters on ventilation units • Clear leaves and debris from outdoor units of air conditioners and heat pumps • Check condensate drains for air-conditioning indoor units and condensing furnaces and boilers • Clean evaporator and condenser heat exchanger coils • Check burners to ensure proper operation • Check refrigerant levels • Check electrical connections to ensure proper operation of blowers and other electrical components • Have combustion heating systems cleaned and tuned by professionals, according to the manufacturer's recommendations
Water	• Repair leaking fixtures • Drain water heaters according to manufacturer's recommendations • Ensure P-traps are filled with water
Solar	• Trim landscaping to ensure no shading of photovoltaics or thermal collectors
Appliances	• Clean heat exchangers on refrigerators • Clean clothes dryer ducts to clear lint

FUTURE TRENDS

As with other types of buildings, residential buildings are seeing ever-evolving movements toward green building. Some of the trends in the residential sector will be discussed in this section (Dodge Data and Analytics 2020, National Association

of Realtors 2019, GBRI 2019, Ecohome 2020, Lerner 2020, Welles 2020, Kato 2019, Esajian 2017, DOE 2015).

Zero Energy Homes

According to the US Department of Energy (DOE), a zero energy building, or what is also referred to as a *net zero energy* or *zero net energy* building, produces enough renewable energy to meet its own annual energy consumption requirements, thereby reducing the use of non-renewable energy in the building sector (DOE 2015).

The first step is to increase efficiency (i.e., including efficient building construction, efficient systems and appliances, operations and maintenance, and change user behavior) and then address remaining needs with on-site renewable energy generation. Useful how-to guides and resources are available from the DOE on best practices, lessons learned, and recommendations on strategies within typical construction budgets.

The concept typically does not involve disconnection from the utility grid, but energy is pulled from the utility when renewable resources are not available, and excess energy generation on site is sent back to the grid. While zero energy is a goal for many buildings, the available roof space on single-family homes relative to the typical energy usage by such homes makes the goal particularly attainable for these types of buildings. As costs of photovoltaics continue to decrease, making these homes within reach of more consumers, care must still be taken to ensure that loads are decreased sufficiently while maintaining a healthy indoor environment so that any necessary energy to attain net zero operation over a year can feasibly be situated on site. Other similar efforts aiming for this goal are termed *zero energy ready* (i.e., efficient home without renewables), *near zero energy* (i.e., acknowledging that coming close is worthwhile and that weather dependencies make hitting net zero somewhat uncertain), or *beyond net zero* (i.e., generating more energy over the course of the year than consumed).

Notable efforts are also underway in Europe. The EPBD provides a framework definition for nearly zero energy buildings (nZEBs) for all buildings, including residential. Accordingly, nZEBs are buildings that have a very low energy usage. The nearly zero or very low amount of energy required should be covered to a significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

As of January 2021, all new residential buildings in the European Union comply with the mandatory nZEB requirements. In some cases, like the Brussels Capital Region, the nZEB requirements were officially defined in 2011 and enforced as of 2015 and today nZEB requirements are mandatory for all new buildings. Some EU Member States are also targeting existing homes that undergo major renovations to comply with nZEB requirements, although at less strict limits.

In most European countries, the nZEB definitions refer to maximum primary (source) EUIs as the main indicator, while in others (e.g., the United Kingdom, Norway, and Spain) carbon emissions are used as the main indicator or as a complementary indicator to primary energy use (BPIE 2015). Most jurisdictions aim to have an annual primary EUI not higher than 50 kWh/m²·yr (15.8 kBtu/ft²), although there are large national variations, such as less than 20 kWh/m² (6.3 kBtu/ft²) in Denmark and 160 kWh/m² (50.7 kBtu/ft²) in Austria (BPIE 2015). Different requirements are usually set for single-family houses and apartment buildings, and adjusted for different climate zones. Relevant information on nZEB European national definitions, best practices, indicators for energy performance, passive and active systems, and use of renewables are available at the ZEBRA2020 data tool (<https://zebra2020.eu/tools/>). Similar resources on energy performance indicators for residential buildings are available in the EU Building Stock Observatory. The main construction and technical characteristics, as well as refurbishment trends in the residential building stocks of 20 European countries, and a tool for monitoring refurbishment activities are available from a recent European project (EPISCOPE, see reference at the end of this chapter). Regional and national studies in Europe highlight the trends and developments in energy upgrading of the European housing stock (Visscher et al. 2016).

Electrification

A trend is emerging in the building community to completely electrify buildings to do away with any fossil fuel combustion on site. The thought is that emissions from a central power plant can be better controlled, and the electric supply will eventually transition to clean sources. Several communities have passed laws requiring new buildings to be totally electric. For residences, such an effort means transitioning from gas furnaces to heat pumps, gas water heaters to electric water heaters (preferably heat pump water heaters), and gas cooking appliances to electric ones. The added benefits of electrification are safety and air quality; the elimination of combustion appliances significantly reduces the risk of carbon monoxide poisoning and decreases the number of pollutants emitted in the homes, such as nitrogen dioxide. Challenges emerge, however, in designing buildings appropriately to use electric appliances, developing heat pumps suitable for even the coldest climates, and determining ways to retrofit homes cost-effectively from gas to electric appliances.

Despite the movement toward electrification, unvented combustion devices are still popular among a segment of households. Such devices may include gas ranges or unvented heating appliances. ASHRAE developed a position document regarding the impact of such equipment on IAQ, which is available online (ASHRAE 2020).

Grid-Integrated and Smart Homes

As an increased focus is given to accommodating increased levels of intermittent nondispatchable electric generation resources, such as wind and solar on the grid, integrating the home into the grid for demand response is a key opportunity to promote greater reliability. Similarly, smart technology is beginning to gain greater acceptance by occupants in the home. Some of that technology is focused on security (e.g., cameras) or convenience (e.g., automatic lighting), but much of it will be focused on improved sensing, indoor environment control, and energy systems management. Integration of the sensors and controls within a home, coupled with communications to the electric distribution utility, promises to allow for improved indoor comfort, more efficient use of energy in homes, and better coordination with renewable resources available on the grid.

Modular Construction

To minimize construction waste and promote greater quality in assembly, many home builders are trending toward modular construction. While some create entire homes within a controlled factory environment, other builders construct assemblies within factory settings for final fabrication on-site. This allows builders to minimize material waste and use methods to foster well-aligned assemblies and properly fit components. Such approaches should result in tighter envelopes. Additionally, these methods promise to reduce construction costs.

Low-Emitting Products

A key principle of IAQ is to first reduce source emissions before attempting to remove or control those emissions. To that end, a trend is emerging toward using low-emitting products within homes. From more natural insulation to cabinets and flooring products that meet industry standards for low emissions, such products are the first line of defense to promote a healthy environment.

Resilient Construction

In an acknowledgment of the need to build homes to face a range of natural hazards, resilient construction techniques are gaining acceptance worldwide. A green home is one that allows residents to occupy it safely, regardless of the environment, and one that will be durable to a range of natural hazards.

Pandemic-Adaptive Construction

The coronavirus pandemic of 2020 was an event that significantly altered lives, society, and the manner in which building comfort and safety systems are operated and designed. For the decades that follow, dwellings should be designed to incorporate the lessons learned from this challenging pandemic. These elements include high-speed broadband internet service and other accommodations for

working from home, effective and efficient dwelling-unit mechanical ventilation, and spaces for infected and vulnerable occupants. These special spaces should be kept at negative pressure for the infected and positive pressure for the vulnerable, with separate toilet facilities, if possible. The ASHRAE Epidemic Task Force (ETF) developed pandemic guidance for residential buildings, which can be found at <https://www.ashrae.org/technical-resources/residential>.

Residential multifamily buildings require the same pandemic-resistant provisions recommended for single-family detached buildings but are more complex because of the physical connection and proximity of dwelling units and occupants. Shared HVAC equipment and the likelihood of transfer air flowing from one dwelling unit to another can increase the risk of viral transmission between occupants if design and maintenance are not thoughtful. The ASHRAE ETF developed pandemic guidance for multifamily buildings as well, which can be found at <https://www.ashrae.org/file%20library/technical%20resources/covid-19/covid-19-guidance-for-multifamily-building-owners-and-managers.pdf>.

Equipment Trends

Heat Pumps. To meet the trends of electrification noted in the Electrification section, heat pumps are gaining popularity as the primary heating approach in homes. Developing units with greater capacity at low temperatures is a key research focus that will enable comfortable living conditions with efficient electric heating in a broader range of climates.

Tankless Water Heaters. Builders are now expressing a greater interest in consideration of tankless water heaters for their project, due to the general population's understanding of the benefits of these systems. While much of the popularity can be attributed to non-energy issues such as occupying less space in the home and providing hot water on demand, these units tend to have a lower energy consumption than storage water heaters because they do not maintain a tank of hot water for use. Hence, standby heat loss is not an issue with these units. These are particularly good solutions for point-of-use applications (e.g., kitchen sinks).

Solar. The decreasing cost of solar PVs is leading to increased installations on residences. As previously noted, the relatively small energy consumption of typical single-family residences relative to their roof areas makes net-zero operation feasible in many locations. For multifamily buildings, it may not be reasonable to expect that the entire building would be net zero, but the roof area may be adequate to make a significant impact on overall energy consumption. Future PVs also promise to allow for installation in a building-integrated manner, meaning that PVs may be installed economically on a range of surfaces, including vertical surfaces, and that rooftop PVs may be better integrated architecturally with roofing systems. The latter trend may decrease the reluctance of homeowners concerned with the appearance of a PV array on their roofs. Continued efforts to increase the efficiency of

solar panels will have the result of allowing a smaller footprint to meet the needs of the home.

In seeing revenue decreases with more solar installations, some utilities and jurisdictions may move toward time-of-use pricing or may not reimburse homeowners for energy produced at the same rate they charge for energy consumed from the grid. To better use locally generated electricity from solar panels, a combination of battery storage with PV is gaining attention. Such installations will also aid in resilience by allowing for the use of the locally generated electricity when the grid is not operational.

PVs trends include using microinverters to convert each panel's DC output to AC as opposed to a central inverter to do that task. The advantage of microinverters is that they allow for a range of orientations of solar panels to match the roofline. Central inverters operate better when all panels receive the same amount of irradiation. Central inverters have the advantage of higher conversion efficiencies and may allow for easier detection of faults and replacement when faults occur.

Solar thermal technologies provide heat that can be used for any low-temperature heat application in residential buildings. Solar energy is commonly used for domestic hot-water (DHW) heating. The technology is mature and has been commercially available in many countries for several decades. In typical DHW solar heating applications, water is heated directly in the collector or indirectly by a heat transfer fluid that is heated in the collector, passes through a heat exchanger, and transfers its heat to the DHW. The heat transfer fluid is transported by either natural or forced circulation. Natural circulation occurs by natural convection (thermosiphoning), whereas forced circulation uses pumps. Because of the intermittent nature of solar radiation, hot-water storage and an auxiliary heater must be installed to handle demand.

The trend in solar heating is toward systems that provide both DHW and space heating; these are termed solar combi systems. As a result of the higher demand expected, solar combi systems require significantly larger solar collector areas. Important issues to consider are building integration of the solar collectors and system design and installation (Bucker and Riffat 2015). Currently, solar combi systems represent about 25 of the solar thermal systems installed worldwide. Prior to installing a combi system, it is recommended to investigate if it is more economical to heat DHW using electricity generated by a PV solar system.

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ASHRAE GreenTip #14-1

Air Leakage Metrics

With the increased interest in energy efficiency to curb climate change, lower energy costs, and increase comfort, air leakage measurement has become more important. Of the many air leakage metrics used by analysts, the most common are:

- **Leakage at 50 Pa (CFM₅₀).** This is measured with the use of a blower door at the standard pressure of 50 Pa (0.20 in. w.c.).
- **Air Changes per Hour (ACH).** Air changes per hour through the dwelling at normal pressure normalized by house volume. This metric is problematic because of the challenge of determining “normal pressure.”
- **Air Changes per Hour at 50 Pa (ACH₅₀).** This is air changes per hour through the dwelling at 50 pascals of pressure normalized by house volume. This metric is used by the most recent editions of the *International Energy Conservation Code* (IECC) to establish leakage thresholds, such as 3 ACH₅₀ for northern climates in the US.
- **Equivalent Leakage Area (EqLA).** This is the cross-sectional area of a sharp-edged hole (shaped like a blower door fan hole) that would have the same leakage flow rate as the dwelling if both were subjected to a 10 Pa indoor/outdoor pressure difference. This leakage metric is the origin of the CFM₅₀-value-divided-by-10 rule to yield the approximate square inches of leakage in the dwelling envelope.
- **Effective Leakage Area (ELA).** This is the cross-sectional area of a sharp-edged hole (shaped like a blower door fan hole) that would have the same leakage flow rate as the dwelling if both were subjected to a 4 Pa indoor/outdoor pressure difference.
- **Specific Leakage Area.** The effective leakage area (ELA) is divided by the conditioned floor area.
- **Leakage at 50 Pa/floor area.** The air leakage at 50 Pa (CFM₅₀) is divided by the floor area.
- **Leakage at 50 Pa/surface area.** The air leakage at 50 Pa (CFM₅₀) is divided by the exterior dwelling surface area. This metric normalizes the leakage based on the surface area of the envelope, which is where the leaks are. Some practitioners include only the surface area that is above grade.

- **Leakage Coefficient.** The dwelling leakage rate when there is an indoor/outdoor pressure difference of 1 Pa across the building envelope. This value is determined by a blower door testing at multiple pressures.

PREFERRED METRICS

The derivation of any air leakage metric usually begins with a blower door test. This device includes four major parts, which include an adjustable frame that securely fits into most exterior and interior door openings; a powerful fan that is calibrated for a precise fan-pressure/airflow relationship at the fan; a manometer (usually digital) and related hoses and fittings with the capability of measuring fan pressure, building pressure, and corresponding building leakage rate; and a variable-speed control for the fan. The standard blower door test uses a difference between indoor and outdoor building pressures of 50 Pa (0.2 in. w.c). It is most common for dwellings to be tested under negative than positive pressure because it is an easier test to conduct.

When a blower door test is completed, the resulting air leakage metric is usually expressed as CFM_{50} , where the subscript 50 indicates the building pressure difference was the standard 50 Pa. If, for example, the blower door procedure determines that the flow through the fan is 1200 CFM_{50} for a detached dwelling, it is assumed that this is equal to the leakage rate through the building exterior envelope in one minute at the designated pressure difference; whatever air flows through the fan also flows through the exterior envelope. Although CFM_{50} has the advantage of being determined quickly and accurately and is repeatable in low-wind environments, it has its shortcomings. Its primary weakness is that it is not normalized for building size. Other air leakage metrics overcome this.

ACH_{50} incorporates the CFM_{50} metric, but it normalizes the value for building volume, so the leakage rates in different dwelling sizes can be compared. Beginning with the 2012 International Energy Conservation Code (IECC), ACH_{50} is used to specify dwelling tightness levels. Air leakage rates for new dwellings must be 3 ACH_{50} or less for climate zones 1 and 2 and 5 ACH_{50} or less for climate zones 3 through 8.

$$\text{ACH}_{50} = (\text{CFM}_{50} \times 60 \text{ min/h}) / \text{dwelling volume}$$

Although ACH_{50} is a better metric than CFM_{50} because it is normalized for volume, the volume is not the most reliable normalization factor; the leakage in a building occurs directly on the exterior surfaces. Yes, the volume is enclosed by the exterior surfaces, but the surface-to-volume ratio changes as the size of a building changes. This change in surface area to volume ratio between smaller and larger buildings can make the air leakage metric misleading when comparisons are done of different building sizes.

The best air leakage metric is likely leakage at 50 Pa/envelope surface area, or $\text{CFM}_{50}/\text{ft}^2$ ($\text{Liters}_{50}/\text{s}$ per m^2). It normalizes the leakage rate to the air leakage at the standard 50 Pa with the envelope surface area; of course, this is precisely where the leakage occurs.

In 2015, the Passive House Institute of the US (PHIUS) changed its tightness requirement from 0.6 ACH_{50} to 0.05 $\text{CFM}_{50}/\text{ft}^2$ of the gross envelope area. PHIUS was concerned about the changing surface-to-volume ratio with house size—an inherent problem with the ACH_{50} metric. Their latest adopted air leakage metric allows clear comparisons of dwelling leakage rates no matter the building size and allows precise evaluation and adoption of building-tightening techniques.

ASHRAE GreenTip #14-2

Mechanical Balanced Energy Recovery Ventilation

GENERAL DESCRIPTION

The primary reason to ventilate a space is to provide for indoor air quality that does not harm the human beings living in and using the space. It has been noted that outdoor air is generally far less harmful to the occupants than indoor air. The American Lung Association lists the solutions to better indoor air quality (IAQ), in order of effectiveness as: (1) source control, (2) ventilation, and (3) filtration. Once you have done all that you can do with eliminating or lower indoor contaminants (1), the next best thing you can do is to ventilate the space with outdoor air. As building standards continue to improve the thermal performance by increasing airtightness of the building shell, the result is reduced natural air changes of the indoor space and worsening of the IAQ. It thus becomes necessary to add continuous mechanical ventilation to keep the IAQ healthy.

Any type of ventilation increases the energy cost of the building. There are many strategies to ventilate a building, but the most energy efficient and beneficial to IAQ is by ventilating using a balanced mechanical heat or energy recovery ventilator, ERV (energy recovery in most instances).

An HRV/ERV exhausts a set amount of air from the dwelling while simultaneously supplying the same amount of fresh outdoor air into the building. The two separate airstreams pass through an energy transferring mechanism within the HRV/ERV core. This mechanism transfers the energy—sensible thermal energy only for an HRV and sensible and latent (moisture) for an ERV—from the leaving air to the incoming air, or vice versa depending on the season, thus lowering the energy load being introduced into the building via the mechanical ventilation. Most HRV/ERVs also filter the incoming outdoor air.

When evaluating an HRV/ERV, there are four key metrics that should be compared: (1) sensible transfer efficiency, (2) latent transfer efficiency (for ERV only), (3) electricity used for moving the air, and (4) level of filtration. Other options include defrost

strategy, control capabilities, annual service requirements, and upfront costs, including ductwork installation.

Selecting an HRV or ERV depends on the climate and the specific needs or conditions of the dwelling. A general rule to keep in mind is that energy always transfers from greater to lesser. That is, higher temperature transfers to lower temperature and likewise for moisture differences. Generally, an ERV is better for hot and humid locales because it directs some of the humidity back to the outdoors rather than bringing it all indoors, as an HRV will do. Using the same rationale, if a dwelling is too humid indoors during the winter heating season, an HRV is a better choice for ridding the dwelling of this moisture. Generally, ERVs are a better choice for hot and humid climates, and HRVs are better for cold and dry climates, but other factors are often more important than the climate, such as dwelling tightness level and the number of occupants.

VENTILATION RATE

All indoor spaces benefit from increased ventilation based on the assumption that the outdoor air is healthier than the indoor air; many studies have demonstrated that this is the case. The biggest unanswered question is how much ventilation does the space need or, better stated, what ventilation rate will achieve acceptable indoor air quality. This ventilation rate is typically determined by code, either the *International Residential Code (IRC)* or ASHRAE Standard 62.2, *Ventilation and Indoor Air Quality in Residential Buildings*. If there is no enforceable ventilation code in a location, it is recommended that ASHRAE Standard 62.2 be followed.

SOURCES OF FURTHER INFORMATION

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Section 3: Postdesign— Construction and Beyond

CHAPTER FIFTEEN

EXISTING BUILDINGS

INTRODUCTION

About three-quarters (71%) of the total worldwide building area that will exist in the year 2030 and over half (54%) in 2050 have already been constructed. For developed industrial nations, these predictions increase to 83% for 2030 and 73% for 2050 (Statista 2016). Therefore, the greatest opportunity to reduce the overall environmental impacts of buildings is to renovate existing buildings, especially in developed industrial countries. Extending the life of an existing building through a renovation project means new embodied energy that would otherwise go into a new building, and the development of a new site can be avoided. A renovation project requires fewer materials than a new construction project and provides an opportunity to make the building significantly more energy- and water-efficient. Finally, a renovation project makes it possible to deliver improved indoor environmental quality (IEQ) to building occupants.

This chapter addresses the energy performance of existing buildings, audits covering various aspects of sustainability and IEQ, how to improve building sustainability and IEQ, and several approaches to renovating and maintaining existing buildings to enhance their performance in these areas. Refer to the sections of this publication specifically on recommissioning, continuous monitoring, and building labeling (since these actions are also important for the continuing energy efficiency of existing buildings), as well as the chapters on renewable energy (since both energy efficiency must be increased and nonfossil fuels must be deployed to reduce GHG emissions significantly).

ENERGY PERFORMANCE OF EXISTING BUILDINGS

Per the International Energy Agency's (IEA) 2018 statistics, existing commercial and residential buildings were globally responsible for more than 36% of primary energy use and approximately 39% of CO₂ emissions. In the United States, commercial buildings are responsible for about one-third of these impacts, while residential buildings are responsible for the remaining two-thirds (EIA 2009,

Table 15-1: Average Building Energy Use Intensity (EUI) by Year Constructed, Thousands of Btus per ft² (kWh/m²)

Building Type	1959 or Before	1960 to 1979	1980 to 2012*
Residential	52.1 (164.3)	48.6 (153.3)	40.1 (126.5)
Commercial	67.3 (212.2)	90.2 (284.5)	80.4 (253.5)

*Residential building energy use intensity is for 1980–2009

2012). Clearly, improving the performance of both existing commercial and residential buildings are key strategies for reducing world energy use and greenhouse gas (GHG) emissions. In the European Union, residential buildings use 27% of the total final energy and 18% of the total emissions, while nonresidential buildings represent 15% and 12%, respectively (Eurostat 2022).

It may seem intuitive that newer buildings should be more energy efficient than older buildings. While this is true for most residential buildings, it is not generally true for commercial buildings, at least in the United States. The data in Table 15-1 are taken from the 2009 Residential Energy Consumption Survey (EIA 2009) and the 2012 Commercial Building Energy Consumption Survey (EIA 2012).

Note that the average EUI of commercial buildings constructed between 1960 and 1979 is higher than those for commercial buildings constructed either before or after that time period. While significant opportunities often exist to improve the energy performance of buildings constructed in any time period, it would appear that commercial buildings built between 1960 and 1979 may be particularly good candidates for energy improvement projects.

BUILDING AUDITS

Audits are recommended to be performed prior to considering energy-efficiency improvements to assess the building's condition, assisting in benchmarking and setting goals for the project, assigning one of the labels or certifications described in Chapter 2, or meeting a regulatory requirement. These goals are often overlapping. Building audits range from the relatively simple (e.g., an audit to obtain an ENERGY STAR score) to the complex (e.g., an audit to obtain LEED certification). This section addresses energy audits, water audits, IEQ audits, and audits addressing other sustainability categories.

Energy Audits

Energy audits have been conducted at least since the mid-1970s, after the oil embargo focused attention on the amount of energy wasted by modern buildings. ASHRAE has been at the forefront of developing formal energy audit procedures.

ASHRAE's *Procedures for Commercial Building Energy Audits* (ASHRAE 2011), and ASHRAE Standard 211-2018, *Standard for Commercial Energy Audits* (ASHRAE 2018f) gives guidance for performing energy audits. Four energy audit levels of effort are detailed, including Preliminary Energy Use Analysis, Level 1 Walk-Through Survey, Level 2 Energy Survey and Analysis, and Level 3 Detailed Analysis of Capital Intensive Modifications. Note that the boundaries between these levels of effort are somewhat fluid.

The **Preliminary Energy Use Analysis** includes gathering and analyzing energy bills for at least a one-year period, developing an Energy Cost Index (EUI) and an Energy Cost Index (ECI) based on gross conditioned floor area, and comparing these to those for buildings having similar characteristics. ENERGY STAR Portfolio Manager is a good source for such benchmark data (U.S. Environmental Protection Agency). Portfolio Manager is used to determine target energy use and cost indices, and thereby estimate the approximate savings that could be obtained by making building upgrades. ASHRAE Standard 100-2018, *Energy Efficiency in Existing Buildings* provides a detailed table of target EUIs by building activity and climate zone (ASHRAE 2018a).

The **Level 1 Walk-Through Survey** includes a relatively brief survey of the building focused on identifying a list of potential energy efficiency measures (EEMs), also often referred to as energy conservation measures (ECMs). These can range from no-cost measures (such as setting thermostats back or up at night) to capital intensive measures (i.e., replacing boilers or chillers). Approximate installation costs and energy cost savings may or may not be provided as part of this effort.

The **Level 2 Energy Survey and Analysis** includes a more in-depth building survey, as well as more accurate installation cost and cost savings estimates. Establishing cost savings requires a good understanding of baseline operating conditions, proposed operating conditions, utility rates, and interactions among ECMs. Cost savings may be calculated using either spreadsheet models or—particularly when there are significant interactions between ECMs—whole-building simulation models. The results of the Level 2 survey should allow the building owner or manager to determine which measures are worth developing further for potential implementation.

Finally, the **Level 3 Detailed Analysis of Capital Intensive Modifications** includes additional data-gathering as well as more rigorous engineering and economic analysis than is performed in a Level 2 survey. Sometimes referred to as an investment grade audit (IGA), this level of effort is intended to facilitate the building owner or manager to make sound major capital investment decisions.

Water Audits

Water audits can be similar to energy audits, and are often included as part of an energy audit. Historically, the low cost of building water use compared to the cost of building energy use has resulted in auditors paying less attention to water than to energy. However, today more emphasis is being placed on auditing buildings'

water use and finding ways to reduce the same as the availability of water becomes more constrained in many geographical areas and as municipalities increase rates to repair aging water and sewer infrastructure.

ASHRAE's *Performance Measurement Protocols for Commercial Buildings: Best Practices Guide* (ASHRAE 2012) defines three water audit or “performance measurement procedure” levels of effort: Basic Evaluation, Diagnostic Measurement, and Advanced Analysis. The Basic Evaluation includes gathering and analyzing water bills for at least a one-year period, determining usage per unit area of the building and per unit area of irrigated landscape, and comparing these indices for those of buildings having similar characteristics. ENERGY STAR Portfolio Manager is a good source for such benchmark data. Doing this allows the auditor to determine the potential for savings. The Basic Evaluation also includes a simple walk-through survey to identify water use issues. On the basis of these data, the auditor should be able to develop recommendations for reducing water use.

The Diagnostic Measurement and Advanced Analysis are progressively more detailed efforts to be used if the recommendations implemented after performing the Basic Evaluation do not result in the desired level of savings. The Diagnostic Measurement procedure includes determining the number of people of each gender occupying the building and then calculating the daily water flow for each fixture type (water closets, urinals, and sinks). The Advanced Analysis procedure includes submetering of specialized uses, such as cooling tower makeup water, kitchens, subdivided landscape areas, and processes. The submeter data can then be used to develop a detailed building water use model. Completing one or both of these two procedures can reveal additional opportunities for reducing water used in the building and on the irrigated landscape.

IEQ Audits

Performance Measurement Protocols for Commercial Buildings: Best Practices Guide (ASHRAE 2012) also sets out three IEQ audit levels of effort. The IEQ categories addressed are thermal comfort, indoor air quality (IAQ), lighting, and acoustics. As is the case with water audits, the three levels of effort are **Basic Evaluation**, **Diagnostic Measurement**, and **Advanced Analysis**. The **Basic Evaluation** is a two-part process consisting of an occupant survey and field observations. The **Performance Measurement Protocol** recommends two online, automated surveys: one developed by the Center for the Built Environment at the University of California, Berkeley, the other by the Usable Buildings Trust based in the U.K. Both of these surveys have large databases of accumulated results against which occupant responses can be compared. Field observations should be conducted after completion of the occupant survey. The Protocol contains checklists and spreadsheets to help ensure that all relevant data is captured for the four IEQ categories considered. On the basis of the Basic Evaluation, the auditor should be able to recommend operational changes for improving building IEQ.

The **Diagnostic Measurement** and **Advanced Analysis** are progressively more detailed efforts to be used if further testing or design changes are required to fully address building IEQ issues. The **Diagnostic Measurement** procedure adds physical measurements (e.g., temperatures, infiltration airflows, outdoor airflows, illuminances, and sound levels) plus additional analysis based on these measurements. The **Advanced Analysis** procedure adds calling in specialists in the four IEQ categories as needed to perform additional testing and develop designs for building modifications. Completing one or both of these two procedures can establish a path toward resolving any IEQ issues that cannot be resolved through use of the Basic Evaluation procedure alone.

Audits Addressing Other Sustainability Categories (Building Labels)

Guidance for auditing sustainability categories in addition to and including energy efficiency, water efficiency, or IEQ is offered by U.S. Green Building Council (USGBC 2014a), BRE Global (BRE), and other building-labeling programs globally. In the USGBC publications, that guidance is often—but not always—embedded in the descriptions of individual LEED prerequisites and credits. For example, to obtain the “Light Pollution Reduction” credit in the “Sustainable Sites” category, the assessment team may take perimeter illuminance measurements with building exterior and site lights on and off to demonstrate that the former condition results in illuminance levels no more than 20% higher than the latter condition. BRE consistently provides assessment criteria and evidence that must be submitted to receive credit in each sustainability category. To obtain credit for minimizing “Night time light pollution,” for example, the assessment team may submit (a) photos confirming the external luminaires are designed to restrict upward light and light spill, (b) confirmation that light is switched off after a set time, and/or (c) light survey results and recommendations. Refer to Chapter 2 for more information on building-labeling programs.

Clearly, building audits can encompass a very wide range of activity. The building owner’s requirements should always be elicited and documented at the outset. Those requirements should then drive the scope and depth of the audit process.

IMPROVING BUILDING SUSTAINABILITY AND IEQ

The ultimate goal of performing a building audit is often—though not always—to improve building performance (i.e., to reduce its operating costs, lessen its impact on the environment and/or to improve IEQ for building occupants). As part of its “Energy Savings Performance Contract” (ESPC), the U.S. Department of Energy has developed a comprehensive list of 19 technology categories (TCs) and associated ECMs. Despite the nominal focus on energy conservation and efficiency, these categories also include water conservation and efficiency and IEQ improvements. These categories and examples of associated building upgrades are shown in Table 15-2.

Table 15-2: Department of Energy Technology Categories and Examples of Upgrades

TC	TC Description	Examples
1	Boiler plant improvements	Install oxygen trim controls to improve combustion efficiency. Install economizer in boiler flue to improve fuel utilization efficiency. Replace existing boilers with more efficient boilers to improve fuel utilization efficiency.
2	Chiller plant improvements	Reset chilled-water temperature during periods of low loads to improve chiller plant efficiency. Replace constant-volume primary pumping with variable primary or primary-variable secondary pumping to improve chiller plant efficiency. Replace existing chillers with heat recovery chillers or more efficient chillers.
3	Building automation systems (BASs)/ energy management control systems (EMCSs)	Upgrade from pneumatic control to direct digital control. Integrate HVAC and electrical equipment into existing BAS/EMCS. Install a new BAS/EMCS to serve the entire facility.
4	Heating, ventilating, and air conditioning (HVAC) systems (excepting chillers and boilers)	Convert constant-volume air distribution system to variable-volume air distribution to reduce energy use. Replace existing packaged direct expansion (DX) units with more efficient packaged DX units or variable-refrigerant-flow (VRF) units. Install energy recovery wheels or heat pipes on dedicated outdoor air systems.
5	Lighting improvements	Retrofit existing lighting fixtures with more efficient lamps and ballasts/drivers to reduce energy use and to improve light levels and/or color rendering. Install occupancy sensors to switch lights off when space is not in use. Provide daylighting via skylights or windows to reduce energy use and provide a connection to the exterior environment.
6	Building envelope modifications	Install or replace weather stripping and caulk window and door frames to reduce energy use and to improve thermal comfort. Replace windows to reduce energy use and to reduce glare. Install solar shading to reduce energy use and to increase potential for using daylighting.

Table 15-2: Department of Energy Technology Categories and Examples of Upgrades (Continued)

TC	TC Description	Examples
7	Chilled water, hot water, and steam distribution systems	Repair and/or replace steam traps to reduce energy use. Insulate piping to reduce energy use. Replace electric domestic hot water (DHW) heaters with natural gas DHW heaters to reduce source energy use and energy costs.
8	Electric motors and drives	Replace larger existing AC motors with more efficient motors. Replace smaller existing AC motors with electrically commutated motors to reduce energy use and/or improve controllability. Install variable-speed drives on motors to reduce energy use and/or improve controllability.
9	Refrigeration	Reset refrigerator or freezer unit temperatures to optimize food quality and reduce energy use. Consolidate multiple refrigerator or freezer units into a smaller number of units to reduce energy use. Replace refrigeration units with more efficient refrigeration units.
10	Distributed generation	Install cogeneration system to provide space or process heating, cooling, and electric power. Install steam microturbine in place of a large pressure reducing valve to provide electric power. Install fuel cells to provide electric power.
11	Renewable energy systems	Install solar hot-water system to provide domestic hot water or space heating. Install solar photovoltaic system to provide electric power. Replace HVAC units with ground-coupled heat pump system to reduce energy use.
12	Energy/utility distribution systems	Install power factor correction equipment to reduce power factor charges. Replace existing transformers with more efficient transformers. Install natural gas distribution system to enable fuel switching.
13	Water and sewer conservation Systems	Replace existing water closets and urinals with low-flow plumbing fixtures. Install weather-based irrigation system controls to reduce water use. Install a condensate drain piping system to reclaim water from air-handling units for reuse.

Table 15-2: Department of Energy Technology Categories and Examples of Upgrades (Continued)

TC	TC Description	Examples
14	Electrical peak shaving/load shifting	Program BAS/EMCS to shed loads in response to signals from electric utility or to maintain building demand below a preset maximum value. Install chilled-water or ice thermal storage system to shift chiller operation to off-peak hours. Install absorption, natural gas engine-driven, or steam turbine-driven chillers to reduce peak electric loads.
15	Energy cost reduction through rate adjustments	Switch to more favorable electric rate schedule. Consolidate electric meters to reduce monthly fixed charges. Purchase natural gas from third party supplier to obtain a more favorable rate.
16	Energy related process improvements	Implement recycling program for scrap materials or used packaging to reduce energy use and costs. Implement manufacturing improvements to reduce energy use. Implement water treatment process improvements to reduce energy use.
17	Commissioning	Review and reprogram BAS/EMCS to match equipment operating hours and temperature set points to the building owner's requirements. Adjust, repair, or replace economizer controls to make effective use of air-side free cooling. Rebalance airflows to reduce energy use and help ensure ventilation standards are met.
18	Advanced metering systems	Install individual utility meters for each building on a campus to improve monitoring capability. Install submeters for large pieces of equipment or systems to improve monitoring capability. Install advanced metering infrastructure to automatically read utility meters.
19	Appliance/plug load reductions	Install client software to adjust computer power settings when computers are not in use. Install occupancy-sensor-based controllers to reduce energy use by vending machines when space is not occupied. Replace existing laundry equipment with more efficient laundry equipment.

Many additional examples of building upgrades addressing energy use, water use, and IEQ are provided in Informative Annex E of ASHRAE Standard 100 (ASHRAE 2018a).

U.S. Green Building Council (USGBC 2014a) provides ideas for improving building and site sustainability in areas not addressed by the U.S. Department of Energy Technology Categories or ASHRAE Standard 100, as well as for areas that are covered by those categories but that are unlikely to result in energy or water savings. Table 15-3 provides examples of upgrades suggested in the LEED rating system for operations and maintenance in the categories of Location and Transportation, Sustainable Sites, and Materials and Resources. Note that many of these examples consist of establishing policies and practices to achieve the desired goals, rather than installing new equipment or systems.

HISTORIC BUILDINGS

Older buildings require more in-depth investigation than modern buildings when considering the application of state-of-the-art energy-efficiency measures (EEMs) or the modification of their operation for improved efficiency. It is imperative to first determine the building's original construction and how it was designed to operate for passive heating, cooling, ventilating, and daylighting.

Energy savings can often be attained by reinstalling passive elements initially designed for creating environmental comfort. Through the years, skylights may have been covered, operable windows made nonoperable, working shutters removed, and passive operations for ventilating forgotten.

The second important reason for understanding the building's construction and operation is that blindly instituting modern EEMs could result in several issues that result in building material and building content damage. This is particularly true for those buildings designated as or eligible to be designated as "historic." A few examples include:

- The destruction of exterior masonry when previously uninsulated masonry walls are insulated. Often uninsulated historic masonry buildings depended on vagrant heat from the interior to heat the exterior of the masonry and thus evaporate water on the building's masonry exterior. Care must be taken to ensure water is kept off of exterior masonry walls when insulation is added.
- Covering or destroying a building's historically important character-defining features. A few examples include adding insulation that covers originally bare interior and exterior walls, adding a vestibule, or replacing of historic windows with modern-looking ones.
- The creation of condensation in a building in a hot and humid climate when establishing an unoccupied setup temperature that is too high. If the building temperature is raised too high during unoccupancy and then the temperature is

Table 15-3: Three LEED Sustainability Categories and Examples of Upgrades

Sustainability Category	Examples
Location and Transportation	• Set up a carpool matching website to promote carpooling. • Provide preferential parking for employees who participate in a rideshare program. • Provide subsidies to encourage employees to use public transit.
Sustainable Sites	• Plant native or adapted vegetation to provide habitat and promote biodiversity. • Install a system to capture and treat stormwater flowing off of impervious surfaces to reduce runoff. • Clean high reflectance roofs and pavement periodically to reduce the heat island effect. • Shield exterior lighting fixtures to reduce light pollution. • Use manual or electric powered equipment (e.g., lawnmowers) for site maintenance to reduce pollution.
Materials and Resources	• Establish a purchasing policy for ongoing consumables that sets requirements for post-consumer recycled content. • Establish a purchasing policy for furniture and furnishings that requires wood products to be certified by the Forest Stewardship Council. • Establish a waste reduction and recycling program that reuses, recycles, or composts specified percentages of ongoing and durable goods waste.

lowered for occupancy, the dew point may be reached. Pay attention to dew points and consider adding a desiccant wheel or full DOAS to keep the air drier.

- The rotting of wooden joists and the possible creation of condensation when insulating the inside of a masonry wall containing a beam in a joist pocket. Possible solutions include leaving a gap in the insulation near the joist, insulating the joist cavity, providing passive heat flow to the joist via metal plates, actively heating the joist end, or chemically treating the wood.

These examples were taken from ASHRAE Guideline 34-2019, *Energy Guide-line for Historic Buildings*, which is recommended for detailed guidance on the procedures and precautions to be taken when planning energy-efficiency improvements for historic buildings (ASHRAE 2019e).

DELIVERY MECHANISMS FOR UPGRADES TO EXISTING BUILDINGS

There are three general approaches that may be taken to implementing upgrades and new policies (henceforth included under the term *upgrades*) for existing buildings.

Those are: self-implementation by the building owner, design of upgrades by an engineering firm and implementation by a contractor or contractors, and design and implementation by an energy services company (ESCO). As is the case with audit levels of effort, the boundaries between these three approaches are somewhat fluid.

If a building owner has sufficient capability in-house, they may elect to conduct the building audit, design the upgrades desired, and implement the upgrades without using any consultants or contractors. Advantages to this approach include maximization of control over the project and—depending on labor rates—minimization of costs. Disadvantages include the diversion of labor resources to an effort that may not be part of the building owner’s core mission and the inability to take advantage of any specialized expertise or skills that consultants and contractors may be able to offer.

More commonly, the building owner will engage with consultants to audit the building and design the upgrades desired. Those consultants may include engineers, architects, and others with specialized knowledge. The owner will then engage with a general contractor or individual trade contractors to implement the upgrades. This approach does not suffer from the two disadvantages listed above for the self-implementation approach. However, depending again on labor rates, this approach may cost more overall than self-implementation. An additional disadvantage to this approach may be that if the consultant(s) and general contractor do not provide adequate oversight and coordination of trade contractors, the upgrades may not perform as well as originally estimated. This is because energy conservation measures may interact with each other and with building systems in complex ways that cross the boundaries of particular trades and consultant expertise. If the upgrades perform suboptimally, projected energy savings and other benefits will not be fully realized.

Another common approach is for the building owner to engage with an energy services company (ESCO) to undertake all steps: auditing the building, designing the upgrades, and installing the upgrades. In essence, the ESCO acts as the general contractor for the entire process. The ESCO will typically hire consultants with specialized knowledge and contractors with specialized skills as needed. Most ESCOs will also guarantee a percentage of the energy and other utility cost savings anticipated to result from the building upgrades. Such a guarantee makes it easier for the building owner to obtain a loan from a lending institution if he or she is either unable or does not wish to pay the entire project cost upfront. This approach, known generally as “energy performance contracting,” also does not suffer from the two disadvantages listed for the self-implementation approach. It may or may not cost more than the other two approaches, depending on labor rates and ESCO markups. Additionally, energy performance contracting is more likely to avoid the problem of underperforming upgrades than the other two approaches, particularly if a savings guarantee is included. A disadvantage to this approach is that the primary focus of ESCOs—as the name suggests—is on energy savings. If the building

owner is mainly interested in making improvements that go beyond energy savings, the ESCO may not be the best entity to manage the overall upgrade process.

However, a final potential advantage to an ESCO-managed process is that it may be possible to use the guaranteed utility cost savings to pay for other upgrades that do not result in cost savings. If, to use an example provided in the previous section, a building owner wishes to increase site sustainability by planting native or adapted vegetation, it may be possible to use excess energy savings to pay for that improvement. Of course, it may be possible to implement this measure using the other two approaches as well, although the cost savings guarantee offered by the ESCO would make this easier to structure from a financial standpoint.

Governments and utility companies offer a variety of policies and incentives to support the implementation of energy upgrades to existing buildings. Some examples include: grants, loans, tax credits, rebate payments, and net metering of renewable energy installations. For projects in the United States, the Database of State Incentives for Renewables & Efficiency (DSIRE) is an excellent online resource for identifying these programs by ZIP code.

MEASUREMENT AND VERIFICATION

Measurement and Verification (M&V) of building performance is often required for both building upgrade projects and new buildings receiving green certification. In the case of building upgrade projects that are financed from utility cost savings, the lending institution will generally require that those savings be measured and verified over the term of the loan to minimize its risk. Similarly, most green certification programs require that energy use, water use, and IEQ parameters be measured and verified to demonstrate that the new building is performing as designed.

M&V of utility cost savings involves comparing measured energy and/or water use before and after project completion, then making appropriate adjustments for changes in conditions, such as weather and hours of operation. M&V plans must be developed for a specific upgrade or building based on the needs of the owner and/or lending institution for accuracy and cost. M&V plans fall into two general categories—*retrofit isolation*, which focuses on a particular energy or water conservation measure (such as a lighting retrofit), and *whole building*, which focus on overall building energy and water use. Generally speaking, M&V plans based on a retrofit isolation approach are less costly to implement than plans based on a whole-building approach but are also less accurate. The reason that whole-building approaches are more accurate is that they are better able to account for interactions between multiple building upgrade measures. Thus, a whole building M&V approach is generally best if the building upgrade project includes two or more highly interactive energy or water conservation measures.

Three widely recognized M&V standards are the *International Performance Measurement and Verification Protocol (IPMVP®)* (EVO 2022); *M&V Guidelines: Measurement and Verification for Performance-Based Contracts* (DOE 2015), and

ASHRAE Guideline 14-2014, *Measurement of Energy, Demand, and Water Savings* (ASHRAE 2014).

IPMVP addresses both building upgrade projects and new construction. The second and ASHRAE (2014) are oriented primarily toward building upgrade projects. The first and second references include many examples of M&V plans for specific building upgrade measures.

OPERATIONS AND MAINTENANCE

Operations and maintenance (O&M) is a critical element during the lifetime of a building to sustain high performance and proper IEQ and effectively manage proper and uninterrupted building operations. This is even more important for high-performance “green” buildings so they continue to perform “better” than they have traditionally done.

The operation plans focus mostly on maintaining equipment and systems to comply with specific (high) performance requirements. Modern control and automation systems provide an opportunity for monitoring the performance of systems as they relate to energy and water consumption, IAQ (ventilation rates and possibly CO₂ levels), thermal and visual comfort conditions, etc. A well-thought-out, written plan for operation would include the response actions to deviations of the indoor conditions from design or set points or if CO₂ levels exceed a predetermined value in a building zone. It is also recommended that the building operations team include an evaluation of energy consumption in a more detailed fashion than just the aggregated monthly utility bill. This evaluation should at least include monitoring of the energy consumption for key systems such as the HVAC or lighting, and preferably would be done on a finer level of detail to include the energy consumption of key equipment, such as a chiller.

While equipment and energy systems are key to building operations and performance, occupants’ interaction with building systems strongly influences system performance and building energy use. Understanding occupant actions such as thermostat adjustment, appliance usage, switching lights on/off, window opening/closing, or movement within the building are central to achieving the energy performance goals and acceptable IEQ. Disregarding occupant preferences that could be inferred from their presence, movement, and interactions in the operation practice leads to suboptimal building performance and higher occupant dissatisfaction with their indoor environment. The operation team should leverage occupant information related to building control systems to develop effective operation strategies aimed at reducing energy and water consumption while improving occupant comfort and productivity. An occupant-centric operation plan is even more crucial for the optimal performance of existing buildings to compensate for the often overlooked “occupant” element during building design. Such a plan should incorporate an occupant-centric control system that is capable of:

- occupant sensing for detection of occupancy information, occupant preferences, environmental control actions, and indoor environmental parameters, which are then transferred to the control system; and
- developing control algorithms and optimizing sequences of controls using occupant sensing information as feedback to improve building performance and occupants' experience.

The biggest challenge in implementing occupant-centric controls is the reluctance of operators and facility managers to adopt these new control systems and revise the existing control strategies. The team should be made familiar with the occupant-centric control scheme and its potential energy savings. Emphasis should be on reducing the knowledge gap related to data-driven analysis methodologies or key performance indicators; and their practical applications in designing optimal control strategies. Moreover, an effective communication channel between the operators and occupants must be in place to ensure that occupants' needs are being conveyed to the operations team through direct and frequent feedback.

An important key to successful O&M is the effective management of the personnel entrusted to operate and maintain the building. Operating staff should not be frequently rotated or change work shifts to avoid negatively affecting the familiarity of operating personnel with how the system(s) respond to varied inputs, especially across seasons. Frequent changes in outdoor service providers or changes in their internal organization point of contact can also create knowledge gaps, which can hamper the ability of the operating team to respond effectively to changes in operational needs or environment.

The number of O&M staff should be assessed beyond its overhead cost role, and consider a comparative cost analysis of possible implications that can help properly prioritize O&M personnel plans. For example, if you have a 200,000 ft² (20,000 m²) property of leasable space, how much does one additional staff member cost compared to a couple of additional hours or days of having the building offline? Accordingly, one needs to evaluate staffing levels not just in the context of their direct cost but also in the context of costs avoided.

Staff expertise and appropriate training are related to the number of staff, especially for complex building installations, new equipment, and so on. One approach to help reduce the training cost is to bundle a training program with other building owners that will spread the costs. Maintaining a high-performance team and knowledgeable staff is a rational way to maintain a high-building performance.

As the capabilities of automated controls, software, and computing power have increased exponentially and the cost of same has dropped precipitously, there is an increasing convergence in communication protocols, which has enhanced the ability to transfer data across platforms and to work with that data in meaningful ways. One of most useful methods to use that data is to develop rapid failure mode recognition and response (fault detection and diagnosis [FDD]) capabilities. There are several for-

mal maintenance approaches. *Preventive maintenance*, i.e., periodic maintenance at predetermined time intervals, can be used to detect and mitigate equipment degradation to extend its lifetime. Furthermore, accounting for the equipment condition when determining the maintenance needs (*conditioning monitoring*) can be more beneficial. *Proactive maintenance management* (PMM) programs incorporating FDD technologies are already available in the market, using computerized maintenance management systems (CMMS) based on computer-based control systems. Some aspects of this instantaneous feedback are directly incorporated into the manufacturer's equipment control systems. Some versions are being applied at the system level as an overlay or umbrella that ties things together. CMMS can enhance facility O&M and performance. CMMS tools can be used to capture data provided by FDD systems and provide a key platform for the development of proactive maintenance management programs.

Building commissioning is not just for new buildings. It can also greatly benefit existing buildings during occupancy and operation. Retrocommissioning (RCx) is performed as an initial commission of an existing building to capture lost savings from inefficient building management practices. Recommissioning a building after the initial RCx can further help to verify, improve, and document the building's performance. Following a continuous (ongoing) commissioning process can help maintain, improve, and optimize the building performance of existing buildings and all their systems and produce long-lasting benefits. ASHRAE offers several resources and guidance documents to support an effective commissioning process and support staff in developing and maintaining effective O&M practices.

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CHAPTER SIXTEEN

EMERGING TRENDS AND EPILOGUE

INTRODUCTION

This chapter highlights key areas that are taking the forefront in the buildings industry and the built environment. One is related to climate change and the push to “decarbonize buildings”—that is, to reduce the carbon footprint of a building through its whole life cycle. The need to the global temperature rise in check has long been the goal of climate activists, based on the issues mentioned in the sections below, with a goal of limiting this to 1.5°C (2.7°F) a common theme. Another area is increasing the resilience of buildings and the built environment in response to the impacts of climate change.

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report titled “Global Warming of 1.5° C,” which made a strong case for limiting the global temperature rise to no more than 1.5°C over preindustrial levels. According to the report, crossing that boundary would significantly increase the risk of negative outcomes for humans and other species, including water shortages; reduced food security; the spread of tropical diseases; and the intensification of poverty, migration, extreme weather events, and species loss and extinction.

For a two-thirds chance of limiting warming to 1.5°C, carbon dioxide (CO₂) emissions will need to reach net zero (i.e., sources and sinks of CO₂ must come into balance) by 2038. That probability is reduced to one-half if the time taken to achieve net-zero CO₂ emissions is extended ten years to 2048 (IPCC 2018). Given the severity of the consequences and the limited time remaining for humanity to make the requisite technological, economic, and political transformations, the United Nations (UN) and others organizations refer to climate change as “the defining crisis of our time” (UN 2020).

To tackle the climate crisis, top-down policies to reduce greenhouse gas (GHG) emissions are becoming more prevalent worldwide. Sweden started levying a carbon tax as part of its energy tax in 1991; currently, Sweden’s carbon tax

is the highest in the world. In the US, California has a cap-and-trade program, which was implemented in 2012.

As stated in Chapter 1 of this volume, residential and commercial buildings are directly or indirectly responsible for nearly 40% of CO₂ emissions in most developed countries. It will therefore be necessary for those of us in the building industry to make major changes in how we construct, operate, and disassemble buildings at the end of their useful lives if we are to rise to the challenge of addressing the climate crisis. ASHRAE recognized this challenge in the spring of 2021 by forming the Task Force on Building Decarbonization (TFBD). The TFBD focuses on developing and delivering decarbonization recommendations and practices for industry stakeholders and training and educational materials for the industry.

With all that in mind, the first part of this chapter is focused on emerging trends in the building industry that have the potential to reduce the CO₂ and other GHG emissions attributable to buildings throughout their life cycles to net zero by the end of the 2030s. Consideration is given to reducing the embodied carbon in building materials and achieving net-zero operational carbon. This chapter also considers emerging strategies to make buildings more resilient to the changing climate and the increased intensity of natural disasters that will result as humanity works to reduce its GHG emissions to net zero over the coming decades.

REDUCING EMBODIED CARBON

As the building industry is starting to make significant reductions in operational carbon emissions, emissions associated with embodied carbon are starting to get more attention. Embodied carbon of a building is the aggregate of all GHG emissions associated with raw material extraction, processing, manufacturing, transportation, construction, and installation of all building components prior to operation. Some practitioners also include some aspects of the building operational stage emissions in this category, such as the replacement of equipment, refrigerant leakage, and end-of-life stage emissions (disassembly, demolition, and disposal).

According to Architecture 2030, embodied carbon is responsible for 11% of the global GHG emissions, where concrete, iron, and steel account for a significant portion (Architecture 2030). For the HVAC&R industry, the key focus is on refrigerants. Project Drawdown lists refrigerant management as one of the top 10 solutions for mitigating the climate crisis (Drawdown 2017). In December 2020, the California Air Resource Board approved stronger restrictions on the use of high global warming potential (GWP) refrigerants to help reduce hydrofluorocarbon (HFC) emissions by 40% of before-2013 levels by 2030 (CARB 2020).

Due to growing industry demands, environmental product declaration (EPD) data for building core and shell materials are increasing in availability. Architects and structural engineers are playing an important role in demanding products with a reduced carbon footprint. However, there is a lack of EPD data for building mechanical, electrical, and plumbing (MEP) products. Despite the lack of data,

MEP consulting engineers are exploring innovative ways to design (and sometimes reuse) building systems with life-cycle impact in mind.

Structural and Architectural Materials. Some of the strategies that are currently being explored for reducing embodied carbon in structural and architectural materials are listed below:

- adaptive reuse of existing buildings
- reuse of building components
- increase in structural efficiency and optimization to reduce total volume of structural materials
- comparison of environmental product declarations (EPD) for products to identify lower carbon options
- low-carbon structural materials (e.g., green concrete, recycled steel, and mass timber)
- conscious design with reduced volume of carbon intensive materials (e.g., aluminum, plastic, etc.)
- increase in exposed flooring and exposed structural members
- design for easier disassembly to minimize waste at end of product life

Refrigerant Management. Some of the strategies that are currently being explored for refrigerant management are

- consideration of natural refrigerants such as ammonia (R-717), carbon dioxide (R-744), propane (R-290), hydrocarbons, water (R-718), and air (R-729)
- use of low-GWP refrigerants
 - Refrigeration: GWP below 150 for refrigeration facilities
 - Air conditioning: Refrigerants with GWP below 750, such as R-1234ze, R-1234yf, and R-1233zd for air-conditioning equipment
- designing HVAC&R systems with reduced refrigerant charge
- consideration of providing automatic refrigerant leakage detection and recovery systems
- proper installation of refrigerant-based systems by registered installers
- periodic maintenance of refrigerant-based systems to mitigate leakage

NET-ZERO OPERATIONAL CARBON

Achieving net-zero operational carbon by 2030 is the ambitious goal of the next decade (AIA 2030). Net-zero operational carbon refers to buildings operating with zero fossil fuel use. Historically, commercial buildings have relied on fossil fuels for building heating and domestic hot-water heating. Building cooling does not necessarily result in fossil fuel use since most cooling equipment is powered by electricity; however, fossil fuels are generally used in the production of power by the utility. Therefore, opportunities to shift away from fossil fuel use should be

sought out, regardless of where the fuel is used. Building MEP engineers cannot reduce the operational carbon used by utilities, but they can control the amount of electricity and fossil fuel used with lighting, plug loads, cooling, and heating.

At the building level, there is a two-step approach to achieving net-zero operational carbon. It starts with reducing the building energy demand, followed by employing renewable energy technologies for heating, cooling, and power generation.

Grid-Sensitive Design. Solar photovoltaic (PV) power generation devices has increasingly been used on projects in the United States and worldwide. Because the power generated by PV systems varies with solar irradiance, PV systems are typically connected to the grid to feed or receive electricity as needed to satisfy load demand profiles throughout the day. Solar-generated electricity is low in the morning, peaks around noon, then drops in the afternoon. At the utility level, the electricity demand varies with the consumer but typically rises in the early morning, drops by mid-afternoon, then peaks even more in the evening. Often, more electricity is generated by the PV system during the peak than peak load demand. This mismatch between demand and supply creates grid stability and reliability challenges with grid-connected PV systems. Utilities must figure out how to dispatch resources to match demand and supply. One way to improve the grid stability is to use battery energy storage with electric-charging vehicles to stop and utilize the excess energy from flowing into the grid at solar peak time and reduce the high electricity demand at night when solar power is absent.

All Electric Buildings with No Natural Gas. Reducing the natural gas use for building heating and domestic hot-water heating has been an ongoing endeavor in the heating world for MEP engineers. At first, steam and high-temperature hot-water boilers with mediocre efficiencies were used for building heating. Then condensing boilers using low-temperature hot-water started to emerge. These boilers have better efficiencies, up to 96% in some situations, which reduces natural gas use. Heat pumps and heat recovery chillers are the newest alternatives for generating heat without using natural gas (Witchger and Huss 2021). With heat recovery chillers, the consideration is for system integration to coordinate the heating and cooling loads since there must be an instantaneous balance of heating and cooling for these to work. In large applications, in addition to saving natural gas, heat recovery chillers also save water that cooling towers might otherwise use.

Renewable Natural Gas. Renewable natural gas is biogas processed to high purity standards from renewable sources such as landfills, livestock operations, wastewater treatment, and other biomass sources (USDE n.d.). Typically, in the US, renewable natural gas is used in vehicles running on compressed natural gas or liquefied natural gas, but it can also be used to generate electricity via gas turbines (mostly biogas from landfills). In Europe, biogas has similar uses, plus it can also be delivered to help supplement the local or national gas grids.

BUILDING RESILIENCE

According to Lloyd's of London, damages from weather-related losses increased fourfold from about \$50 billion per year in the 1980s to about \$200 billion per year in the 2010s. Lloyd's attributes these losses to climate change and suggests that these losses are likely to increase as global temperatures continue to rise (The Guardian 2014).

Incorporating *resilience*—which the AIA defines as *inherent durability or flexibility*—into building designs is increasingly important to minimize the risks associated with climate-change-related hazards (AIA n.d.). Resilience strategies depend to a large extent on geographical location. On the coast of Florida, where storms and hurricanes are intensifying, these strategies include adding resistance to wind-driven rain and flooding. In the mountains of Colorado, where rising temperatures result in more frequent and intense wildfires, resilience strategies include using fire-resistant building materials and establishing “defensible space” around the building. Adding electric generation and storage capacity plus associated islanding controls is essential in all geographical locations to maintain building operations in case of grid failure due to extreme weather, wildfire, or other disruptive events. This can be done at either the building level or the campus or community level as a “microgrid” (Strahl et al. 2016).

In addition to planning for hazards driven by climate change, architects and engineers to recognize that climatic design conditions are very likely to change over the course of a building's lifetime. A recent study found that for Europe, China, southeast Asia, the eastern United States, and southern Australia, dry-bulb temperatures have been rising by 0.36°F to 1.08°F (0.6°C to 1.8°C) per decade over the past three decades (Thevenard and Shephard 2014). AIA defines *adaptation* as *accommodating needs throughout service life* (AIA n.d.). Architects and engineers should anticipate regionally specific climatic changes over the expected lifetime of the building and incorporate adaptive strategies into their designs, such as leaving space for additional cooling equipment in the central plant.

Climate change also contributes to the incidence of epidemics and pandemics (ProPublica 2020). Adaptive strategies to minimize infection risk in buildings during disease outbreaks depend on the method of transmission. Airborne disease transmission can be controlled—at least to some extent—by increasing outdoor air ventilation flow rates and improving filtration efficiency (ASHRAE 2022). Therefore, potential adaptive strategies could include ensuring that all occupied spaces can be provided with 100% outdoor air if necessary and that filter racks can accommodate MERV 13 or higher level filtration. Surface disease transmission can be controlled—again, to some extent—by frequent surface cleaning. An adaptive strategy, in that case, would be to specify easily cleanable interior surfaces. Testing surfaces for pathogens on a regular basis is an operational strategy that could help keep building occupants safe (ABC News 2020). While it's not possible to antici-

pate what types of disease outbreaks might occur over the life of a building, building designers and operators can include and plan for adaptive strategies to mitigate disease transmission in the future.

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APPENDIX

BUILDING-TYPE-SPECIFIC GREENTIPS

INTRODUCTION

The GreenTips contained in the chapters of this book focus on a specific technology or design concept that could be considered for a high-performance building. However, one can also compile a list of recommendations related to a specific building type. Similar to the building-type-specific Advanced Energy Design Guides, this appendix contains a compilation of several building-type-specific set of GreenTips.

The intent of the GreenTips in this appendix is to give the design engineer a general idea of concepts that are common to certain building types. The focus is generally on HVAC-related design, although it should be apparent that there is a multitude of design choices that result in a truly green building.

ASHRAE GreenTip A-1

Performing Arts Spaces

GENERAL DESCRIPTION

Performing arts spaces include dance studios, black box theaters, recital halls, rehearsal halls, practice rooms, performance halls with stages and fixed seating, control rooms, back-house spaces, and support areas.

HIGH-PERFORMANCE STRATEGIES

Acoustics

1. Place less acoustically sensitive spaces around more sensitive spaces as acoustic buffers.
2. Work closely with the acoustic consultant, structural engineer, architect, and construction manager to integrate strategies that eliminate the distribution of vibration and equipment noise from the HVAC systems to the performance spaces.
3. Understand the different conditions for noise criteria.
4. Locate equipment as far away from acoustically sensitive spaces as practical. This includes rooftop air-handling units, which should not be installed above acoustically sensitive rooms.
5. The architect needs to provide enough space for the HVAC engineer to design duct systems to minimize noise transfer to acoustically sensitive spaces. Sound levels can be attenuated by the following: lowering air turbulence through proper duct design with lowered velocities, smooth bends, and preferred duct aspect ratios of 3:1 or lower; gradual diameter transitions; placing of terminal devices as far from elbows and takeoffs as possible; and designing appropriately long duct length leads to and from fans and bends. Absorptive liners can be added to attenuate high-frequency noise. These measures require space. Fan vibration transmission is reduced by flexible duct connectors, applying dampening lagging to ducts, low-pressure drop sound attenuators and silencers, or fiberglass lined plenums at least ten times the duct cross-sectional area. For high-frequency noise, noise-cancellation technology is used.

6. Do not route piping systems through or above spaces that are acoustically sensitive.

Energy Considerations

1. Consider using demand-controlled ventilation for high-occupancy spaces.
2. Consider using heat recovery for spaces served by air-handling units (AHUs) with large amounts of outdoor air component. ANSI/ASHRAE/USGBC/IES Standard 189.1 Section 7 can serve as a guide for deciding to do energy recovery ventilation.
3. Consider strategies that allow the significant heat gain from the theatrical lighting equipment to stratify, rather than handle all of the equipment heat gain within the conditioned space zones in the building.
4. Because of the significant variation in the cooling load throughout the day, incorporating a thermal energy storage system into the central plant design will reduce the size of the chiller plant equipment, saving capital costs and energy and operational costs.
5. Consider the use of desiccant wheels to remove moisture to avoid the need for reheat in performance halls.

Occupant Comfort

1. Consider low-velocity underfloor air distribution (UFAD) strategies for large halls with fixed seating. High-velocity air entering under the feet of occupants causes discomfort due to convective heat losses, whereas low-velocity air should not provide such discomfort.
2. Consider separating stage-area air distribution from seating-area air distribution in halls.
3. Consider humidification control for all spaces where musicians and vocalists will practice, store musical instruments or sensitive equipment, and perform.

KEY ELEMENTS OF COST

1. If properly integrated, an underfloor air distribution system (UFAD) should not add significant capital costs to the project.
2. Heat recovery strategies should be assessed using life-cycle analyses. All components of the strategy must be taken into account, including the negative aspects such as adding fan static pressure and, therefore, using more fan energy when enthalpy wheel, desiccant wheel, or heat pipe strategies are considered.

SOURCES OF FURTHER INFORMATION

ASHRAE. 2013. *UFAD Guide: Design, Construction and Operation of Underfloor Air Distribution Systems*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2019. Chapter 49, “Noise and Vibration Control.” In *ASHRAE Handbook—Applications*. Peachtree Corners, GA: ASHRAE.

ASHRAE. 2021. Chapter 8, “Sound and Vibration.” In *ASHRAE Handbook—Fundamentals*. Peachtree Corners, GA: ASHRAE.

ASHRAE GreenTip A-2

Health Care Facilities

GENERAL DESCRIPTION

Healing patients is the primary mission of health care organizations, and the facilities where they practice or deliver those services must share and support that same mission. Health care facilities represent a wide range of space types that can consist of some doctors' offices that involve little to no special infrastructure, to research and specialty hospitals and diagnostic centers that involve an array of specialized medical equipment and supporting infrastructure components that cost into the tens of millions of dollars. Certainly, energy use and other sustainability features are significantly impacted by the type of health care facility.

Health care facilities and their systems must be flexible to accommodate remodeling and changes to the delivery of health care services, especially with anticipated changes to insurance and reimbursement. Changes are also driven by the advancement of medical technology and practices. Sustainable practices that are selected need to be capable of changing with the changes in the facility. The degree of flexibility is often an economic consideration. Another key health care consideration is system reliability and uptime. When sophisticated systems are evaluated for installation, care should be taken to ensure excellent equipment reliability and ease of maintenance.

The tips provided here are based on the common inpatient hospital facility considerations. Many outpatient facilities are similar to other office building types, and their green HVAC tips are likely to apply for some of these health care facilities. Certainly, for some facilities, such as outpatient surgery facilities, it will be helpful to also review the office buildings (GreenTip #6 in this Appendix).

Design teams must have extensive inpatient facility experience in addition to including green/sustainable experts. Many of the sustainable certification programs, guidebooks, and references promote an integrated design and delivery approach to incorporate sustainable features. By using an integrated design team of knowledgeable and experienced professionals who will carefully plan and

execute sustainable options, the time, cost, and redesign will be minimized.

HIGH-PERFORMANCE STRATEGIES

The suggestions provided are focused on the uniqueness of inpatient health care facilities. They do not represent the vast array of sustainable ideas and tips that apply generally to all building types. In addition, the recommendations are more focused on those that impact HVAC. For recommendations and tips outside of HVAC, a few sources include US Green Building Council's LEED for Healthcare, Green Guide for Healthcare, ANSI/ASHRAE Standard 189.3, *Design, Construction, and Operation of Sustainable, High-Performance Health Care Facilities*, and ANSI/ASHRAE/ASHE Standard 170-2021, *Ventilation of Health Care Facilities*. Another organization to investigate is Practice Greenhealth, and other publications to consider are *GreenSource: The Magazine of Sustainable Design, Health Facilities Management*, and *HERD (Health Environments Research and Design Journal)*.

Safety and Infection Control

1. Consider high-efficiency particulate air (HEPA) filtration for all air-handling equipment serving the facility. Double HEPA filters may be used to compensate for lower airflow rates.
2. Consider air distribution strategies in operating rooms and trauma rooms that zone the spaces from most clean to least clean. Start with the cleanest zone being the operation/thermal plume location at the patient (the volume of air directly above the patient which is warmed due to the patient's body temperature), then the zone around the doctors, then the zone around the room, and finally, the zone outside the room.
3. Pressurize rooms consistent with American Institute of Architects (AIA) and/or ASHRAE guidelines (e.g., pressurized operating rooms, reduced pressure in rooms where patients are contagious, and installing adjacent vestibules to reduced pressure rooms to further control transmission of airborne pathogens).

4. Consider providing air exchange rates in excess of AIA guidelines in operating rooms, intensive care units, isolation rooms, trauma rooms, and patient rooms.
5. Provide redundancy of equipment for fail-safe operation and optimal full- and part-load energy-efficient operation.
6. Model intake/exhaust location strategies to ensure no reintroduction of exhaust into the building.
7. If adding atria containing plants, ensure that soils and plants are free of potential contaminants and include in the operations manuals the procedures to maintain as such.
8. Follow the steps outlined in ANSI/ASHRAE Standard 188-2021 *Legionellosis: Risk Management for Building Water Systems*. Take steps to prevent contamination from Legionella, especially for patients with compromised immune systems, to include the following.
 - Carefully design potable water systems to prevent Legionella growth in piping. Biofilms and scale can develop in piping where water may sit in dead legs or in piping of areas closed off for some reason. Limit dead legs to five pipe diameter lengths. Maintain hot water tanks at temperatures of at least 140°F (60°C). Legionella thrive and multiply when held at temperatures ranging from 95°F to 115°F (35°C to 46°C).
 - Maintain decorative fountains and cold water storage tank water temperatures below 68°F (20°C).
 - Use potable, noncirculated water at or below 68°F (20°C) for cold-water humidifiers.
 - Design piping systems to allow complete system flushing.
 - Specify point-of-use fittings to minimize bacteria growth and to regulate for safe, nonscalding shower temperatures.
 - Caution owners and operators of the importance of maintaining safe levels of water treatment chemicals for cooling towers, hot tubs, whirlpool baths, fountains, and swimming pools.

Energy Considerations

Hospitals typically have an Energy Utilization Index (EUI) much greater than that of office buildings. According to the World Health Organization (WHO), the use of electricity in the United States

adds more than \$600 million in direct health costs and more than \$500 billion in indirect costs. US hospitals spend 1% to 3% of their operating budget on energy, or around 15% of net operating income (DOE 2009). Reducing energy costs can play a significant role in a hospital's organization profit or net operating income. Keep in mind, for a hospital operating on a 4% margin, it takes \$25 of gross revenue to generate \$1 of profit or net operating income. Every dollar of energy savings is a dollar added to the profit or net operating income. According to Target 100 and ASHRAE's *Advanced Energy Design Guide for Large Hospitals*, it is possible to reduce a new hospital's energy use by 50% or 60% over the minimum requirements to meet ANSI/ASHRAE/IESNA Standard 90.1-2004. Typically, the amount of energy savings comes down to an economic decision. Life-cycle economic cost analysis is recommended, including maintenance of the various components and systems. Often, the highest savings are achieved with systems that have fairly sophisticated equipment and more complicated operating control sequences. Appropriate assumptions must be applied to the cost of maintenance. Equally important, the design team needs to clearly outline to the building operators the expected maintenance requirements as part of the system selection process. This is an area commonly omitted from of the systems selection and economic analysis.

With the amount of energy savings potential, there are a significant number of options to consider. Energy modeling is recommended to help sort out the interplay of building envelope, lighting, HVAC, and service hot-water energy-saving options. Design teams and the health care operational staff should consider developing energy usage targets and goals at the onset of the project. Those will be useful in guiding the expectations and decision making.

For facilities to realize the potential of any design, three key steps are needed. First, ensure the systems are operating as intended. The design and construction team needs to functionally test and prove all systems are operating per the intent. Following occupancy, it should be an expectation that additional system shakedown will be needed. The actual operating conditions, both in terms of occupancy and facility operations as well as varying weather conditions, will uncover additional issues from that of the

functional testing preoccupation that will need to be addressed. Second, a real commitment to monitoring, benchmarking, and having a continuous improvement process in place is equally important to optimize the energy-saving potential. Third, which is really a sub-part of the second idea, is a commitment to budget and fund proper maintenance over the life of the buildings and systems.

Two health-care-specific resources for energy-saving ideas for building envelope, lighting, HVAC, and service water heating are outlined for the various climate zones in the United States are part of the *Advanced Energy Design Guides* (AEDG) series:

- *Advanced Energy Design Guide for Small Hospitals and Health-care Facilities* (30% better than ANSI/ASHRAE/IES Standard 90.1-1999).
- *Advanced Energy Design Guide for Large Hospitals* (50% better than ANSI/ASHRAE/IES Standard 90.1-2004). Large hospitals being defined as facilities over 100,000 ft² (9300 m²).

The AEDGs provide case studies and how-to tips for implementing the various suggested strategies. Two other excellent studies that have been referenced already are from the work done through the University of Washington's Integrated Design Lab. See the report “Target100! Envisioning the High Performance Hospital: Implications for A New Low Energy, High Performance Prototype” (2010) and review the website Targeting 100! website (Reference listed at the end of this GreenTip). There are two critical observations from these reports that are consistent from the modeling results used in the two AEDG for health care facilities:

- Space heating (reheat) because of the mandatory air exchange requirements is the largest single energy use area.
- There is a significant amount of heat rejection from a variety of processes.

Energy recovery strategies that capture the heat which would otherwise be lost to use for space heating and water heating are great opportunities to explore. Recent modification to ASHRAE Standard 90.1 make the use of energy recovery more prevalent, and use the requirements of that Standard and Standard 189.1, Section 7

for direction on when energy recovery should be applied. The references provide a variety of ways that can be done. Other recommendations include using (1) variable-air-volume (VAV) systems in noncritical spaces working in conjunction with lighting occupancy sensors and (2) dedicated outdoor air systems (DOAS).

Occupant Comfort

Energy considerations are important, but an overall well-designed green health care facility will also include focus on other factors. These factors are addressed with the following recommendations for occupant comfort:

1. Acoustics of systems and spaces must be designed with patient comfort in mind.
2. Daylight and views should be provided while minimizing the HVAC load impact of these benefits.
3. Provide individual temperature control of patient rooms with the capability of adjustment by patient.
4. Building pressurization relationships/odor issues should be carefully mapped and addressed in the design and operation of the building.

KEY ELEMENTS OF COST

1. HEPA filtration costs are significant in both first cost and operating costs. The engineer should work closely with the infection control specialists at the health care facility to determine cost/benefit assessment of the filtration strategies.
2. Heat recovery strategies should be assessed using life-cycle analyses. All components of the strategy must be taken into account, including the negative aspects, such as adding fan static pressure and, therefore, using more fan energy when heat wheel or heat pipe strategies are considered. Again, use ASHRAE Standards 90.1 and 189.1 for design guidance (or code compliance).

SOURCES OF FURTHER INFORMATION

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- FGI. 2018c. *Guidelines for Design and Construction of Outpatient Facilities*. <https://fgiguideguidelines.org/guidelines/2018-fgi-guidelines/>.
- FGI. 2018d. *Guidelines for Design and Construction of Residential Health, Care and Support Facilities*. <https://fgiguideguidelines.org/guidelines/2018-fgi-guidelines/>.
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- NFPA. 2021. *NFPA 99: Health Care Facilities Code*. Quincy, MA: National Fire Protection Agency.

Online Resources

- Health Facilities Management
www.hfmmagazine.com/subscribe.
- Health Environments Research and Design Journal
<http://journals.sagepub.com/home/HER>
- Practice Greenhealth
<https://practicegreenhealth.org/>.
- Target 100!
<http://idlseattle.com/t100/>.
- The Center for Health Design
www.healthdesign.org.
- WHO. 2009. WHO Guideline 2009–Natural Ventilation for Infection Control in Health-Care Settings. World Health Organization, Geneva, Switzerland.
http://www.who.int/water_sanitation_health/publications/natural_ventilation.pdf.

ASHRAE GreenTip A-3

Laboratory Facilities

GENERAL DESCRIPTION

Laboratory facilities are infrastructure intensive and include many different types of spaces. The HVAC systems for these different types of spaces must be designed to address the specific needs of the spaces being served. The first considerations should always be safety and system redundancy to ensure the sustainability of laboratory studies. Life-cycle cost analysis for different system options is critical in developing the right balance between first and operating costs.

HIGH-PERFORMANCE STRATEGIES

Safety

1. Design fume hoods and associated air distribution and controls to protect the users and the validity of the laboratory work.
2. Pressurize rooms to be consistent with the *ASHRAE Laboratory Design Guide*, Second Edition (ASHRAE 2015) and any other code-required standards. Use building pressurization mapping to develop air distribution, exchange rate, and control strategies.
3. Optimize air exchange rates to ensure occupant safety while minimizing energy usage.
4. Design storage and handling exhaust and ventilation systems for chemical, biological, and nuclear materials to protect against indoor pollution, outdoor pollution, and fire hazards.
5. Model intake/exhaust location strategies to ensure that lab exhaust air is not reintroduced back into the building's air-handling system.

Redundancy

1. Consider a centralized lab exhaust system with a redundant ($n + 1$) exhaust fan setup.
2. Redundant central chilled-water, steam, or hydronic heating, air-handling, and humidification systems should be designed for

fail-safe operation and to optimize full-load and part-load efficiency of all equipment.

Energy Considerations

1. Recent modification to ASHRAE Standard 90.1 make the use of energy recovery more prevalent, and use the requirements of that Standard and Standard 189.1, Section 7 for direction on when energy recovery should be applied. Carefully design heat recovery for hazardous spaces.
2. Use VAV systems to minimize air exchange rates during unoccupied hours.
3. Consider the use of computational fluid dynamics (CFD) and other modeling software to establish safe air change rates for particular laboratory needs and follow up with monitoring to verify its effectiveness. Consider low-flow fume hoods with constant-volume controls where this concept can be properly applied.
4. Look for opportunities for sharing spaces to reduce conditioned space volume, (e.g., preparation areas and laboratory support spaces could be shared between labs). The number of laboratories can also be reduced if work schedules can be shifted and the same space can be used through the day and night.
5. Isolate and minimize the size of laboratory space for those processes requiring greater airflow for safety.

Occupant Comfort

1. Air systems should be designed to allow for a collaborative working environment. Acoustic criteria should be adhered to in order to maintain acceptable levels of noise control.
2. Daylight and views should be considered where lab work will not be adversely affected. When appropriate, glazed walls to other spaces or hallways will permit views without requiring the laboratory to be on an outside wall.

KEY ELEMENTS OF COST

1. Heat recovery strategies should be assessed using life-cycle analyses. All components of the strategy must be taken into account, including the negative aspects, such as adding fan static pressure and, therefore, using more fan energy when strategies using enthalpy wheels, desiccant wheels or heat pipes are considered. Again, use Standards 90.1 and 189.1 for design guidance.
2. Low-flow fume hoods should be evaluated considering the impact of reducing the sizes of air-handling, heating, cooling, and humidification systems.

SOURCES OF FURTHER INFORMATION

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- ASHRAE. 2019. *ASHRAE Handbook—HVAC Applications*. Chapter 16, Laboratories. Peachtree Corners, GA: ASHRAE.
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Online

Labs 21, Environmental performance criteria
<http://labs21.lbl.gov/EPC/intro.htm>.

ASHRAE GreenTip A-4

Student Residence Halls

GENERAL DESCRIPTION

Student residence halls are made up primarily of living spaces (e.g., bedrooms, living rooms, kitchen areas, common spaces, study spaces, and data/communications closets). Most of these buildings also have central laundry facilities, assembly/main lobby areas, and central meeting/study rooms. Some of these spaces also include classrooms, central kitchen and dining facilities, and other specialty facilities. Many of the strategies outlined below can also be applied to hotels and multiunit residential complexes, including urban luxury condominium developments.

HIGH-PERFORMANCE STRATEGIES

Energy Considerations

1. Recent modifications to ASHRAE Standard 90.1 make the use of energy recovery more prevalent, and use the requirements of that Standard and Standard 189.1, Section 7 for direction on when energy recovery should be applied.
2. Use VAV systems with economizers or induction systems for public/common spaces and consider VAV also for sleeping areas.
3. Specify that the static pressure set point for the central supply fans be based on the most open VAV box position.
4. Specify demand-controlled ventilation for areas with variable use (i.e., study spaces, lounges, meeting rooms, etc.), following the requirements specified in ASHRAE Standards 90.1 and 189.1.
5. Use natural ventilation (operable windows) and hybrid natural ventilation strategies.
6. Use variable-speed drives for chilled-water pumps and HVAC fans, including fan-coil units.
7. Consider using a ground-source heat pump (GSHP) system.
8. Consider using skylights in corridors for daylighting. Also integrate electrical lighting with daylighting through controls.

Occupant Comfort

1. Systems should be designed to appropriately control noise in occupied spaces.

2. Daylight and views should be optimized, while minimizing load impact on the building.
3. Consider providing occupant control in all dorm rooms. However, provide overrides for the case when a window is open.

KEY ELEMENTS OF COST

1. While there is a premium to be paid in first cost for energy control measures (ECM), many utility companies have energy rebate programs that make this concept acceptable, even on projects with tight budgets.
2. Heat recovery strategies should be assessed using life-cycle analyses. All components of the strategy must be taken into account, including the negative aspects such as added fan pressure and, therefore, using more fan energy when enthalpy wheel, desiccant wheel, or heat pipe strategies are considered. Again, use Standards 90.1 and 189.1 for design guidance.
3. Hybrid natural ventilation strategies could be used, such as operable windows, properly designed vents, using the Venturi effect to optimize natural airflow through the building, and the shutdown of mechanical ventilation and cooling systems during ambient temperature ranges between 60°F and 80°F (16°C and 27°C). These measures will significantly reduce operating costs. The costs of the operable windows and vents will need to be weighed against the energy savings.

REFERENCES AND RESOURCES

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SOURCES OF FURTHER INFORMATION

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ASHRAE GreenTip A-5

Athletic and Recreation Facilities

GENERAL DESCRIPTION

Athletic and recreational spaces include natatoriums, gymnasiums, cardio rooms, weight-training rooms, multipurpose rooms, courts, offices, and other support spaces.

HIGH-PERFORMANCE STRATEGIES

Energy Considerations

1. Follow the requirements of Standard 189.1 for the inclusion of demand-controlled ventilation for high-occupancy spaces.
2. Similarly, follow Standard 189.1 for the determination of when heat recovery for spaces served by AHUs with a significant amount of outdoor air component.
3. Consider strategies that allow the significant heat gain in high-volume spaces to stratify, rather than handling all of the heat gain within the conditioned space zones in the building.
4. Consider heat recovery/no-mechanical-cooling strategy for the pool area in moderate climates.
5. Incorporate occupied/unoccupied mode for large locker room and toilet room areas to set back the air exchange rate in these spaces during unoccupied hours and save fan energy.
6. Consider heating pool water with waste heat from pool dehumidification system.
7. Consider using a water-based geothermal heat pump system (GHPS).

Occupant Comfort

1. Consider CO₂ sensors or other mechanisms to determine the level of occupancy in all spaces that have infrequent, dense occupancy.
2. Consider high-occupancy and low-occupancy modes for air-handling equipment in gymnasiums using a manual switch and variable-frequency drives.

3. Consider hybrid natural ventilation strategies in areas that do not have humidity control issues (e.g., pools, training rooms).

KEY ELEMENTS OF COST

1. The pool strategy, item 6 in the Energy Considerations, should reduce first cost and operating costs.
2. Heat recovery strategies should be assessed using life-cycle analyses. All components of the strategy must be taken into account, including the negative aspects, such as adding fan static pressure and, therefore, using more fan energy when strategies using enthalpy wheels, desiccant wheels or heat pipes are considered. The location of outdoor air intakes and exhaust outlet points should be a factor in the original building design to minimize ducting length to get to the heat recovery units.
3. Demand-controlled ventilation adds minimal first cost and often provides paybacks in one to two years.

SOURCES OF FURTHER INFORMATION

- ASHRAE. 2019. Chapter 5, Places of Assembly, and Chapter 7, Educational Facilities. In *ASHRAE Handbook—HVAC Applications*. Peachtree Corners, GA: ASHRAE.
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ASHRAE GreenTip A-6

Commercial Office Buildings

GENERAL DESCRIPTION

Commercial office buildings are made up primarily of office spaces, meeting rooms, and central core facilities such as toilet rooms, storage space, and utility rooms (including telephone and data). Some of these spaces also include central kitchen and dining facilities. The strategies outlined below can also be applied to most large-scale commercial office buildings.

HIGH-PERFORMANCE STRATEGIES

Energy Considerations

1. Consider a dedicated outdoor air system (DOAS) with total energy recovery (TER).
2. Use high-efficiency fan-coil units or chilled-beam/induction systems in conjunction with the DOAS concept.
3. Use natural ventilation and hybrid natural ventilation strategies.
4. Use energy conservation measures (ECM) for fan-coil units.
5. Use ground source heat pumps (GSHP) where feasible.
6. Consider using underfloor air distribution (UFAD).
7. Develop zone temperature adjustment strategies to allow for demand response programs during peak demand periods.
8. Include occupancy sensor control capability to shut off receptacle controlled plug loads when practical.
9. Incorporate energy-efficient lighting strategies that share integrated occupancy controls with the HVAC system.

Occupant Comfort

1. Systems should be designed to appropriately control noise in occupied spaces.
2. Daylight and views should be optimized, while minimizing heating and cooling load impact on the building.

KEY ELEMENTS OF COST

1. Although there is a premium to be paid in first cost for ECMs, many utility companies have energy rebate programs that make this concept acceptable, even on projects with tight budgets.

2. Energy recovery, UFAD, and DOAS strategies should be assessed using life-cycle analyses. Ventilation energy recovery should be evaluated based on the requirements of IgCC/189.1. All components of the strategy must be taken into account, including the negative aspects, such as adding fan static pressure and, therefore, using more fan energy when heat wheel or heat pipe strategies are considered.
3. Hybrid natural ventilation strategies could be used such as using operable windows, properly designed vents, the Venturi effect to optimize natural airflow through the building, and the shutdown of mechanical ventilation and cooling systems during ambient temperature ranges between 60°F and 80°F (16°C and 27°C). This will significantly reduce operating costs. The costs of the operable windows and vents will need to be weighed against the energy savings.

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ASHRAE GreenTip A-7

K-12 School Buildings

GENERAL DESCRIPTION

K-12 school buildings are made up primarily of classrooms, gymnasiums, libraries, an auditorium, a central kitchen, and dining facilities. (Also see GreenTip #5 on athletic and recreation buildings and GreenTip #6 on commercial office buildings.)

HIGH-PERFORMANCE STRATEGIES

Energy Considerations

1. Follow IgCC/189.1 for the determination of when heat recovery for spaces served by AHUs with a significant amount of outdoor air component.
2. Follow the guidance in ASHRAE's Advanced Energy Design Guide for K-12 School Buildings.
3. Use dedicated outdoor air systems (DOASs) with energy recovery combined with fan coils or chilled-beam/induction systems for spaces.
4. Use natural ventilation and hybrid natural ventilation strategies.
5. Use ECMs for fan-coil units.
6. Use GSHPs where feasible.

Occupant Comfort

1. Systems should be designed to appropriately control noise in occupied spaces.
2. Daylight and views should be optimized while minimizing load impact on the building.

KEY ELEMENTS OF COST

1. Although there is a premium to be paid in first cost for energy conservation measures (ECM), many utility companies have energy rebate programs that make this concept acceptable, even on projects with tight budgets.
2. Energy recovery strategies should be assessed using life-cycle analyses. All components of the strategy must be taken into

account, including the negative aspects, such as adding fan static pressure and, therefore, using more fan energy when heat wheel or heat pipe strategies are considered. The location of outdoor air intakes and exhaust outlet points should be a factor in the original building design to minimize ducting length to get to the heat recovery units.

3. Hybrid natural ventilation strategies could be used, such as using operable windows, properly designed vents, using the Venturi effect to optimize natural airflow through the building and the shutdown of mechanical ventilation and cooling systems during ambient temperature ranges between 60°F and 80°F (16°C and 27°C). These actions will significantly reduce operating costs. The costs of the operable windows and vents will need to be weighed against the energy savings.

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ASHRAE GreenTip A-8

Data Centers

GENERAL DESCRIPTION

Data centers are energy-intensive buildings using 20 W/ft² (215 W/m²) to greater than 1000 W/ft² (10 764 W/m²). They support information technology (IT) spaces, electronic equipment, and electronic communications. These facilities are known by many different names: data centers, computer rooms, server rooms, telecom rooms, datacom, or information technology equipment (ITE) rooms. (The term ITE will be used in the remainder of this article to designate these spaces.) The HVAC systems for data centers can be as diverse as the data centers themselves and include various forms of air or liquid cooling. While the first considerations must be reliability of the infrastructure and IT systems to minimize the risks and losses associated with outages, it is also necessary to minimize energy consumption. To this end, many strategies of redundancy, operational practice, and service diversity are used, along with green practices such as outdoor air, free cooling, air containment, and automatic control. In the end, the purpose of a data center is always to provide a suitable environment (power, cooling, and security) for the electronic equipment in an energy-efficient, scalable, and reliable manner.

HIGH-PERFORMANCE STRATEGIES

Reliability and Scalability

1. Install only the necessary redundancy to meet the owner's reliability requirements; optimize redundancies.
2. Use zoning strategies for different types of ITE based on power densities and preferred cooling strategies for each type.
3. Rightsize the cooling and power infrastructure for the IT loads with sufficient stages to operate at best efficiency points as loads change.
4. Design scalable infrastructure that can change with the rapid changes in ITE and its software (data center occupants).

Energy Considerations

The first step is to review and follow ASHRAE Standard 90.4-2019, *Energy Standard for Data Centers*. Beyond that, consider the following.

1. Use air management best practices (e.g., separate hot/cold air-streams, maximize temperature differences across HVAC heat exchangers, eliminate air leaks, use preferred ITE equipment cooling classes, etc.) to achieve ITE inlet temperature uniformity as described in ASHRAE's fifth edition of *Thermal Guidelines for Data Processing Environments* (2021).
2. Install monitoring and control equipment (building management systems) to measure efficiency and performance of HVAC as well as IT systems.
3. Install data center infrastructure management (DCIM) systems to measure and manage ITE and infrastructure systems more holistically.
4. Use cooling plant best practices (e.g., VFDs, optimize chiller/condenser supply temperatures, chilled water vs. DX, etc.).
5. Consider liquid cooling when heat loads or total cost of ownership (TCO) requirements demonstrate energy savings.
6. Avoid high-energy-consuming humidity controls such as reheat. Control humidity using dew point sensing. Consider alternatives such as desiccant dehumidification and adiabatic humidifying.
7. Use air or water economizers where TCO and risks are acceptable.
8. Improve power distribution efficiencies (e.g., evaluate transformer efficiency, reduce number of power conversions, use higher voltages, consider DC power, minimize power run distances, optimize redundancy strategy).
9. Capture and reuse waste heat where possible.
10. Determine optimal operating temperature and humidity ranges using the steps defined in ASHRAE's fifth edition of *Thermal Guidelines for Data Processing Environments*. (The recommended range should be used as the starting point if no optimization has been performed.)

Electronic Equipment and Environmental Requirements

1. Implement server virtualization where applicable.
2. Collaborate with IT department on ITE purchases. When prudent, select the appropriate higher ASHRAE Classes of hardware (A2, A3, and A4) to permit higher operating temperatures, balance TCO, reliability, locale, and other owner objectives. The reader is referred to the fifth edition of *Thermal Guidelines for Data Processing Environments* (2021).
3. Enable power management features on ITE.
4. Specify high-efficiency power supplies and eliminate unnecessary power conversions. Consider DC-powered hardware if available.
5. Remove “comatose” ITE hardware.
6. Perform technology refreshes to increase computer performance per watt.
7. Optimize IT equipment supply air conditions per Thermal Guidelines for Data Processing Environments.
8. Control HVAC systems based on entering air conditions at the ITE.
9. Determine appropriate gaseous and particulate contamination control measures for the data center location.

KEY ELEMENTS OF COST

1. Infrastructure redundancy comes with a significant capital cost as well as energy-efficiency penalties. The engineer should work to optimize the required redundancy without exceeding the owner's business requirements and risk models.
2. TCO is an important concept for data centers that requires careful evaluation of IT hardware classes, deployment and technology refresh strategies, system redundancies, energy efficiency, cooling transport media (air, water, refrigerant), scalability, etc.

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TERMS, DEFINITIONS, AND ACRONYMS

ΔT	=	change or change in temperature T
AC	=	air conditioning
ACGIH	=	American Conference of Governmental Industrial Hygienists
AHU	=	air-handling unit
AIA	=	American Institute of Architects
ANSI	=	American National Standards Institute
BAS	=	building automation system
BEES	=	Building for Environmental and Economic Sustainability
BF	=	ballast factor
BIM	=	building information modeling
bioclimatic chart	=	a psychrometric chart with a plot of the conditions for primarily passive strategies
BOMA	=	Building Owners and Managers Association
BREEAM®	=	Building Research Establishment Environmental Assessment Method
brownfield	=	real estate property that is, or potentially is, contaminated
Btu	=	British thermal unit
C	=	centigrade (temperature scale)
CAN	=	Canada
CAV	=	constant air volume
CBE	=	Center for the Built Environment
CCHP	=	combined cooling, heating, and power
CDT	=	cold deck temperature
CFC	=	chlorofluorocarbon
cfm	=	cubic feet per minute
CFR	=	current facility requirements
charrette	=	collaborative and interdisciplinary effort to solve a design problem within a limited time
CHP	=	combined heating and power
CHW	=	chilled water
condenser	=	device to dissipate (get rid of) excess energy in A/C systems
COP	=	coefficient of performance
CxA	=	commissioning authority
daylighting	=	lighting (of a building) using daylight directly or indirectly from the sun
D/B	=	design/build
dB(A)	=	A-weighting decibels

D/B/B	=	design/bid/build
DDC	=	direct digital control
DE	=	district energy
DG	=	distributed generation
DHW	=	domestic hot water
DOAS	=	dedicated outdoor air system
DOE	=	U.S. Department of Energy
DSF	=	double skin facade
DX	=	direct expansion
E	=	ventilation effectiveness
EA	=	energy and atmosphere
EDC	=	environmental design consultant
EDG	=	engine-driven generator
ENERGY STAR [®]	=	a government-backed program/rating system that helps consumers achieve superior energy efficiency
energy source	=	on-site energy in the form in which it arrives at or occurs on a site (e.g., electricity, gas, oil, or coal)
energy resource	=	raw energy that (1) is extracted from the earth (wellhead or mine mouth), (2) is used in the generation of the energy source delivered to a building site (e.g., coal used to generate electricity), or (3) occurs naturally and is available at a site (e.g., solar, wind, or geothermal energy)
enthalpy	=	the thermodynamic property of a system resulting from the combination of observable properties (per unit mass) thereof: namely, the sum of internal energy and flow work; flow work is the product of volume and specific mass (i.e., energy transmitted into or out of a system or transmitted across a system boundary)
entropy	=	a measure of the molecular disorder of a system, such that the more mixed a system is, the greater its entropy, and the more orderly or unmixed a system is, the lower its entropy
E&O	=	errors and omissions
EPA	=	U.S. Environmental Protection Agency
EPBD	=	Energy Performance of Buildings Directive
EPC	=	energy performance certificate
EU	=	European Union
F	=	Fahrenheit (temperature scale)
F-chart	=	method of calculating solar fraction
fenestration	=	window treatment
GHG	=	greenhouse gas
gpf	=	gallons per fixture
gpm	=	gallons per minute
GSHP	=	ground-source heat pump
guideline	=	within ASHRAE, a document similar to a standard, but with less strict rules on developing a consensus and not written in code language
HCFC	=	hydrochlorofluorocarbons
HEPA	=	high-efficiency particulate air
HID	=	high-intensity discharge
HVAC&R	=	heating, ventilating, air-conditioning, and refrigerating
hybrid ventilation	=	combination of natural and mechanical outdoor air ventilation
hydronic	=	pertaining to liquid flow
IAQ	=	indoor air quality

IDP	=	integrated design process
IEA	=	International Energy Agency
IEC	=	indirect evaporative cooling
IEQ	=	indoor environmental quality
IES	=	Illuminating Engineering Society of North America
insolation	=	entry into a building of solar energy
IPCC	=	Intergovernmental Panel on Climate Change
IPMVP	=	International Performance Measurement and Verification Protocol
K	=	Kelvin or absolute (temperature scale)
kW	=	kilowatt
kWh	=	kilowatt-hour
kW _R	=	refrigeration cooling capacity in kW
latent load	=	thermal load due strictly to effects of moisture
LCA	=	life-cycle assessment
LCCA	=	life-cycle cost analysis
LCEA	=	life-cycle environmental assessment
LD	=	liquid desiccant
LED	=	light-emitting diode
LEED	=	Leadership in Energy and Environmental Design
leeward	=	the downwind side—or side the wind blows away from
L/f	=	liters per fixture
low-E	=	low emissivity
LPD	=	lighting power density
LP	=	liquefied petroleum
L/s	=	liters per second (airflow and water flow)
media	=	energy forms distributed within a building, usually air, water, or electricity
MERV	=	minimum efficiency reporting value
mhp	=	motor horsepower
M&V	=	measurement and verification
NADCA	=	National Air Duct Cleaning Association
NC	=	noise criteria
NO _x	=	oxides of nitrogen
NOAA	=	National Oceanic Atmospheric Administration
nonrenewables	=	energy resources that have definite, although sometimes unknown, quantity limitations
NR	=	natural refrigeration
NREL	=	National Renewable Energy Laboratory
NZEB	=	net zero energy building
OC	=	on center
O&M	=	operations and maintenance
OPR	=	Owner's Project Requirements
OSHA	=	Occupational Safety and Health Administration
P3	=	public-private partnership
parametric analysis	=	in situations where multiple parameters affect an outcome, an analysis that determines the magnitude of one or more parameter's impact alone on that outcome
plug loads	=	loads (electrical or thermal) from equipment plugged into electrical outlets
POTW	=	publicly owned treatment works
precooling	=	cooling done prior to the time major cooling loads are anticipated
PV	=	photovoltaic

R (as in R-19)	=	thermal heat transfer resistance
RC	=	room criteria
renewables	=	resources that can generally be freely used without net depletion or that have the potential to renew in a reasonable period of time
RES	=	renewable energy source
RFP	=	request for proposal
ROI	=	return on investment
sensible load	=	thermal load due to temperature but not moisture effects
sg	=	specific gravity
SHW	=	space hot water
skin	=	building envelope
SMACNA	=	Sheet Metal and Air Conditioning Contractors National Association
SR	=	synthetic refrigeration
SRI (Chapter 2)	=	Smart Readiness Indicator (Chapter 2)
SRI (Chapter 7)	=	Solar Reflective Index (Chapter 7)
SS	=	sustainable sites
standard	=	within ASHRAE, a document that defines properties, processes, dimensions, materials, relationships, concepts, nomenclature, or test methods for rating purposes or code enforcement
sustainability	=	providing for the needs of the present without detracting from the ability to fulfill the needs of the future
TC	=	technical committee (an ASHRAE group with a common interest in a particular technical subject)
TCLP	=	toxicity characteristic leaching procedure
TES	=	thermal energy storage
Title 24	=	shortened form for California's Building Energy Efficiency Standards (Title 24, Part 6 of the California State Building Code)
ton	=	cooling capacity, equal to 12,000 Btu/h
TRACI	=	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
USGBC	=	U.S. Green Building Council
VAV	=	variable air volume
VE	=	value engineering
VFD	=	variable-frequency drive
VOC	=	volatile organic compound
VRF	=	variable refrigeration flow
WE	=	water efficiency
windward	=	the upwind side, or side the wind blows toward

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