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ZERO ENERGY

ACHIEVING ZERO ENERGY

Advanced Energy Design Guide for Small to Medium Office Buildings

Developed by:
ASHRAE
The American Institute of Architects
Illuminating Engineering Society
U.S. Green Building Council
U.S. Department of Energy

Advanced Energy
Design Guide
for
Small to Medium Office Buildings

Achieving Zero Energy

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Acknowledgments

Advanced Energy Design Guide for Small to Medium Office Buildings: Achieving Zero Energy is the second Advanced Energy Design Guide (AEDG) to provide strategies and recommendations for achieving a zero energy building; that is, a building that can produce as much on-site renewable energy as it consumes. Like the zero energy AEDG for K-12 school buildings that preceded it, this Guide continues shifting buildings from energy consumers to energy producers, with their owners reaping the benefits.

The Guide was primarily written by the 12 committee members of ASHRAE Special Project 140 (SP-140) representing ASHRAE, The American Institute of Architects (AIA), Illuminating Energy Society (IES), U.S. Green Building Council (USGBC), and the U.S. Department of Energy (DOE).

The chair would like to thank the members of the committee for the countless hours spent, especially the time outside their normal jobs, to make this Guide possible. The creativity and persistence in creating a guide that moves well beyond today's norms will help lead the building industry into the future. This Guide represents the current thinking about next-generation building design and operations, including guidance on plug loads, envelope, lighting, HVAC, and renewable energy systems. The committee brought hundreds of years of experience in low-energy design to this Guide.

The project was made possible with financial support from DOE through the National Renewable Energy Laboratory (NREL). This provided for the bulk of the project committee's expenses. In addition, this support provided leadership support for the committee as well as modeling analysis, which was invaluable in guiding the committee's decisions. The chair would also like to personally thank Sarah Zaleski and Amy Jiron for their DOE leadership in zero energy buildings. Their efforts in the Building Technology Office are paving the future path for energy consumption in buildings.

The project committee met four times in person and held 20 conference calls over the course of the special project. The chair would especially like to thank the families of the committee members, as their dedication to this project meant time away from family activities. In addition, the chair acknowledges the support from the project committee members' employers: Alexandria Real Estate Equities, ClimateCraft Inc., CMTA Inc., Eastern Connecticut State University, MKK Engineering, NREL, Owens Corning, Puget Sound Energy, Skidmore Owings & Merrill LLP, Syska Hennessy Group, TD Bank Group, Trane, and University of Colorado Boulder.

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Thanks also go out to the authors of the previous AEDGs that paved the way for this type of work. Many of the thoughts, recommendations, and presentations have their roots in the 30% and 50% AEDGs. Using these templates helped to bring this Guide to completion in a timely fashion.

Finally, this Guide would not have been possible without the dedication of Lilas Pratt, ASHRAE staff. Her organizational skills and dedication to taking ideas, thoughts, and draft text from the committee and bringing it all together are what really make this Guide a single document. Her coordination abilities and guidance created this first-rate publication. It is safe to say that this Guide would not exist without her contributions.

The chair hopes that this Guide provides inspiration to build zero energy office buildings and shifts buildings from consumers to producers of energy. It should provide confidence that achieving zero energy is possible today and is not a dream. Together we can change the way buildings use energy.

Paul Torcellini
Chair, ASHRAE Special Project 140
May 2019

Abbreviations and Acronyms

A/E	architectural/engineering
AEDG	Advanced Energy Design Guide
AFF	above finished floor
AFUE =	annual fuel utilization efficiency
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	air-handling unit
AIA	The American Institute of Architects
ANSI	American National Standards Institute
ASTM	ASTM International
BAS	building automation system
BOD	Basis of Design
BP	Advanced Energy Design Guide code for “building and site planning”
Btu	British thermal unit
cfm	cubic feet per minute
c.i.	continuous insulation
CO_2	carbon dioxide
COP	coefficient of performance, dimensionless
CRI	Color Rendering Index
Cx	commissioning
CxP	commissioning provider
CZ	climate zone
DCV	demand-controlled ventilation
DL	Advanced Energy Design Guide code for “daylighting”
DOAS	dedicated outdoor air system
DOE	U.S. Department of Energy
DX	direct expansion
ECM	electronically commutated motor
EER	energy efficiency ratio, Btu/W·h
EF	energy factor
EL	Advanced Energy Design Guide code for “electric lighting”
EN	Advanced Energy Design Guide code for “envelope”
E_t	thermal efficiency, dimensionless
EUI	energy use intensity
F	slab edge heat loss coefficient per foot of perimeter, Btu/h·ft·°F
fc	footcandle

FC	filled cavity
GSHP	ground-source heat pump
Guide	*Advanced Energy Design Guide for Small to Medium Office Buildings—Achieving Zero Energy*
HSPF	heating seasonal performance factor, Btu/W·h
HV	Advanced Energy Design Guide code for “HVAC systems and equipment”
HVAC	heating, ventilating, and air-conditioning
IEER	integrated energy efficiency ratio, Btu/W·h
IES	Illuminating Engineering Society
in.	inch
in. w.c.	inches of water column
IPLV	integrated part-load value, dimensionless
ISCOP	integrated seasonal coefficient of performance
ISMRE	integrated seasonal moisture removal efficiency
kW	kilowatt
kWh	kilowatt-hour
LC	Advanced Energy Design Guide code for “lighting controls”
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
LLLC	luminaire-level lighting control
LPD	lighting power density, W/ft^2
LPW	lumens per watt
Ls	liner system
M&V	measurement and verification
MERV	Minimum Efficiency Reporting Value
N/A	not applicable
NEMA	National Electrical Manufacturers Association
NPLV	nonstandard part load value
NREL	National Renewable Energy Laboratory
OPR	Owner’s Project Requirements
OSHA	Occupational Safety and Health Administration
PL	Advanced Energy Design Guide code for “plug loads and power distribution systems”
PPL	plug and process load
ppm	parts per million
PV	photovoltaic
QA	quality assurance
R	thermal resistance, h·ft^2·°F/Btu
RE	Advanced Energy Design Guide code for “renewable energy”
REC	renewable energy certificate
RFP	request for proposals
rh	relative humidity
SAT	supply air temperature
SEER	seasonal energy efficiency ratio, Btu/W·h
SHGC	solar heat gain coefficient, dimensionless
SWH	service water heating
U	thermal transmittance, Btu/h·ft^2·°F
UEF	uniform energy factor
USGBC	U.S. Green Building Council
VAV	variable air volume
VRF	variable refrigerant flow
VSD	variable-speed drive
VT	visible transmittance, dimensionless
W	watt
WH	Advanced Energy Design Guide code for “service water heating”
WWR	window-to-wall ratio
ZE	zero energy

Foreword: A Message to Building Owners and Managers

The first time I heard someone talk about zero energy buildings was in 2003. A group of us were working on a residential green demonstration home in western Washington, one of the team had heard the term, and it was thrown out as a goal. Frankly, we weren't even completely sure what it meant. While that project ended up a long way from being zero energy, I was immediately captivated, sank my teeth in, and have yet to let go.

In the following 15 years, the concept of and the know-how, technology, and design integration around zero energy have grown enormously. Rather than head-scratching about how to get there, a number of leading engineering, design, and contractor firms have a firm handle on the approach. Supportive technologies and their relative costs have improved, from envelope to mechanical systems to switching technologies to renewables. I view this Guide as a coming of age of sorts for zero energy—a transition from awkward teenage years to early adulthood.

Even though the overall maturity of the zero energy building ecosystem has grown quickly, buildings actually performing at zero energy number in the low hundreds. I believe a major factor in this is the 2008 economic downturn—in many ways, the market has only recently fully recovered, in that developers' and companies' financial footing has been solidly restored. Reflecting this is the significant spike in interest and focus on zero energy buildings in the last couple of years, and I anticipate a rapid market shift.

A good example of this is the Catalyst Building, the brainchild of McKinstry's CEO, Dean Allen. Currently under construction, Catalyst, located in Spokane, Washington, will be one of the world's largest zero energy office/education buildings. Catalyst includes an array of next-generation zero energy elements, including a brand new all-electric district energy system; cross-laminated timber construction; utility-controlled, grid-integrated thermal storage; and an advanced plug-load management system. But what is most remarkable about Catalyst is that it is a market-rate project, being developed with normal returns and no subsidy. Catalyst is proof that zero energy is scalable today.

And it is that scaling to which we must pivot. Given that 40% of all energy used in the United States today is used by buildings, zero energy buildings must quickly become the norm and not the exception.

The good news for designers, developers, and owners alike is that, done right, zero energy buildings have the potential to be much better buildings than the norm—*zero energy* is a concept with bundled benefits. Often, total cost of ownership is less. Properly designed and constructed, better insulated and tighter envelopes mean a quieter, more thermally comfortable workspace and a more durable building. Well-daylighted buildings connect workers to nature.

Thoughtful design which is ethically responsive to today's environmental realities is inspiring and comforting. The reality is also that zero energy buildings call on not just muscle power but also brain power—the kind of high-value-added construction that results in well-paying jobs and a strengthening of the domestic economy. A more efficient economy makes the country more competitive and resilient to fuel-price shocks. Another unsung benefit to zero energy buildings is that team members bring their A game. I have yet to meet someone working on a zero energy building who was not profoundly excited to be contributing. Every time, the result is a better building overall. And each of these elements results in a more valuable asset, a future-proofed, forward-looking building for the twenty-first century.

Another exciting element of zero energy as a concept and practice is that it continues to grow and evolve, each time making greater impacts and better results. Emerging topics include the following:

- Full integration of nature into design, not just taking advantage of nature-provided services. At our core as humans, we are animals, and animals thrive in nature—why do we spend so much time when indoors pining to be outside?
- Recognition that zero energy buildings rely on and have a relationship with the electrical grid. Grid-aligned zero energy buildings will grow to respond to the grid energy curve, reducing their own footprints while using and providing electricity at optimal times for maximum grid efficiency.
- Embodied energy and environmental footprint of construction—as buildings become more efficient, the embodied carbon of the construction of the building comes to the fore. The global warming potential of refrigerants is a particularly critical element of this growth edge, for which the HVAC world must take leadership.

A final benefit and reality of zero energy buildings is their interdisciplinary, integrated nature. The best zero energy buildings are a seamless blend of shelter, design, and systems, blending to provide an ideal environment for peak human happiness and performance. I am very impressed that ASHRAE has created a testimony to this reality in this Guide, reflecting a highly integrated design approach.

The engineering profession has been called on in many crises of the past, and it is being called upon once again. But at the end of the day, all decisions are personal decisions. Make zero energy personal. Make it your personal mandate to be part of and drive one of the first thousand modern zero energy buildings ever built (recognizing that many buildings were zero energy prior to electricity!). Leave your mark on history. Use this Guide to be part of the zero energy revolution, a revolution which will play a key role in transitioning humanity to a sustainable, renewably powered future.

Brad Liljequist
McKinstry

Brad Liljequist is the Zero Energy Senior Program Manager for McKinstry, a design, build, operate, and maintain (DBOM) engineering design and construction company based in Seattle, for which he leads the company's zero energy efforts across the country. Previously, he directed energy and community programs for the International Living Future Institute and developed the first certified multifamily zero energy project in the United States, zHome, as well as Issaquah Fire Station 72, winner of the national ASHRAE Technology award in 2012. He is the author of The Power of Zero: Learning from the World's Leading Zero Energy Buildings *(2016, Ecotone Publishing—An imprint of International Living Future Institute, Portland, OR).*

Introduction

1

Buildings consume 40% of the energy consumption in the United States and a similar percentage globally (EIA 2018). To make significant improvements to building energy use, ambitious and measurable goals need to be set. Zero energy buildings are designed first to significantly reduce energy consumption and then to meet remaining loads with renewable resources, ideally located on site. These buildings are usually connected to the utility grid to receive energy whenever renewable energy production is insufficient to meet required loads and to return energy to the grid when renewable energy production exceeds the loads. This Guide provides insight on how to achieve a zero energy office building at a cost that is comparable to office buildings built to typical energy codes in use today.

A zero energy office building can lead to healthy, high-performance work environments and allow occupants to be more productive while saving operational expenses. For an organization, zero energy buildings can demonstrate a corporate commitment to excellence. This leadership can in turn help retain employees, gain customers, and increase client satisfaction. All these benefits contribute to minimizing the impact of the built environment as well as making good business sense.

GOALS OF THIS GUIDE

The goals of this Guide are to demonstrate that zero energy office buildings are attainable and to provide direction through recommendations, strategies, and solution packages for designing and constructing zero energy office buildings in all climate zones. Like the zero energy Advanced Energy Design Guide (AEDG) for K-12 school buildings that preceded this Guide, absolute energy targets are provided rather than showing a percentage of energy reduction from a designated baseline.

This Guide provides design teams with strategies for achieving energy savings goals that are financially feasible, operationally workable, and readily achievable. Energy efficiency and renewable energy technology are rapidly improving, and technologies that did not make sense financially or technically a few years ago are feasible today. As a result of this progress, zero energy office buildings can be achieved today within the budget of conventional buildings. This Guide provides a pathway to zero energy that will help lead to a fundamental shift from buildings as consumers of energy to buildings as producers of energy.

As demonstrated throughout this Guide, setting measurable goals is the key to success. Setting measurable goals is the first commitment toward completing a successful zero energy project while maintaining a reasonable budget. The Guide is written with two key concepts in mind:

- Achieving very low energy use intensity (EUI) is the primary goal, whether or not on-site renewable energy is a feasible goal in the near or long-term future of the facility.
- Maintaining this level of performance requires a continuing commitment to skillful, adaptive operation; responsible maintenance; and monitoring of building performance.

The intended audience of this Guide includes building owners, developers, architects, design engineers, energy modelers, contractors, commissioning providers, facility managers, and building operations staff. Much of the information provided in this Guide may be applicable to those seeking to achieve zero energy on other building types as well as on both new and retrofit projects.

ZERO ENERGY DEFINITION

There are a number of different terms commonly used to describe buildings that achieve a balance between energy consumption and energy production: *zero energy*, *zero net energy*, *net zero energy*. The term used throughout this Guide is *zero energy* (ZE) for consistency with the U.S. Department of Energy (DOE) definition of zero energy. The specific definition of a zero energy building used in this Guide is based on source energy, as defined by DOE (2015):

> 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.

This definition provides a standard accounting method for zero energy using nationwide average source energy conversion factors, facilitating a straightforward assessment of zero energy performance of buildings. Although the DOE national averages do not take into account regional differences in energy generation and production, nor precise differences in transmission losses due to a project's location, they do provide an equitable and manageable formula intended to facilitate scaling-up of zero energy buildings across the country and beyond. Because of its wide adoption across the country, this definition also facilitates alignment with federal policy and incentives as well as with many state and municipal initiatives.

This Guide provides target EUI information in both site energy and source energy. Either can be used to calculate the energy balance of a project.

- *Site energy* refers to the number of units of energy consumed on the site and typically metered at the property line or the utility meter.
- *Source energy* refers to the total amount of energy required to produce and transmit a given amount of energy of each fuel type to the site. Each step from energy extraction to actual consumption has energy losses. Source energy takes into account the efficiency of the production and transport process. It is calculated by multiplying the site energy of each fuel source by a factor specific to that fuel. For example, for electrical energy it takes approximately 3 kWh of total energy to produce and deliver 1 kWh to the customer because the production and distribution of electrical energy is roughly 33% efficient.

On the energy generation side of the equation, the on-site renewable energy generation is then also multiplied by these same factors, to give credit for the total avoided source energy consumption.

This Guide focuses on the design decisions needed to achieve energy goals and accommodate renewable energy on site, which is the last step needed to achieve a zero energy building. In many situations, renewable energy is limited by site constraints, local regulations, and utility restrictions. Regardless of the limitations, the energy efficiency of a building has a large impact because it reduces the renewable energy needed, whether that energy is produced on site or somewhere else. This Guide focuses on achieving energy use targets to achieve a zero energy ready building. Renewable energy may then be added on site, if available, or procured off site, if desired. Chapter 3 provides details on setting goals, setting energy boundaries, and using the definition of a zero energy building to achieve success.

BENEFITS OF A ZERO ENERGY OFFICE BUILDING

ENVIRONMENTAL STEWARDSHIP AND CORPORATE IMAGE

Completing a zero energy office building, or an office building with the low EUI required to be ready for zero energy when renewable energy sources are added, demonstrates leadership and a clear commitment to sustainability and environmental stewardship. A zero energy office building signals a shift toward excellence in expectations that can also impact other areas of how an organization operates and delivers for its employees, customers, and other stakeholders. Investing in a zero energy building is one of the most impactful things an organization can do to protect natural resources and mitigate climate change.

OCCUPANT SATISFACTION

Occupant satisfaction should be a key consideration for all building owners and employers. Focusing on the occupant benefits of a zero energy office can be an excellent business strategy, because staff salaries represent over 90% of the total operating costs in commercial office buildings (CBE 2007). Just 10% of costs come from energy, maintenance, and mortgage/rent (Terrapin 2012). This makes staff retention a high priority, and satisfied occupants are less likely to seek other job opportunities. Carnegie Mellon University's Center for Building Performance and Diagnostics has summarized recent findings for productivity gains and health gains related to views, natural ventilation and daylighting (B&D 2018).

Occupant satisfaction is complex, but some aspects of satisfaction, such as physical and visual comfort, access to daylighted spaces, views to the outdoors, and natural ventilation, are achieved through effective building design and operation as discussed throughout this Guide. One useful resource when exploring design for improved occupant performance and well-being in offices is World Green Building Council's *Health, Wellbeing and Productivity in Offices: The Next Chapter for Green Building* (WGBC 2014).

Occupants have a large influence over the performance of a building, governing operations, and many of the energy loads. They are the champions for energy efficiency and can help achieve organizational energy and environmental goals. They are also the organization's most valuable resource. Therefore, the productivity of occupants can be improved with a healthy, comfortable, energy-efficient work environment. Zero energy buildings can be a vehicle for providing workplaces with these characteristics. The Bullitt Center's zero energy office is one example of a building that offers occupants daylight, views, and natural ventilation, as shown in Figure 1-1.

SOUND FISCAL MANAGEMENT

Zero energy buildings often have substantially reduced energy bills compared to traditional buildings. Typically energy is the largest cost for an organization outside of salaries and benefits. This makes it the largest controllable cost. Reducing this cost has a dramatic impact on the bottom line. Zero energy office buildings can both reduce energy consumption dramatically and mitigate the risk of future energy cost volatility. Utilities and utility rate structures will not remain static as the generation mix and distribution system is changing. Investing in energy efficiency and renewable energy minimizes the risk associated with fluctuations in util-

Figure 1-1 Bullitt Center Net Zero Energy Office
Used with Permission, © Nic Lehoux

ity prices. One way to think about this is that today's investment "locks in" future energy costs through the savings.

As this Guide shows, zero energy office buildings can also have lower maintenance costs. Many energy-efficiency strategies result in less operational time for mechanical and electrical equipment. Reducing the strain on this equipment yields reduced maintenance costs. The most effective systems are simpler and smarter. Effective design should create less complex buildings where heating, ventilating, air-conditioning, and control systems may be operated and maintained by less highly skilled technicians, who are generally easier to recruit. Wall, window, and roof systems are critical for achieving low EUI goals. These systems are designed for the life of the building; creating them to be durable and long-lasting will help maintain the energy savings for the life of the building. The testing and commissioning recommended by this Guide ensures that zero energy buildings are constructed and will perform as designed. Zero energy office buildings should have lower life-cycle costs than other buildings and continue to conserve resources throughout the lifetime of the building.

SCOPE

This Guide was developed through a collaboration of ASHRAE, The American Institute of Architects (AIA), Illuminating Engineering Society (IES), U.S. Green Building Council (USGBC), and the U.S. Department of Energy (DOE). A project committee that represents a diverse group of professionals and practitioners in HVAC, lighting, and architectural design as well as building owners drafted the guidance and recommendations presented herein.

The Guide provides user-friendly guidance for the construction of new small to medium office buildings. Much of the guidance also applies to retrofits of existing buildings, depending on the depth and breadth of the retrofits. The guidance addresses processes, polices, strategies, and technologies and includes energy-efficiency targets and how-to strategies. The recommendations in this guide are voluntary and are not designed to be code-enforceable. As a result, they are not intended to replace, supersede, or circumvent any applicable codes in the jurisdiction within which a building is constructed. In addition, there are many pathways to zero energy and, as technologies improve, more pathways will be developed. Therefore, this Guide provides ways, but *not the only ways*, to achieve energy-efficient and zero energy office buildings.

While this Guide cannot specifically address all possible configurations of buildings, the recommendations apply to office buildings ranging from roughly 10,000 to 100,000 ft^2 with a building height of less than 75 ft. Many larger office buildings are made up of sections in this size range, thus the guidance herein can be extended to larger buildings. The Guide does not cover process loads or atypical spaces such as those for food service or laboratories or other spaces with higher energy loads and ventilation requirements. Space types covered by the Guide include office areas, circulation spaces, storage areas, break rooms (with a refrigerator, ice machine, dishwasher, microwave, sink, small appliances, and vending), small data centers/closets, workout rooms, and conference and meeting spaces. The Guide does not consider specialty spaces with extraordinary heat generation, large ventilation requirements, or pollution generation.

Much of the Guide may also be applicable to buildings undergoing complete or partial renovation, additions, and or changes to one or more building systems; however, upgrading existing exterior building envelopes to achieve the low EUIs needed to reach zero energy is likely to be very challenging. With that in mind, any time changes are made to a building, there is an opportunity to move that building toward zero energy. This may entail replacement of a boiler, changing out light fixtures, or simply painting the space. Design decisions can be made that will reduce the energy impact of the building. The icons next to the how-to strategies in Chapter 5 indicate strategies that are particularly well suited for existing buildings to be renovated or modernized. Any time design decisions are made is an opportunity to save energy.

This Guide focuses on reducing energy consumption in a building. There are also overlaps with other important aspects of sustainability. Acoustics, indoor air quality (IAQ), water efficiency and quality, landscaping, access to views, and effective space planning are just some of the other benefits of an effective design. The objective of creating a zero energy building that is cost-effective is designing with all these parameters in mind at once. All these create buildings for the future.

DEVELOPING THE GUIDE

To establish reasonable energy targets for achieving zero energy performance in all climate zones, a prototypical office building was modeled and analyzed using hourly building simulations. In previous AEDGs for office buildings, two prototypes were used—one to represent smaller buildings and one to represent buildings with deep floor plates. However, advancements in lighting have reduced the sensitivity of the ratio of interior to exterior office spaces and, as a result, limited differences are seen within the size range discussed in this Guide. Therefore, one prototype building was carefully assembled to represent office building construction, with information was drawn from several sources. A typical office building layout is shown in Figure 1-2.

Hourly simulations were run using the recommendations in this Guide. The prototype was simulated in the climate zones adopted by the International Energy Code Council (IECC) and ASHRAE in developing energy codes and standards. These include nine primary climate zones subdivided into moist, dry, and marine regions for a total of 19 climate locations. All materials and equipment used in the simulations are commercially available from two or more manufacturers.

The simulation results led to the determination of a target EUI for each of the 19 climate locations. The target EUIs are shown in Figure 1-3. Figure 1-3a shows the site EUIs by climate zone and Figure 1-3b shows the source EUIs by climate zone. Chapter 3 shows specific EUI target values in Table 3-1 and a map of U.S. climate zones in Figure 3-1.

The EUIs were verified to not exceed the amount of renewable solar energy that could be generated by photovoltaic (PV) panels reasonably accommodated on the roof of the prototype building. These EUIs are intended not as prescriptive requirements but as starting points of minimum performance that can be cost-effectively attained. Further optimization through

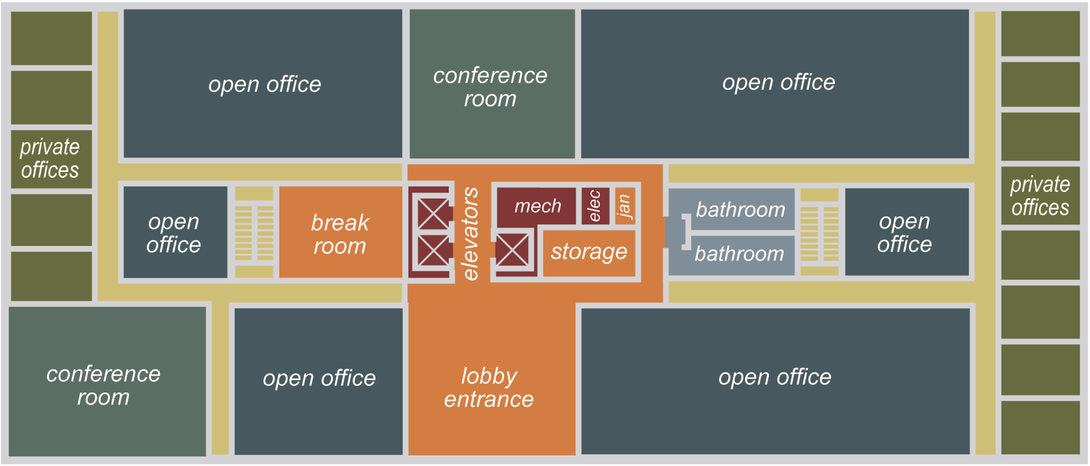


Figure 1-2 Typical Office Plan

building simulation and integrated design is recommended to reach the lowest possible EUI for each project striving for zero energy.

To facilitate reaching these EUI targets, the Guide provides recommendations for the design of the building configuration and of building components, including the building outside envelope, fenestration, lighting systems (including electrical interior and exterior lights and daylighting), HVAC systems, building automation and controls, outdoor air requirements, service water heating, renewable energy generation systems, and plug and process loads. These recommendations are discussed in Chapter 5.

HOW TO USE THIS GUIDE

This chapter outlines the case for zero energy, a general idea of what to expect in the Guide, how the Guide was developed, and how to use it.

Chapter 2, Principles for Success, identifies the main principles fundamental for success in implementing a zero energy building.

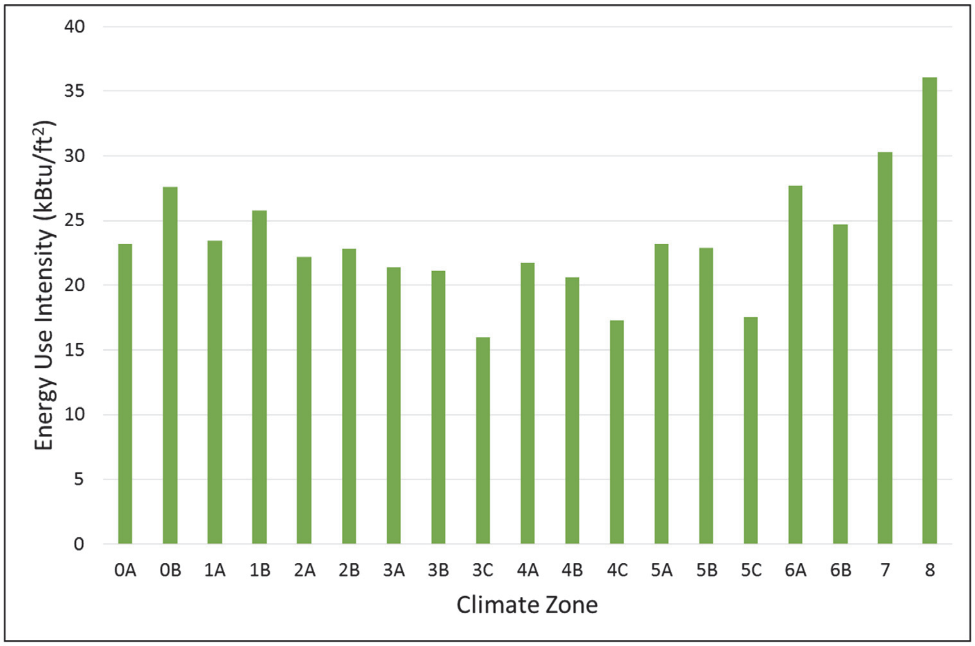
Chapter 3, A Process for Success, outlines how to achieve a zero energy building from a process standpoint. The chapter discusses how to determine a target EUI and provides recommended EUI targets in both site and source energy.

Chapter 4, Building Performance Simulation, provides information on how to incorporate building simulation into the design process. Though it is not a definitive source for how to use simulation tools, the chapter provides an overview on most relevant approaches for analyzing the various components of design covered in the Guide.

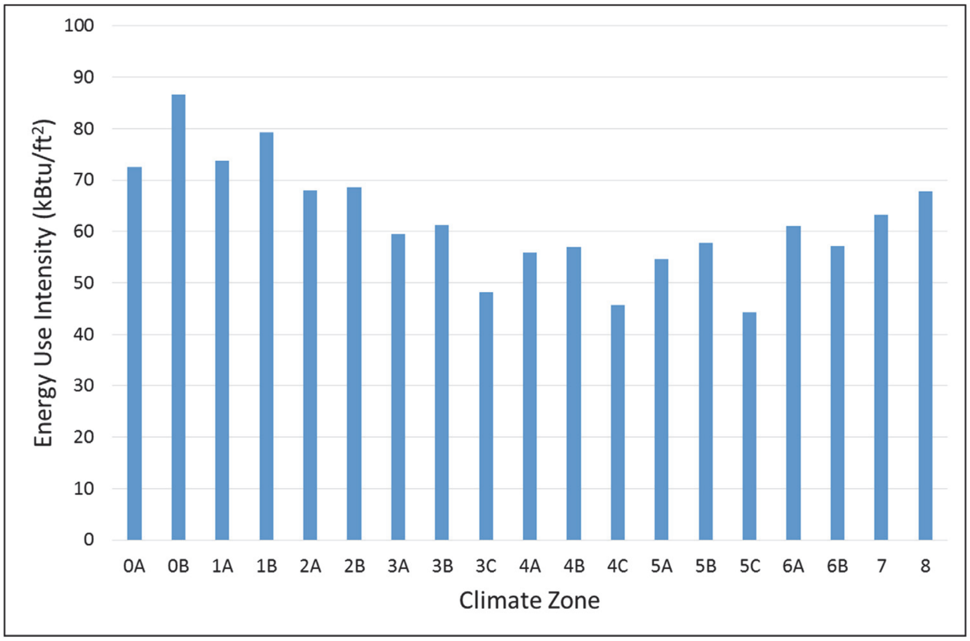
Chapter 5, How-to Strategies, provides specific strategies and recommendations regarding the design, construction, and operation of zero energy office buildings. The chapter has suggestions about best design practices, how to avoid problems, and how to achieve the energy targets advocated in this Guide. The chapter is organized into easy to follow how-to strategies.

Icons next to the how-to strategies in Chapter 5 highlight those strategies that contribute to four different categories of information:

- ⚡ Reducing peak demand and increasing alignment with the electricity grid
- 🔒 Energy resilience
- $ Capital cost savings
- 🔧 Building retrofit strategies



(a)



(b)

Figure 1-3 **(a) Site EUI Comparison by Climate Zone and (b) Source EUI Comparison by Climate Zone**

Appendices provide additional information:

- Appendix A—Envelope Thermal Performance Factors
- Appendix B—International Climatic Zone Definitions
- Appendix C—Quantifying Thermal Transmittance Impacts of Thermal Bridges

Case studies and technology example sidebars are interspersed throughout the Guide for examples of how to achieve zero energy and to provide additional information relevant to that goal.

The Zero Energy Buildings Resource Hub (www.zeroenergy.org) provides additional information, resources, and case studies for zero energy buildings.

Note that this Guide is presented in Inch-Pound (I-P) units only; it is up to the individual user to convert values to metric.

The recommendations in this Guide are based on typical prototype operational schedules and industry best practices as well as typical costs and utility rates. The operational schedule, actual costs, and utility rates of any one project may vary, and life-cycle cost analysis (LCCA) is encouraged for key design considerations on each specific project to properly capture the unique project costs and operational considerations.

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BULLITT CENTER

The Bullitt Center satisfies all of its own energy, water, and waste needs and was designed using a process that moves beyond traditional linear design and construction to look at how to design a building with virtually no environmental footprint. Designed as a leasable Class A office building, the Bullitt Center also serves as a living laboratory of environmental awareness highlighting the interconnectedness of sustainable design to architecture, energy use, materials sourcing, government policy, and financing. The state-of-the-art building can easily be updated in the future as advancements are made without impacting building operation.

CLIMATE ZONE 4C

EUI
12.0

Seattle, Washington

KEY ENERGY-EFFICIENCY AND SUSTAINABLE FEATURES

- LED lighting with additional task lighting
- Tall windows and daylighting integrated with electric lighting via sensors
- Automatic, external operable shades
- Passive cooling and natural ventilation through automated operable windows
- Radiant-floor heating and cooling in office spaces
- Rainwater catchment for potable water (56,000 gal cistern)
- Low-flow fixtures, foam flush toilets, and composting toilet system
- Gray water collection system, treated on site for irrigation and drainfield
- Locally sourced timber construction

For more information, visit https://millerhull.com/project/bullitt-center/
and https://living-future.org/lbc/case-studies/bullitt-center/

Bullitt Center Exterior
Used with Permission, © Benjamin Benschneider

Interior Common Area
Used with Permission, © Nic Lehoux

Project Data

Site area: 10,000 ft^2
Conditioned gross area: 52,000 ft^2
Number of floors: 6
Context: Urban
Occupancy model: Multi-tenant
Occupants: 100–150 ft^2/person
Year completed: 2013
Delivery method: Construction management/general contractor (CM/GC)
Construction cost: $18.5 million ($365/ft^2)

Energy Data

Predicted EUI: 16 kBtu/ft^2·yr
Predicted RE EUI: 16 kBtu/ft^2·yr
Predicted net EUI: 0 kBtu/ft^2·yr

Actual EUI: 12 kBtu/ft^2·yr
Actual RE EUI: 12 kBtu/ft^2·yr
Actual net EUI: 0 kBtu/ft^2·yr

ZE Status: Living building

Building Systems

LPD: Office = 0.4, stairs = 0.29, conference = 0.9, restroom = 0.45

HVAC systems: Closed-loop GSHP, radiant floor heating and cooling
Heat recovery system: DOAS with heat recovery

RE type and size: 14,303 ft^2 solar array; 242 kW

Building Envelope

Roof overall R-value: R-38

Wall construction: Metal siding, metal studs, insulation, gypsum
Wall insulation type: Mineral wool
Wall overall R-value: R-21

WWR: 29%
Window type: Triple glazing
Window assembly U-factor: 0.25
SHGC: 0.43
VT: 0.53

Project Team

Owner: Bullitt Foundation
Developer: Point 32
Architect: Miller Hull
Energy consultant: PAE Engineers
Engineers: DCI Engineers, Luma Lighting Design, 2020 Engineers, PAE Engineers
Contractor: Foushee (tenant improvement)
Construction Manager: Schuchart (shell and core)
Other: Solar Design Associates, NW Wind & Solar

Other Metrics

Performance monitoring: Yes
M&V: Yes

Certifications

Certification/year: Certified Living—Full Petal 2013

BOULDER COMMONS

CLIMATE ZONE 5B

pEUI
23.7

Boulder, Colorado

Setting a new bar for sustainability and transforming the mindset around how buildings and communities are designed, Boulder Commons delivers market rate returns and rental rates competitive with comparable, Class A buildings in the area.

Following the design philosophy that "this is not a typical box," the building combines a sophisticated design with readily available, off-the-shelf, leading-edge building systems. The mechanical, electrical, and plumbing systems advance the latest technologies that can control the building within the energy budget.

Following this design philosophy is not as easy as using traditional development models, but it is worth the effort. The building's tenants share the belief that how a company acts matters, including its direct environmental impact on the world.

KEY ENERGY-EFFICIENCY AND SUSTAINABLE FEATURES

- LED lighting with continuous dimming daylighting controls
- Clerestory daylight reflection glass on southeast façade
- ENERGY STAR® appliances
- East-facing solar wall and angled roof-mounted solar array
- Automobile charging in parking garage
- Mobility hub with car-share, bike-share, and ride-share opportunities
- Interior finishes from renewable and regional resources

For more information, visit http://bouldercommons.com/.

Boulder Commons
Photograph Courtesy of Morgan Creek Ventures;
Credit: Bruce Damonte

East-Facing Solar Wall
Photograph Courtesy of Morgan Creek Ventures;
Credit: Bruce Damonte

Project Data

Conditioned gross area: 100,000 ft^2

Number of floors: 4

Context: Urban

Number of occupants: 200

Year completed: 2017

Construction cost: \$235/ft^2 (core and shell)

Energy Data

Predicted EUI: 23.7 kBtu/ft^2·yr

Predicted RE EUI: 25.8 kBtu/ft^2·yr

Predicted net EUI: 2.1 kBtu/ft^2·yr

Project Team

Developer: Morgan Creek Ventures

Architect: Coburn Architects

General contractor: Mortensen Construction

Engineers: Mazzetti

Energy consultant: Integral Group

Construction manager: Project One

Other: Huntsman Architectural Group, GLS, IPS; Encore Electric, MTECH

Other Metrics

Performance monitoring: Yes

Ongoing commissioning: Yes

Building Envelope

Roof type: Steel structure, metal deck

Roof insulation: Rigid—extruded polystyrene

Roof overall R-value: R-27

Wall construction: Metal stud

Wall insulation: Continuous fiberboard over metal stud frame, batt insulation with vapor retarder

Wall overall R-value: R-15

Foundation insulation R-value: R-10 Typical

Sub-slab insulation R-value: R-30 Typical

WWR: N=25%, E=25%, S=50%, W=40%

Window type: Thermally coated, triple-pane

Window assembly U-factors: Fixed = 0.18, operable = 0.22

SHGC: Fixed = 0.19, operable = 0.17

VT: Fixed=0.5, operable=0.38

Building Systems

HVAC systems: VRF

Heat recovery system: Sensible

RE type and size: Solar 717217 kW/h

Principles for Success

2

There are many stakeholders in a new building project, and all of these stakeholders view the building from their perspective and may not consider reducing energy consumption or zero energy as primary goals. This chapter highlights why zero energy buildings are important and the principles for successfully achieving a zero energy goal.

IMPROVING BUILDING PERFORMANCE

This Guide represents the current understanding of how high-performance building systems perform and interact; however, the state of the art is always advancing. New technologies and new understanding of how existing technologies may be utilized offer new strategies for achieving zero energy buildings. Design professionals must understand how their design will be utilized to make a building more user friendly, while building users must understand how to exploit the design intent to achieve the desired level of performance.

Though this Guide focuses on zero energy and energy efficiency, these may not be the only performance goals for a building project. Other sustainability and green-building goals may be simultaneously pursued. Some common performance metrics include the following:

- ***Energy Efficiency.*** Energy use intensity (EUI) is a key performance metric for buildings; it is comparable to a vehicle's annual gasoline consumption normalized for total miles driven. It is the key driver of many decisions and design parameters throughout the project delivery process. One focus of the project team should be to provide strategies and measures that directly reduce the consumption of energy. The building industry needs to propagate and increase understanding around the measurement and comparison of building EUIs across all sectors of the built environment, recognizing that different building types have different expectations for energy consumption.
- ***Peak Demand and Load Shifting.*** While energy has been a key performance metric historically, the time of day that energy is being used is becoming more important. Shifting loads to minimize impacts on the grid, both from an infrastructure viewpoint and a fuel source availability viewpoint, is becoming more important, especially when renewable generation is being added at the building site as well as on the grid.
- ***Water Efficiency.*** Reduction of water consumption for all end uses has an impact on the overall environment. The consumption of indoor, outdoor, and process water requires

energy—both energy to heat indoor hot water and energy to move the water from its source to the point of consumption. Although annual water consumption is easily tracked, projects often do not take into account the energy impacts of water consumption.

- ***Materials Efficiency.*** In any project, construction materials are brought to the site and waste materials depart the site. How to most efficiently handle those materials and reduce their impact on the environment is part of a high-performance building project.
- ***Indoor Environmental Quality.*** High-performance buildings integrate air quality, lighting, views, acoustics, and the overall indoor occupant experience into the design. High-quality indoor experiences encourage productive occupants and significantly reduce impacts to building operations over time. A well-designed, high-quality interior requires fewer buildings calls, modifications, and operational testing, thus reducing total cost of ownership and improving building energy performance.

MOVING TO ZERO ENERGY

Zero energy buildings represent a paradigm shift in the buildings industry. With any new technology or idea, one of the common barriers is initial cost. If energy costs can be reduced through energy savings, then extra capital can be expended as a good financial investment with financial gain over time.

Zero energy buildings are becoming more prevalent. The number of projects being initiated with zero energy as a project goal has increased 700% percent from 2012 to 2018 (NBI 2018). Those owners who succeed in reaching the zero energy goal do so for a number of reasons. Many have buildings built within budget that can be shown to be good financial investments. Some find that their projects showcase their companies' commitments to sustainability and provide a template for future projects.

Creating a zero energy building can also increase a building's leaseability or revenue (USGBC 2015). Studies showcase the advantages of leasing zero energy buildings, and case studies exist to give industry-leading examples. The Rocky Mountain Institute (RMI) *Best Practices for Leasing NZE Buildings* is a good resource (Carmichael and Petersen 2018).

The law of innovation, as discussed in *Diffusion of Innovations* (Rogers 2003) and *Crossing the Chasm* (Moore 2014), can be characterized as a bell curve for when innovative ideas become mainstream. The population of users is broken into five segments that fall across a bell curve: innovators, early adopters, early majority, late majority, and laggards (Sinek 2009). The distribution across the bell curve is illustrated in Figure 2-1.

The tipping point for innovation is in the 12% range (Sinek 2009). As the 700% growth in emerging projects increases and more zero energy buildings are successfully completed, this tipping point for zero energy could be on the not-too-distant horizon.

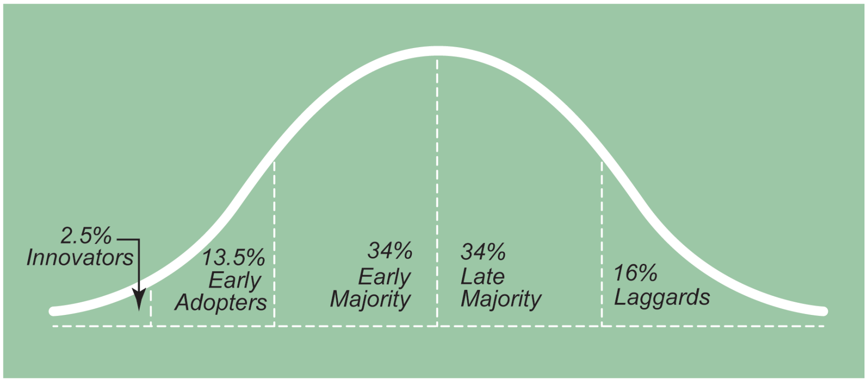


Figure 2-1 Bell Curve for Innovative Ideas Becoming Mainstream

Office buildings have always incorporated a laundry list of potential prioritized amenities in design. Many of these improvements further the *why* of the building, showcasing the occupants' business vision and mission. A beautifully designed, elongated, and sweeping canopy gains attention, welcomes visitors, and becomes a beacon for the entrance of an office building. The occupants are proud of the entrance, and the architecture connects the purpose of the building with the intentional improvement of those who occupy it. But, what is the return on investment for this canopy? Similarly, what is the return on investment for upgrading to terrazzo flooring in the entrance lobby? Zero energy is another improvement that can further the *why* of the building.

As a result, connecting zero energy into the *why* of the building is critical in creating an affordable zero energy building. The cost to obtain zero energy has dropped from over 20% of the project budget in 2009 to less than 4% of the project budget on some recent zero energy projects. This reduction is due to advances in energy conservation technologies, the reduced costs of these technologies, and the reduced costs of renewable generation systems. Meanwhile, estimated building construction costs on the same projects ranged from plus to minus 8% of the projected bid costs. This means that the cost to add zero energy is often within the expected window for bid results. Figure 2-2 illustrates this point.

FUNDAMENTAL PROJECT SUCCESS FACTORS

In every zero energy office project there are fundamental actions that contribute to its success. From the first consideration of zero energy to design to moving in occupants and through the days and years of operation, optimal performance requires attention and focus. Although there are numerous factors that will deliver zero energy success, the six discussed in the following subsections are critical to achievement.

Develop the Culture and Mindset

The first key to success is creating a mindset that a zero energy office project is achievable within budget; is a good financial investment; and can signify excellence, garner encouraging attention, become a positive press event, invoke a sense of community, and invigorate and

Figure 2-2 Cost for Zero Energy Design as Percentage of Project Cost
Used with Permission of CMTA

inspire the workforce occupying the building. To support this, the culture development starts in infancy, when the project is first conceived, and extends through design and construction into operations.

To help start creating the culture, a clear but flexible communications strategy is essential. It will educate, generate enthusiasm, develop new champions, and establish the key expectation that zero energy will be achieved and maintained. When crafting such a strategy, be conscious to connect the benefits of zero energy to each individual stakeholder group who will touch the project throughout its life cycle. Examples of these stakeholder groups include the owner, architect, engineers, general contractor, commissioning provider, facility maintenance team, and occupants. Creating a table listing the benefits for each stakeholder group is one strategy. For example, owners may be interested in reducing utility costs, whereas a general contractor may want to have a model building that will leverage future zero energy work. It is likely that the benefits will resonate with the stakeholders in different ways. Calling out examples of successful projects will breed success. Potential resources for such a strategy include the National Renewable Energy Laboratory (NREL) *A Guide to Zero Energy Schools* (2019) and the NBI Getting to Zero Database (NBI 2019).

It is necessary from the outset to address head-on those who believe that a zero energy office will automatically cost more than a typical high-performance office or that the risks of cost overruns, delays, and eventual failure to achieve zero energy are too great. The first step in building confidence that zero energy will be achieved on budget and on schedule is to select the delivery method and start assembling the team and ingraining in them the expectation for a zero energy project that is on budget and on schedule.

There are many myths surrounding zero energy buildings. Architects, engineers, and owners often look for example zero energy projects that employed positive solutions, thereby combating these myths. The case studies in this Guide provide projects that also challenge these myths.

Identify a Champion

Everything needs a champion. Ralph Waldo Emerson said, “Nothing great was ever achieved without enthusiasm.” That holds true for bringing a zero energy building to life. Establishing an energy champion from within the broader integrated project team and giving them authority on the design team and on the owner’s team will help maintain the energy efficiency priority. This individual must have the authority to make decisions and oversight throughout construction in order to navigate the project through potential roadblocks.

Whether the project has an individual owner, is landlord built, or is developer delivered, finding individuals with the vision, passion, persistence, and powers of persuasion to be a champion and lead the project from planning through occupancy is critical to success.

This champion may appear in different ways. Ideally, the owner would be the champion establishing zero energy and other performance goals for the project. They would decide on a procurement methodology that helps select the best team to meet the goals. This team could be the architectural/engineering (A/E) firm or an expanded team that includes the contractor and facility managers and which has advantages in continuity of meeting performance goals.

As a zero energy project comes into focus, consider including the role of the zero energy champion in the scope of every discipline on the project team (i.e., architect, engineer, contractor, commissioning provider, etc.). They will each bring their specific expertise to the zero energy goal and steer the project through challenges that might put it at risk during the life of the project. In the end, the owner also needs to be a champion, as zero energy is achieved through successful operations and not just design and construction.

Collaborate and Iterate

Zero energy offices demand highly collaborative synergies among those who plan, design, construct, use, operate, and maintain them. There are many project delivery methods, including design-bid-build, design-build, integrated project delivery (IPD), and construction manager at risk (CMAR). Each one has benefits and potential issues that need to be addressed when selecting the most appropriate one. Regardless of the delivery method, the process should be integrated from the outset. An integrated process

> is highly collaborative. This approach requires the whole project team to think of the entire building and all of the systems together, emphasizing connections and improving communication among professionals and stakeholders throughout the life of a project. It breaks down disciplinary boundaries and rejects linear planning and design processes that can lead to inefficient solutions. (USGBC 2014)

The advantages of an integrated process in maximizing synergies across program, site, and system requirements have been noted for many building types, whether or not the goal is zero energy. For zero energy offices, finding synergies through an integrated process is an essential strategy for achieving the low EUI needed within the budget available, as this creates a single integrated system from which no major component can be removed or substantially altered without raising the EUI.

The extensive integration of multiple aspects of a zero energy office project requires a collaborative process to maximize synergies for effective solutions. This process begins at the earliest stages, incorporating more detailed data and technical analysis when setting goals and developing the performance criteria. As predesign evolves through design and construction, an iterative process is characterized by feedback loops, cycles between data analysis, building simulation, and design, which gradually optimizes the design as more design data emerges. The repeated cycles through building simulation analyses to optimize the design are illustrated in Figure 2-3. Ultimately the feedback does not stop with occupancy but is carried over into post occupancy as the occupants develop the most efficient ways to run the building.

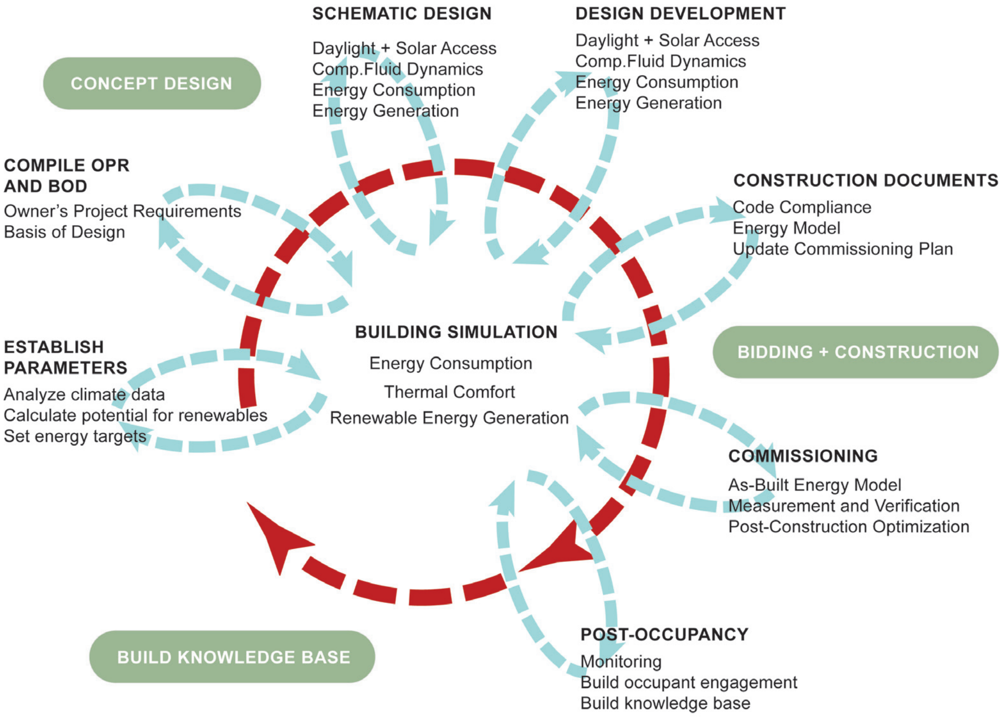


Figure 2-3 Integrated Design Process for a Zero Energy

Aim for the Target

Once the project budget is established and predesign program definition and concept design begin for the project, the zero energy design begins as well. This may occur after the hiring of the A/E team for a design-bid-build or CMAR project or as part of writing the request for proposals (RFP) for a design-build project. This predesign process involves two types of tasks: data analysis that looks at project parameters (such as consumption data from similar projects and climate data for the site) and building simulation that simulates projected performance of the facility and impacts of various energy-efficiency measures. In an integrated process, these steps are typically iterative (as illustrated in Figure 2-3). Through the iterations the EUI for the project will be established. Establishing the EUI target is covered in Chapter 3 in the subsection "Determine the EUI Target." The building simulation process is addressed in Chapter 4. Additional information and resources are available in the NREL guide *Net-Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options* (Pless and Torcellini 2010).

Review Operating Schedules

Zero energy buildings need clarity around their operating schedules. If mechanical systems are heating or cooling at full capacity when only 10% of the occupants are there, if the lights are on throughout the building when only one corner of one floor is occupied, if the copiers, monitors, and other equipment are on, even in sleep mode, overnight when no one is there, then achieving zero energy will be harder or perhaps impossible to achievable.

Over the past decade, the ability to have flexible work schedules that allow for working at off hours of the day and working remotely from the office have changed the typical use profiles. The advent of co-sharing work environments has also impacted use profiles by extending the operating hours to include evening and even weekend hours.

As part of the initial planning for an office, the project team must establish its assumptions and goals for the use of the building. Operations schedules are defined for equipment and decisions can be made for the controls system that allow the building to shut down. To achieve energy goals, unoccupied buildings must substantially reduce their energy use from occupied hours. This ratio of occupied energy to unoccupied energy is a key success metric for building operations.

Engage and Educate

Even with the most sophisticated controls systems, if the occupants have not embraced the zero energy culture and are not educated on what it means to work in a zero energy office, the chances of achieving zero energy operations are significantly reduced. Just as there must be a champion to drive the project from conception to implementation, there needs to be a program that champions zero energy operations. Occupants need to be shown how to best use the zero energy building to meet their needs and save energy. This can be accomplished by creating a program that engages and educates the occupants on the benefits of working in a zero energy office and what they can do to help ensure the zero energy status is achieved. More detailed information on how to engage and educate occupants is provided in Chapter 3 in the subsection "Educate and Engage Building Occupants."

PLANNING FOR ZERO ENERGY SUCCESS

Achieving a fully operational zero energy project requires a commitment to a design, delivery, and operational process. A project team that lacks discipline to a process or a hierarchy of decision making may find itself victim of project creep or budgetary issues, which have ended many valid attempts to achieve fully zero energy projects.

Project teams that find success tend to both employ an energy champion and define and adhere to a hierarchy of energy decision criteria—or a loading order. The loading order is a design pathway for achieving the zero energy goal and can be defined as a simple set of rules to clarify decision-making processes for energy-efficiency strategies and measures that may be considered for inclusion in the project, such as the following:

1. ***Passive Strategies.*** This first category includes optimizing the static elements of the building for maximum energy efficiency. These elements include the building form and configuration, including the building orientation and layout. The building envelope separates the conditioned spaces from weather elements. It is the barrier. A major role of heating, cooling, and lighting systems is to make up for inadequacies in the envelope. While a building envelope cannot meet all the heating, cooling, and lighting needs for a building, a properly designed envelope can greatly reduce the energy consumption of the building. Measures in this category should be prioritized and employed as extensively as possible.
2. ***Plug and Process Loads (PPLs).*** Determining the amounts and schedules for the plug loads should be done early in the design process. Setting watt density targets for operating hours as well as non-operating hours will determine the heat generated from these devices. Often, understanding plug loads will identify possible plug load reductions—sometimes as high as 50%. Over half of the PPLs are specified by the design team for items such as security systems, elevators, and secondary transformers. Design teams need to be actively involved in reducing plug loads. For example, designing appropriate break rooms with highly efficient appliances may reduce plug loads in the office area of the building.
3. ***Systems Efficiency.*** After the static elements of the building have been designed to minimize heating, cooling, and lighting requirements, the design team can select building systems for maximum energy efficiency. This task may result in very different solutions in different climates and for different building programs and requires building energy modeling to gain knowledge to inform these decisions. System and component selection should be developed with the building operating staff to ensure their buy-in of the selected solutions. Part of system selection is the identification of the real-time monitoring systems that will enable the building operational staff to adjust their control procedures to maximize energy efficiency. These energy "dashboards" are critical both to the initial achievement of the zero energy goal and to maintaining that goal over time. Some of the control systems may include "smart" optimization algorithms that may reduce energy consumption even more than projections made during the design phase.
4. ***Renewables.*** The last components of an overall loading order are renewable generation strategies. In almost all zero energy projects, an on-site renewable generation component will be the final system required to move a project from a low-EUI building to a zero energy or positive-energy building. Renewable energy systems are not often a part of the conventional building budget and may represent a budgetary challenge to the project. Various schemes are available for procuring renewable energy systems; some may entail power purchase arrangements that transfer the procurement cost from the capital budget to the operational budget. Additional information on renewable generation systems is provided in the "Renewable Energy" section of Chapter 5.

Following the above priority for design decision making will usually result in larger reductions in the project EUI for the least capital expenditure. Each project must find its own specific design solution based on building program, climate, owner preferences, and other core building goals, but pursuit of these solutions through a disciplined procedure is the best means of finding the most effective and economical solution.

MAINTAINING ZERO ENERGY GOALS THROUGHOUT A PROJECT

A typical project timeline from the start of design through one year of occupancy is in the range of three years. Throughout the project, there are a number of places in the process where zero energy might be removed from the list of project goals. The most critical project stages where roadblocks occur (and why) are as follows:

- ***Owner's Request for Proposals (RFP).*** The owner should document the desire for zero energy during the RFP process, which helps prioritize that goal for the selected design team.
- ***First Project Estimate.*** Scope reduction at this stage could undermine the zero energy goal. Including a detailed quantity survey in the estimate helps identify challenges to the project budget so that zero energy does not fall victim to inaccurate assumptions or unnecessary inclusions.
- ***Bid/Value Engineering Phase.*** A final bid and value engineering process should focus on adding value to the project by cost-shifting items not connected to the mission/vision or the *why* of the building. Value engineering should focus on cost-effective means of achieving the required goals rather than cutting costs by eliminating goals.
- ***Construction.*** Potential cost overruns, delayed schedules, and change orders due to scope creep could threaten the zero energy goal throughout the construction process.
- ***Occupancy/Energy Verification.*** Effective owner and operator training is necessary to achieving and maintaining the zero energy goal; this allows the stakeholders to adapt to the evolving needs of the building occupants and to detect and correct system failures or maladjustments that might inhibit achievement of the zero energy goal.

Figure 2-4 illustrates how many projects lose their zero energy goal at these critical stages during the design and construction processes. The construction process is explored in more detail in Chapter 3 in the section "Establishing a Zero Energy Process."

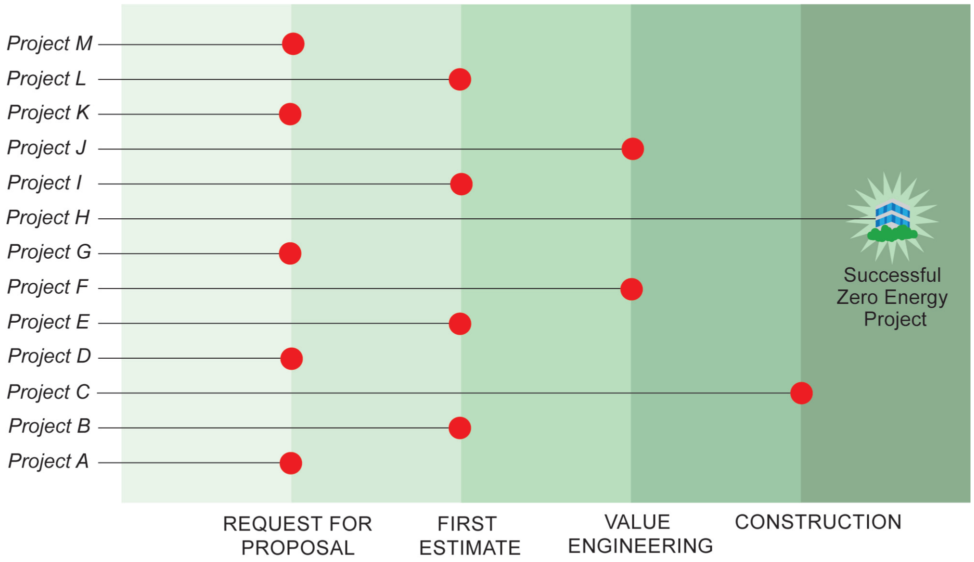


Figure 2-4 Where the Zero Energy Goal Gets Lost

PLANNING FOR THE FUTURE

A final consideration is the ability of the building to adapt to future needs and changes and to minimize future risks and impacts. Planning for the future is about anticipating potential risks and minimizing their impacts before they become an issue. The installation of infrastructure or measures during design and construction can provide the means to do that. The design team should weigh opportunities to include elements in the project that for this purpose. Key areas to consider are discussed in the following subsections.

TECHNOLOGY

Design teams may wish to consider technologies that are not part of conventional practice today but may be just around the corner. These can enhance the flexibility of a building, enable it to exploit some future technology, or enable it better to withstand potential future challenges. Often these measures can be incorporated into the building during initial construction much more inexpensively than they can be incorporated in a retrofit down the line. Examples include the following:

- HVAC systems designed to respond to environmental conditions expected after years of climate change (e.g., a certain number of degrees hotter than today)
- Subsurface or ground-level spaces in anticipation of sea-level rise
- Building electrical systems that incorporate additional renewable energy sources and/or energy storage technologies that might be added in the future when the price drops further

RESILIENCY

More and more building owners are planning for extended utility outages through the design, construction, and operation of their buildings. Storms, other natural events, and man-

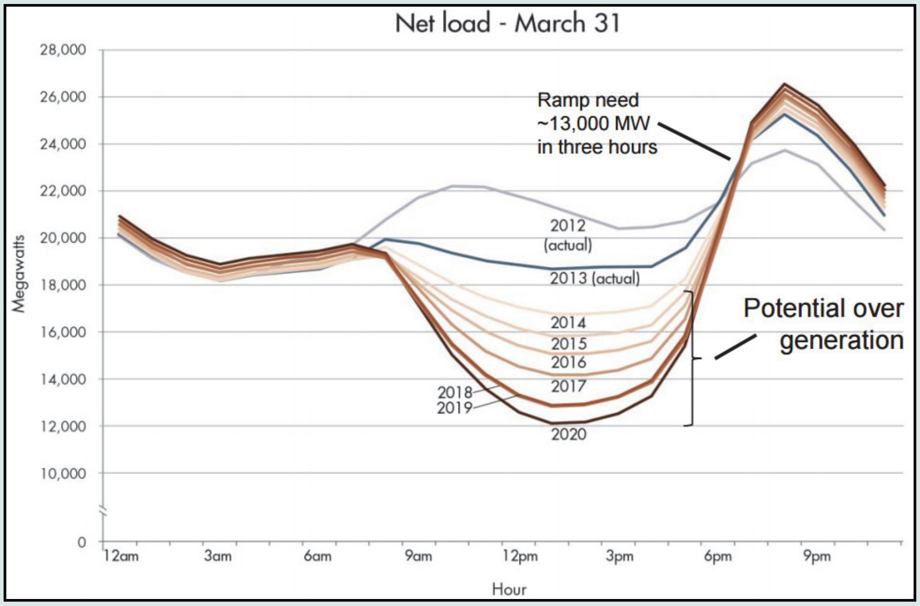
Energy Storage and Grid Considerations

Most zero energy projects are connected to their local electric grid, using the grid as a giant electric battery to provide energy at moments when their on-site renewable energy generation does not cover demand. During times when their on-site renewable generation is higher than demand, energy is exported to the grid for other users. This works as long as other utility customers can use the excess electricity at that time. This is one reason it matters *when* buildings use energy, not just how much energy they use over a year.

At any point in time, grid power production is provided by three major types of assets:

- Base load assets, such as nuclear and combined cycle coal plants that do not easily adapt to shifting loads
- Renewable energy assets, which produce power depending on the availability of the renewable source (such as when the sun is shining or wind is blowing)
- Peaking assets, which are precisely controllable to closely respond to demand, second by second (these generally include gas turbines and some forms of hydroelectric generation)

In some utility grids, the portion of renewable generation is so high that there can be times when total demand load is lower than the combined energy supplied through utility power plants and renewable energy assets. At these points in time, the utilities curtail, or cut off, renewable generation. Buildings with on-site renewables, including some zero energy buildings, may be adding renewable energy to the grid at times when it is not needed and may be taking energy from the grid at times when supply is low. The load profile for a clear summer day for the California utility grid that is often used to illustrate this problem is called the "duck curve." As California adds more renewable generation assets to the grid, it runs the risk of overgeneration during peak solar hours. As the sun begins to set in the late afternoon and solar production falls, grid operators must rapidly dispatch nonrenewable assets to replace the rapidly dropping renewable supply.



Duck Curve Illustration
Image first published by California Independent System Operator (CAISO) in 2013

Because it matters when buildings use energy, there is motivation to design and operate buildings so that they can shift when they demand energy to respond to larger grid needs. In other words, a building that can shift portions of its demand away from peak times and toward times when more energy is available can become more "grid-aligned."

One of the goals of a grid-aligned zero energy building is to alter the energy balance with the grid, reducing its energy export operation when supply is already plentiful (the back of the duck) and increasing its energy export when supply is low (the head of the duck). Multiple technologies exist to help buildings reduce their peak demand from utilities. They can generally be categorized into passive load-reduction strategies and active load-management strategies. Passive load-reduction strategies minimize electric demand at high demand times (the head of the duck), between 5:00 pm and 9:00 pm when cooling loads are still high but photovoltaic (PV) generation is fading. These strategies include minimization of solar heat gain from west exposures while optimizing electric lighting reduction from daylight penetration.

Direct electrical storage is the most effective means of shifting this load. In this method, the excess daytime energy production of the renewable system is stored in a battery to be used after the sun goes down, when the renewable systems are not producing. The most common form of direct energy storage is the battery, typically lithium-ion, due to its round-trip efficiency, energy density, and charge maintenance characteristics.

Thermal storage can provide a benefit by shifting building thermal loads to periods with high utility renewable energy production. Meeting this goal requires a somewhat different strategy than that pursued in traditional peak-load-reduction thermal strategies. For those strategies, cooling might be generated overnight (when demand is low) and used during the afternoon to reduce the peak electric demand. For zero energy buildings, cooling is generated during any period of high renewable energy generation (such as in the morning) when cooling loads are low. The stored cooling energy is used to reduce cooling energy during periods of low renewable generation (such as in the late afternoon) when cooling loads are high and renewable energy generation is waning.

As noted in the "How to Use this Guide" section of Chapter 1, icons are used throughout Chapter 5 to denote recommendations that may be helpful in making a building more grid aligned by either reducing peak demand and/or shifting demand to times when overall grid demand is lower.

made power outages significantly impact building operations and a building's resistance to damage—such as damage that may be caused by flooding or by freezing pipes. Loss of power can also have impacts on human health. Many concepts for creating resilient buildings parallel those of creating zero energy buildings. These concepts include energy-efficiency strategies, on-site renewable energy, and energy storage to operate the building when the grid is not available or is at reduced capacity.

GRID ALIGNMENT

The electrical grid is changing. Between 2010 and 2016, installations of utility-scale photovoltaics (PVs) increased 72% (EIA 2017). This has resulted in periods of the year where substantial amounts of renewable energy are available to electrical consumers. As their prices continue to drop, renewable energy production systems, primarily wind and solar, are be being installed at an increasing rate. To meet consumers' demands for electricity, this renewable energy is balanced with traditional sources. In some areas, the renewable energy is being shed or curtailed to maintain grid stability. The utility load is governed by when customers need the electricity, which typically peaks in the late afternoon and early morning hours. Neither of these times aligns well with renewable energy generation.

Zero energy buildings can help reduce this strain by being designed to be dynamic—adjusting to the changing grid of the future—a future where renewable energy constitutes most of the power production. While the strategies in this Guide are focused on energy consumption, some of these strategies can be used to help buildings be dynamic, adjusting to benefit the utility grid. Additional information on grid considerations is available in the sidebar "Energy Storage and Grid Considerations."

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CINCINNATI DISTRICT 3 POLICE HEADQUARTERS

CLIMATE ZONE 4A

EUI
26.7

Cincinnati, Ohio

A police station is always operational (365/24/7), making the Cincinnati District 3 Police Headquarters the first mission-critical zero energy building in the United States. Energy conservation is prioritized because the additional operating hours lead to more energy consumption than a typical zero energy building, which has a substantial impact on the cost of the renewable energy.

A collaborative, immersive design process was used to challenge the project team to find creative solutions early in the process. This allowed the project to achieve the sustainability and energy goals while meeting all the functional requirements of the building.

KEY ENERGY-EFFICIENCY AND SUSTAINABLE FEATURES

- LED lighting in occupied spaces with 0.54 W/ft^2 overall LPD
- Exterior LED lighting with occupancy sensors
- Orientation and glazing selected to maximize daylight and minimize solar heat gain
- BAS with remote oversight and on-site energy management system
- Bioswales and biofiltration/retention basis to mitigate/cleanse storm-water runoff
- Rain garden with community feature

For more information, visit http://www.hpbmagazine.org/Cincinnati-District-3-Police-Headquarters-Cincinnati-Ohio/ and https://www.cmta.com/results/case-studies/a-design-and-build-project-for-cincinnati-s-district-3-police-headquarters.

District 3 Station Exterior
Used with Permission, © Dish Design

Interior Office Space
Used with Permission, © Dish Design

Office and Meeting Space
Used with Permission, © Dish Design

Project Data

Conditioned gross area: 31,000 ft^2
Building usage: Office, public meeting
Occupancy model: Owner occupied
Number of floors: 2
Context: Urban
Year completed: 2015
Delivery method: Design build
Construction cost: \$372.70/ft^2

Energy Data

Predicted EUI: 35 kBtu/ft^2·yr
Actual EUI: 26.7 kBtu/ft^2·yr
Actual net EUI: –14.8 kBtu/ft^2·yr
ZE status: Zero Energy Certified 2016

Other Metrics

Performance monitoring: Yes
M&V: Yes

Certifications

Certification/year: LEED Platinum, Zero Water

Building Envelope

Roof overall R-value: R-30
Wall overall R-value: R-26
Window type: Bulletproof glass
Window assembly U-factor: 0.29
SHGC: 0.44
VT: 0.70
Measured airtightness: 0.09 cfm/ft^2 at 50 Pa

Building Systems

HVAC system: Geothermal
Heat recovery system: DOAS with recovery wheel and two-pipe coil
RE type and size: 329 kW solar PV system
RECs: 403 annual SRECs

Project Team

Architect: emersion DESIGN LLC
General contractor: Messer Construction
Engineers: CMTA Inc.
Energy consultant: CMTA Inc.
Construction manager: Messer Construction

A Process for Success

3

Chapter 3 weaves the principles for success presented in Chapter 2 into a zero energy project process to be led by the owner or owner's representative. In comparison to a traditional project process, a zero energy goal requires that the owner maintain the focus on zero energy during all planning, design, and operation decisions. The key steps in this process include the following:

- Establishing zero energy as a goal
- Selecting the right contracting process and the right team
- Selecting the energy performance target for the building
- Highlighting the energy goal in all project descriptions and documents
- Quantifying the impact of all design decisions on the energy performance in an iterative process throughout design
- Incentivizing the team to continue to reach for or exceed the goal throughout the process
- Transitioning the energy performance from a design goal to an operational reality
- Setting up a system of ongoing checks and alignments to realize this success over the life of the building

These steps are described in more detail in the following sections, which break the process into planning, design, and operation phases.

ESTABLISHING A ZERO ENERGY PROCESS

Creating a zero energy building is about making good design decisions to deliver a finely tuned product. To create this product, a process is needed to help guide the decision-making process.

The technology and tools to achieve zero energy are readily available at reasonable costs, as shown by many case study examples. Moreover, many different systems and components can be used. Much of what is different about zero energy occurs during project planning—many times before design teams are selected. The most important and sometimes subtle shifts within a typical building zero energy project process are described in the following subsections.

SET THE GOAL

Owners build buildings for many reasons other than achieving zero energy status. These other goals, which include function, organizational mission, public image, economic performance, and occupant amenities, must be reconciled with the zero energy goal. Ideally all the goals will complement each other in the final design and the zero energy goal can mesh with all the other goals such that it is a priority in the design-making process. The first commitment is establishing zero energy as a priority.

Committing to zero energy as a primary goal for a project must come from the highest level of the owner's team. Often this top-down approach challenges other team members of the organization to eliminate the business-as-usual approach to their departments or operation of the building. It is critical to include all major stakeholders in identifying the strategies by which the goal is to be achieved, as they may provide innovative modifications of their standard procedures that might facilitate achieving the goal. These stakeholders include not only building facilities and maintenance staff but also cleaning crews, food services staff, and the telecommunications team. Creating paradigm shifts within an organization has a drastic energy reduction impact on the process and plug loads of a facility, which is a requirement in achieving zero energy. A top-down approach to the zero energy process specific to the National Renewable Energy Laboratory (NREL) campus was described in a paper presented at the 2014 ACEEE Summer Study on Energy Efficiency in Buildings (Scheib et al. 2014).

As noted in Chapter 2 in the section "Maintaining Zero Energy Goals Throughout a Project," a project's failure to reach a zero energy goal can be the result of roadblocks that occur at any stage. At each stage, roadblocks can clog the path to zero energy and prevent the project from achieving its potential. A successful team navigates each of these roadblocks and has strategies and lessons learned to overcome each challenge. They carry ownership of the zero energy goal from stage to stage and elevate the priority of building energy performance. Including zero energy in the owner's preferences during the request for proposals (RFP) stage greatly increases the likelihood that teams with zero energy expertise will be selected. Similarly, proper oversight of the estimating team during the project can eliminate errors due to unfamiliarity with energy efficiency and renewable systems and keep the project on path. Maintaining and communicating the priority of the zero energy goal throughout the process and through the final bid and value-engineering stages ensures that the systems and components necessary for achieving that goal will not be eliminated from the project.

SELECT A PROCUREMENT PROCESS

Building projects may be procured through different project delivery methods. Zero energy buildings have successfully been accomplished independent of the project delivery method; however, some methods make it easier to communicate the goals contractually. Three common project delivery methods include design-bid-build, design-build, and construction manager at risk (CMAR).

Design-bid-build is where the owner or agency contracts with separate entities for design and construction. Typically, this is done sequentially—after design is completed, the project is sent out for a contractor bid and then it is built. As a result, there is less opportunity for innovation and optimization through design enhancements integrated with construction technologies and methods. Building owners often select the lowest bid on this type of procurement, which can create challenges with achieving zero energy. Even if the lowest bidder understands the requirements for zero energy, it may be all but impossible to ensure that all subcontractors and suppliers also do when lowest price is the prime selection criterion.

Design-build offers increased opportunities for integration of design with cost-effective construction methods because the design and construction are carried out by the same entity. Here the challenge is to craft the RFP so that the critical project parameters are maintained throughout the course of design and construction. This typically requires hiring a design team to help develop the RFP. One of the challenges with the design-build RFP process is striking an appropriate balance between defining the critical parameters in sufficient detail and leaving room for possible innovations by the design-build team.

Construction manager at risk (CMAR) is where the owner, architectural/engineering (A/E) team, and contractor are brought together as one project team as early as possible in the design process. With CMAR, the owner negotiates a guaranteed maximum price or maximum allowable construction cost. This option offers a means for the contractor to become part of the project team as early as possible in the process, preferably no later than concept design. The general contractor or construction manager is able to advocate for feasible solutions and troubleshoot issues, and cost control can be maintained through competitive bids of the subcontractors.

The most important elements to have in any process are as follows:

- Buy-in by all team members, including the contractor and architect
- Early commitment to zero energy demonstrated by goal listed in early project documents and the contract
- Communication plan to reach mutually agreeable solutions for meeting the zero energy goal
- Commitment from the team to ensure measured zero energy through the life of the building

Some examples of procurement options used for zero energy projects include the following:

- The U.S. Department of Energy (DOE) successfully procured two zero energy office buildings (RSF I and RSF II) at the NREL campus in Golden, Colorado. A design-build project delivery method was used for both buildings.
- The city of Cincinnati used a design-build delivery method and a caveat for a “Betterment Option” to procure a zero energy police station.
- Warren County schools in Kentucky used a design-bid-build delivery method to procure the first zero energy school in the United States in 2010 and utilized an energy service company (ESCO) to make their most recent school zero energy.
- Arlington Public Schools in Virginia is acquiring solar panels through a power purchase agreement (PPA) to bring Fleet Elementary School to zero energy.

As part of the procurement planning, the project team should consider budgeting for the building and for renewable energy systems separately. Procurement options for renewable energy projects could include an ESCO and PPAs. For additional information on renewable energy sizing, budgeting, and procurement, refer to how-to strategies BP12 to BP19 and RE1 to RE12 in Chapter 5. Also consider budgeting for incentives that reward teams when project goals are exceeded.

HIRE THE PROJECT TEAM

Hiring the right team is the single most important step for the success of any project and therefore is the most important step in successfully completing a zero energy building. Zero energy performance will not be achieved and sustained unless the A/E team hired for the project has the expertise, creativity, and commitment needed to achieve zero energy goals. In addition to the A/E team, a successful zero energy team must include a commissioning provider (CxP) and team members with building modeling expertise. The building modeling team should include building simulations expertise to help guide design decisions keeping the energy goal in mind. The role of the CxP is described later in this chapter, and the building simulation process is described in Chapter 4.

One of best indicators of a team's ability is past performance. Requesting energy performance data from a team's previous projects will show how the team met the challenge of reducing energy consumption on their projects. The best-performing teams consistently provide the best-performing projects with data to show it.

Many owners now track the energy performance of each project and comparing it to projections made during the design process. Using the comparison of projected performance with actual verified performance as a part of the selection process is an effective means for identifying teams that have the design skills to produce the desire level of energy performance.

In addition to hiring the design and construction team, owners should develop a broader integrated project team that includes representatives from typical occupant and facility management groups. Each of these perspectives are necessary to make sure the design decisions that impact operations are viable and represented accurately in the energy modeling process. These people can also support the transition of the building from construction to operation.

The selection of external quality assurance (QA) services should include the same evaluation process the owner would use to select other team members. Qualifications in providing QA services, past performance of projects, cost of services, and availability of the candidate are some of the parameters an owner should investigate and consider when making a selection. While owners may select a member of the design or construction team as the QA provider, most designers are not comfortable testing assemblies and equipment and most contractors do not have the technical background necessary to evaluate performance. Commissioning (Cx) is one method of QA and requires in-depth technical knowledge of building systems as well as operational and construction experience. As a result, this function is best performed by a third party responsible to the owner rather than a member of the design or construction organizations.

In most cases, the CxP is directly contracted with the owner, so engaging a CxP is often done by way of a separate RFP process. There are good reasons to consider engaging a CxP as early, if not earlier, than the design team itself. Typically, a CxP will contribute their technical expertise to the creation of the Owner's Project Requirements (OPR).

INCORPORATE THE GOAL IN THE OPR AND BOD

Establishing the goal of zero energy early in the process and maintaining the priority of that goal throughout the design and construction phases are major factors in successfully accomplishing that goal. Two critical documents for defining the scope, goals, and strategies for the project are the Owner's Project Requirements (OPR) and the Basis of Design (BOD). These two documents define the scope of the project and how that scope is to be achieved.

The OPR is a written document that details the functional requirements of a project from the owner's perspective. It defines, in detail, the owner's expectations for the building. These include the program, occupancy, capacities, loads to be met, environment to be maintained, budget, and any specific owner requirements or preferences for components, systems, equipment, materials, or operating procedures, including energy performance metrics.

The BOD is a document that records the major thought processes and assumptions behind design decisions made to meet the OPR. The BOD informs the owner of the strategies and means by which the requirements of the OPR are to be met, including descriptions of systems, components, and materials, along with the performance metrics for each element. A narrative of the relevance of each design selection to the requirements of the OPR should be included in the BOD.

Thus, the OPR is the owner's "ask" and the BOD is the detailed description of the means by which the requirements of the "ask" will be fulfilled and an explanation of how the proposed solutions meet the requirements of the "ask".

Beyond typical use, these documents can also serve as a common place for the conversation about zero energy, highlighting the design and verification intent of the goal and the most important operational assumptions and strategies for zero energy.

MAINTAIN ZERO ENERGY THROUGH DESIGN

Design and construction of a new office building is a long process. Maintaining continuity of primary goals throughout is crucial to the success of the project. Give ownership in the goal to team members; divide the goal into energy use and energy production targets and require that the projected energy performance be compared with the goal at each stage of design.

DETERMINE THE EUI TARGET

One of the most critical steps in a zero energy project is establishing the energy use intensity (EUI) for the project. EUI is the annual energy consumption of the building divided by the gross building area. Once the EUI target is set it becomes the keystone around discussions for system choices, equipment selections, and how other decisions are measured. It opens up the path to major paradigm shifts from selecting new HVAC systems to modifying IT policies. All decisions can be looked at through impact to the EUI. It removes emotion from the discussions and facilitates performance-based decisions.

Complicated cutting-edge technologies are not necessarily required in zero energy buildings. In fact, simplifying a building's systems increases a building's chances of being optimally constructed and operated. The energy manager at Discovery Elementary School, a zero energy school in Arlington, Virginia, notes, "This is our easiest building to operate; the controls were simplified and in some cases, complicated systems were eliminated."[1]

Establishing a feasible EUI target involves evaluating the project parameters. The following steps are suggested:

- Use the recommended values in Table 3-1, which shows targeted EUIs in both site and source energy. *Site energy* is the energy measured at the building location (or site). *Source energy* accounts for transmissions and transformation losses of the site energy back to the source, such as the gas well or coal mine.
- Demonstrate support for the EUI with examples of buildings that have published low EUIs. Case studies in this Guide and from other sources can help.
- Adjust the EUI based on exceptional loads. First create a list of energy end uses. Loads that are not included in the EUIs calculated as part of this Guide need further analysis to determine their impact (see the "Scope" section in Chapter 1 for loads not covered in this Guide).
- Consider the hours that the office building is occupied. In some cases, adjustments may be needed to account for additional occupancy hours.
- Note that the EUI target does not include any renewable generation.

The targets presented in Table 3-1 are provided for the 19 climate locations—zones and subzones and are based on the simulation analysis done for this Guide (see the section "Developing the Guide" in Chapter 1). The U.S. climate zones are shown in Figure 3-1.

It is important to create realistic EUI targets; however, the higher the EUI target, the larger the on-site renewable energy system will need to be to achieve zero energy. The targets in Table 3-1 are the high-end targets for each climate zone. They are achievable and yet are a stretch from typical construction. In many cases, these targets can be reduced by an additional 20% to provide an advanced tier for efficiency, which also means less costs and room for an on-site renewable system.

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[1] John Chadwick, Assistant Superintendent, Facilities and Operation, Arlington Public Schools, Virginia, phone conversation with the author, January 30, 2019.

Table 3-1 Target Energy Use Intensity (EUI)

Climate Zone	Site Energy, $kBtu/ft^2/yr$	Source Energy, $kBtu/ft^2/yr$
0A	23.2	73.1
0B	27.6	86.9
1A	23.4	73.9
1B	25.7	81.1
2A	22.2	69.9
2B	22.8	71.8
3A	21.4	67.3
3B	21.1	66.6
3C	16.0	50.3
4A	21.7	68.5
4B	20.6	64.9
4C	17.3	54.4
5A	23.2	73.0
5B	22.9	72.0
5C	17.5	55.2
6A	27.7	87.3
6B	24.7	77.8
7	30.3	95.5
8	36.0	113.5

Implement the EUI Target

To achieve a low EUI, an energy reduction study should be performed. The study should focus on the typical climate for and the unique energy usages of the building being designed. Finding synergies through the integrated design of all components impacting the energy consumption is an essential strategy for achieving the low EUIs required. For example, reducing the loads through an efficient envelope can reduce heating and cooling needs to the extent that the mechanical system, and consequently also the electrical service, can be reduced significantly. Chapter 4 provides additional details on the modeling processes involved in an energy reduction study.

Zero energy may be impossible to achieve in some urban locations because of the physical constraints of on-site renewable generation. Shading from other buildings and trees along with the number of stories of the building impact the viability of adding renewables. For these buildings, it is still possible to hit the same low EUI target and be zero energy ready.

The how-to recommendations detailed in Chapter 5 provide the strategies for reducing energy usage that are key to achieving the target EUIs shown in Table 3-1.

VERIFY ZERO ENERGY AT EACH STEP OF DESIGN

Once the performance goal has been established, it must be verified through each step of the design and construction process. Modification of the performance goal should be the result only of a modification of other basic requirements, which would then be documented in revi-

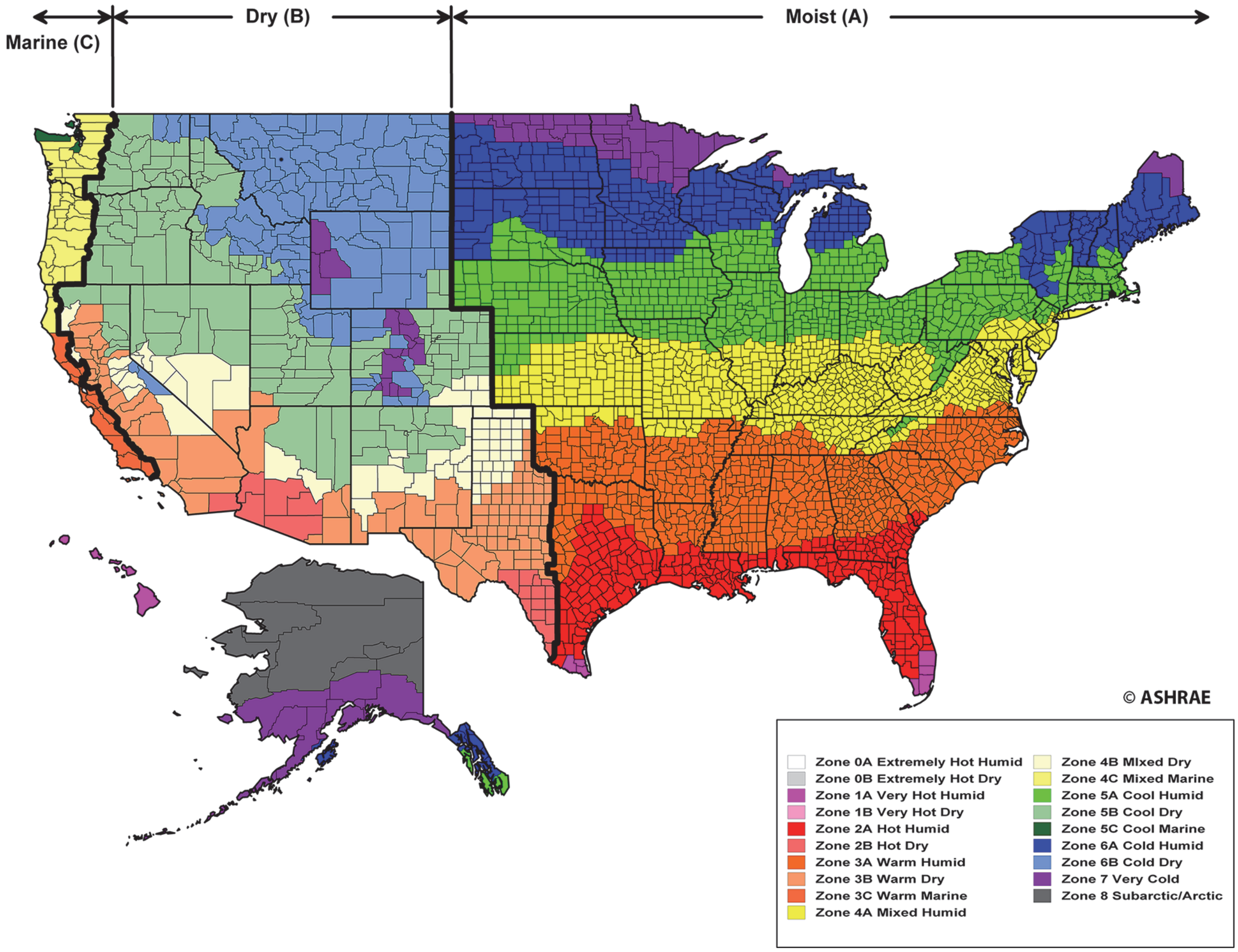


Figure 3-1 Climate Zone Map for U.S. States and Counties
Figure B-1, ASHRAE 2013

sions to the OPR and BOD. Adherence to this rigorous process will help ensure that the actual performance is consistent with that projected during the design and construction phases.

Confirm the EUI through Building Simulation

Energy modeling starts at the onset of the project and progresses with building design. Updates to the energy modeling with every stage of design are required to maintain the EUI targets identified. As the project moves through the design process, the building simulations provide guidance for design decisions that are used to determine the layout, to choose among alternatives, and to uncover opportunities for additional enhancements. Additional information on building simulation is provided in Chapter 4.

Confirm On-Site Renewable Energy Potential

Similar to energy modeling, sizing and production estimates for a renewable energy system must be created at the conceptual design stage. Design of the roof and any required canopies, as prime solar real estate, should be considered with the zero energy goal in mind. Considerations include maximizing the availability of renewable systems, eliminating obstacles to the installation of the photovoltaic (PV) array, and shadowing issues. The zero energy goal should be confirmed at each stage of the design, with the renewable energy potential reported to the design team. For additional information on designing for on-site renewable generation, see how-to strategies BP12 to BP19 and RE1 to RE12 in Chapter 5.

Calculate the Energy Balance

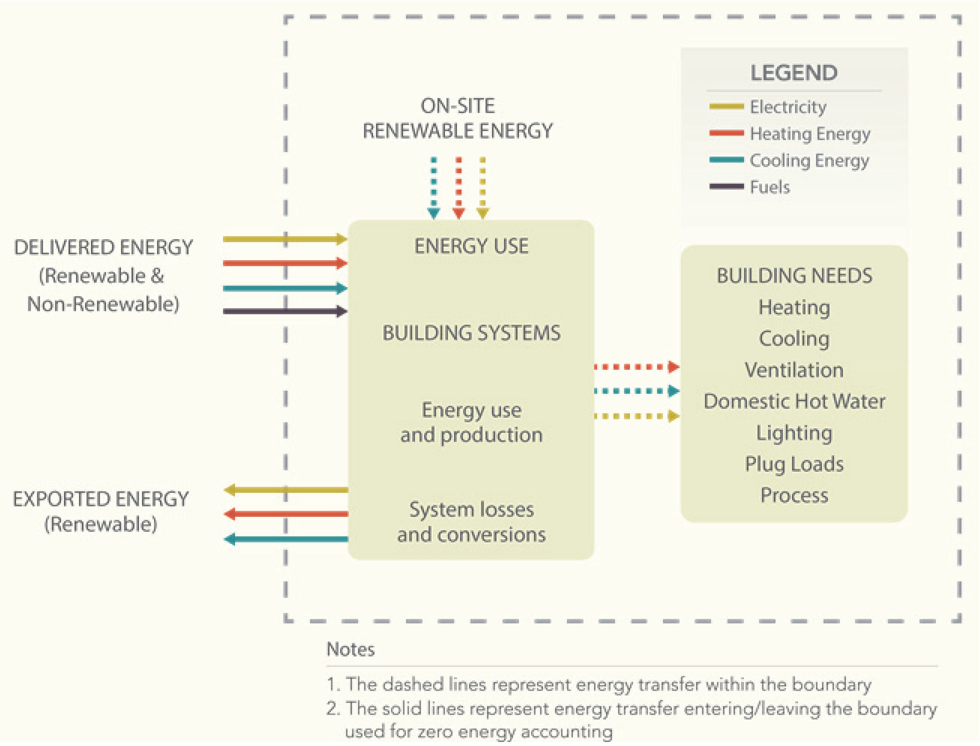
Once quantities for energy consumption and energy generation have been established, the energy factors (EFs) must be applied to determine if the energy generation is adequate to meet the definition of zero energy. Details on how to calculate the energy balance are provided in DOE's *A Common Definition for Zero Energy Buildings* (DOE 2015). Site boundaries of energy transfer for zero energy accounting are illustrated in Figure 3-2.

Two points are worth noting in regards to the calculation of the energy balance and the determination of zero energy performance:

- Energy used for charging vehicles is counted as energy exported from the site.
- A project must retain the renewable energy certificates (RECs). (See how-to strategy RE1 in Chapter 5 for a definition of RECs.)

The energy balance calculation will occur at numerous intervals throughout the design process, leading to further refinements of the project, with additional energy-efficiency measures included if necessary to lower the EUI until it meets the energy generation potential. Typically, a margin of error is recommended to ensure meeting the target. Almost always, buildings use slightly more energy than is predicted and renewable generation sources produce a little less than was expected.

Many teams set a production goal of 5% to 10% above the consumption goal for the first year. This helps eliminate discrepancies caused by systems coming on line and helps challenge the owner to minimize energy consumption as the building ages and the renewable and mechanical systems experience a slight degradation in performance.



Notes

1. The dashed lines represent energy transfer within the boundary
2. The solid lines represent energy transfer entering/leaving the boundary used for zero energy accounting

Figure 3-2 Energy Balance Diagram
Figure 1, DOE 2015

Incentivize the Team to Improve

The process of energy modeling, renewable energy system sizing, and energy balance calculations at each stage of design will reveal the trajectory toward zero energy. To seed the team with excitement and willingness to make hard decisions at all stages in the interest of achieving the goal, provide the design and construction team a financial incentive (a separate budget allocation determined in the planning phase) at each design stage when the team exceeds the zero energy goal. If a team identifies a problem in the path to the goal, the incentive can be gained in full if they correct the path by the next stage.

SUPPORT ZERO ENERGY IN ONGOING OPERATION

The final reward of a zero energy goal comes to the owner and the project team when the building operates as zero energy year after year and when the occupants take part in the success over time. Just as the planning phase requires careful attention to how the goal is passed from owner's vision to team responsibility, the turnover phase requires careful attention to how the goal is passed from the project team to the building operators and occupants. The following subsections describe key steps toward this final success.

CONFIRM ZERO ENERGY THROUGH COMMISSIONING

Quantitatively, early success is obtained when the building performs to the EUI targets that have been specified and the renewable energy is shown to generate its projected amount of energy. The simplest confirmation is based on tracking of overall annual energy through utility bills. On-site metering can also be used and can provide additional insights, including comparisons with the modeling results developed by the design team.

The achievement of the zero energy performance goal can be confirmed after one year of operation. Ensuring the building continues to achieve zero energy year after year requires strong quality assurance (QA) through a Cx process.

QA is a systematic process of verifying the OPR, operational needs, and the BOD and of ensuring that the building performs in accordance with these defined needs. A strong QA approach begins with designating responsible parties to help manage the QA process. While the QA team can be in house or an external third party, note that it is difficult to achieve total project oversight using only in-house resources.

A critical role on the QA team is that of the CxP. The Cx process encompasses the review, testing, and validation of a designated system to ensure that it performs as expected. In a high-performance building, Cx of the following components is a critical part of the QA process:

- Building enclosure, including walls, roof, fenestration, and slab
- Building systems, including heating, ventilating, and air conditioning (HVAC); lighting and lighting controls; plug load management; and renewable energy systems
- Indoor environmental quality (IEQ), including air quality, lighting quality, and acoustical performance

The CxP also operates as an owner's technical advocate during the design review process to help ensure that the requirements of the OPR are being met and that systems can be tested properly. They also provide a technical peer review of the construction documents for the systems being commissioned. This review provides an additional layer of QA.

Within each team, internal QA review by individuals not directly involved with team activities provides assurance that the specific activities and products of that team are consistent. Review of the OPR by the ownership team can ensure that the OPR is consistent with organization requirements fort the facility. Review of the OPR and BOD by the owner's facilities staff can ensure that both the requirements and the proposed solutions are consistent with their standards. The goal of QA is thus twofold: to ensure that the activities and products of each team are internally consistent, and to ensure that the activities and products of each team are consistent with one another. As a result, QA responsibility is shared—within each team and, typically, by a third party that reviews the overall consistency of the joint effort of the teams.

As the project proceeds through the stages of design, it is important that the QA team have ample opportunity to review the design and provide feedback. A log of the QA team's comments should be kept, and noted issues should be resolved. The QA team's review is intended to ensure that the design and supporting documents are developed in adherence to the OPR.

COMMISSIONING FOR ZERO ENERGY SYSTEMS

The following multidisciplinary activities and the noted associated personnel should be considered for integrated approaches in traditional mechanical, electrical, and plumbing system Cx:

- Construction document specifications include requirements for Cx activities, such as participating in reviews and documenting results, conducting Cx meetings, collaborating with other team members, and identifying corrective actions.
- Site-based Cx requires input from at least the following parties: the general contractor; the mechanical, electrical, controls, and test and balance (TAB) subcontractors; the CxP; the owner's representative; and the mechanical, electrical, and lighting designers.
- Prefunctional test procedures usually require evaluation of motors and wiring by the electrical subcontractor and the manufacturer's representative and evaluation of component performance by the manufacturer's representative and the mechanical, TAB, and controls subcontractors. The CxP will generally sample to back-check the values reported in the pre-functional checklist results.
- Functional tests involve the CxP and the controls and TAB subcontractors at a minimum.

In addition to the usual tests of control sequences, it is also important to document that the building meets the necessary indoor air quality (IAQ) requirements. This can be accomplished through physical testing, in which concentrations of typical pollutants are measured and compared to health standards. Also, building flush-outs are usually performed to remove construction-related odors and off-gassing chemicals from the air volume of the space prior to permanent occupancy. This decontamination process should be conducted in accordance with documented preoccupancy purge procedures, which usually involve multiple hours of 100% ventilation air supply.

The selected contractors should build QA plans to demonstrate how they plan to achieve the required performance and should build in milestones for demonstrating performance as part of the Cx process.

Specific and detailed Cx tasks are found in publications by ASHRAE (2015, 2018a) and ASTM International (ASTM 2016, 2018). However, basic descriptions of key Cx strategies for various building elements follow.

Building Envelope

The building envelope is a key element of zero energy design. It includes roofs, walls, windows, doors, floors, slabs, and foundations. Improper placement of insulation, wrong or poorly performing glazing and fenestration systems, incorrect placement of shading devices, misplacement of daylighting shelves, improper sealing or lack of sealing at air barriers, and misinterpretation of assembly details can significantly compromise the energy performance of a building. Therefore, at various points in the construction process, assembly testing or whole-building testing may be performed to ensure the quality of the assembly construction.

Assembly testing includes performing air and moisture tests on individual components of a building, such as a wall, roof, or window. Large fans and spray racks are connected and inspected to determine the levels of air and moisture infiltration.

A mock-up is a small sample of constructed wall or assembly that is used to demonstrate the process and product that will be constructed on a much larger scale. Mock-ups are constructed early in the construction process by the contractor and are inspected by the CxP, architect, and QA team for air and water infiltration so that any issues can be resolved before the construction of the actual assembly. If thorough mock-up testing has been performed, more expensive assembly testing can often be deferred. However, complicated façades such as large curtain wall assemblies or heavily articulated wall extrusions may warrant further testing to ensure performance.

Whole-building testing uses blower door tests to determine the levels of leakage through an enclosure. Testing and remediation should be conducted to achieve the air infiltration rates specified in the OPR. Ideally, these are conducted at a point in time that allows for easy correction of the issue, such as before drywall is installed.

The results of the blower door test should be input into the as-built energy model for an accurate understanding of energy loads. If the results of the blower door test do not meet the OPR criteria or contract requirements, specific leaks may be identified with smoke testing and infrared thermography testing. Infrared testing identifies points of temperature differential at the building envelope, which can correlate with points of infiltration.

Building Systems

Building systems include HVAC, lighting, controls systems, renewable energy, and renewable energy storage. Commissioning these systems involves testing the performance of the active systems of a building. Once the equipment has been successfully energized and started, the systems undergo a series of tests, referred to as *functional performance testing* (FPT), to determine if it is functioning as expected.

Buildings are subjected to a highly dynamic set of conditions that influence their performance, including environmental conditions (seasonal) and internal conditions (fluctuating occupancy). The Cx process attempts to replicate these conditions prior to occupancy, but it is not uncommon for follow-up Cx work to occur as the seasons change to ensure performance in both heating and cooling seasons.

Indoor Environmental Quality

Indoor environmental quality (IEQ) includes IAQ, lighting quality, quality of views, acoustical performance, and thermal comfort. Commissioning of IEQ is less common than enclosure or systems Cx, but it is important to ensure that the zero energy building meets the environmental needs of the occupants.

Whereas systems and enclosure Cx tests component and system performance, IEQ Cx tests the outcomes of these systems' performance from the perspective of occupant needs. Testing should follow risk-based science for acceptable exposure and should include the following:

- ***Indoor Air Quality.*** Testing for carbon dioxide (CO_2), particulate matter, volatile organic compounds (VOCs), formaldehyde, carbon monoxide, ozone, and radon.
- ***Lighting Quality.*** Testing of illuminance, luminance ratios, glare potential, color quality, and daylight efficacy.
- ***Quality of Views.*** Assessment of line of sight for all occupants, view quality to outdoors, and glare control.
- ***Acoustical Performance.*** Testing of HVAC noise criteria, reverberation time, sound transmission, and sound amplification devices.
- ***Thermal Comfort.*** Testing of air temperature, radiant temperature, thermal stratification, and humidity, including individual thermal comfort surveys.

The Cx specifications should clearly articulate all aspects that are being tested for (i.e., specific contaminants and performance thresholds) so that they are included in the scope and so that expectations are aligned between the owner and the testing agencies.

VERIFY ZERO ENERGY IN EARLY OPERATION

Often, the first three months of building occupancy are used to optimize systems and mitigate issues and conflicts. Using the initial energy-use data, calculate the path to zero energy on a month-by-month basis, identifying energy-production and energy-use goals separately. At the end of each month, the performance of the system verses the expectation should be communicated to the design team and owner. Especially during the first three months, it is important to look for major systems scheduling issues and verify scheduling of all systems.

The measurement and verification (M&V) period typically spans 12 to 24 months after substantial completion of the building. During this time, the CxP, design team, contractor, and energy modeler will work together with the owner to review the energy performance of the project. If anomalies are found between the expected performance from the calibrated model and the actual performance, they should be identified and resolved. M&V is a process that needs to be defined by the project team at the outset.

Typical items that can cause a building to stray from the expected energy performance are associated with weather and use (i.e., occupancy patterns). A calibrated energy model inputs the actual data over a period to study whether the building performed as expected.

The scope associated with M&V is vital but is often missed during the selection process. It is important to discuss this scope with the team and identify who will be responsible for the tasks necessary to verify the building is on target to achieve zero energy and, if it is not, what the course of action is.

Every project should document best practices and lessons learned. These will help improve future projects and long-term operations. By educating others on points to avoid, mistakes on future buildings can be minimized

TRACK ZERO ENERGY FOR THE LONG TERM

It takes at least 12 months of postoccupancy performance to verify that a building is (or is not) meeting the zero energy performance goals. This length of time is required to verify that on an annual basis the building is generating the expected amount of renewable energy, the building is consuming the expected amount of energy, and the generation and consumption balance out. It is only after this validation has been completed that a building can be called a zero energy building. However, it is important to continue to maintain the level of efficiency, if not improve on it, year over year. Successful projects often incorporate the following strategies:

- Employ an energy manager to manage the performance of the building as well as serve as a resource to deliver continuous training and education as well as feedback on actual building performance to building occupants in order to drive awareness and behavior change, if necessary.
- Utilize monitoring-based Cx, which leverages software and connected devices to automate the diagnostic process during operations. Such systems can identify anomalies in components or systems operating outside of their expected parameters. For example, if a pump that is supposed to vary its speed continuously runs at full speed for a few days, the system would identify this and notify the facility operator. This allows the operator or CxP to address the issue quickly with minimal impact to the building's energy performance.

It is important to ensure sufficient funds in the operating budget to maintain and operate a building at a zero energy performance level. Doing so will result in long-term operating budget savings. Ensure that maintaining zero energy performance is included in the scope for the facility maintenance team even if this service is outsourced. If the facility maintenance team is on staff, consider including performance bonuses for annual zero energy achievement.

EDUCATE AND ENGAGE BUILDING OCCUPANTS

A zero energy office building has a much greater likelihood of success if the tenants themselves become educated advocates as they occupy and use the building.

An effective way of educating occupants to use the building intelligently is making use of a building monitoring system with an energy dashboard that can be accessed online. The energy dashboard provides data about how the building is performing in relation to numerous factors, including the time of day, the season of the year, the weather, the microclimate, and how the building is being used at any given time. When this performance information from the building monitoring system is shared with the occupants it provides the opportunity to understand how the building responds to their inputs and actions, enabling the occupants to become better users of the building, positively impacting the overall performance. Building dashboards are sometimes available from controls vendors as well as third parties. Some custom vendors also create dashboards. The scope for developing a dashboard should be included in the budget. It is also important that building owners, operators, and tenants are made aware of the opportunities the dashboard provides as early possible in the design process so that they will support the expenditure, provide valuable participation in the process of developing it, and be able to educate occupants on how to make best use of this resource.

Occupants should be included in announcements of zero energy success and solicited for ideas on increasing performance over time, since they are the true environmental sensors of the building and can share ownership in the goal as their ideas are implemented.

Additional opportunities include pre-move education sessions on zero energy, lunch and learn sessions that speak to the building performance, campaigns that focus on energy reduction targets, and celebrations when targets are achieved.

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NREL RESEARCH SUPPORT FACILITY (RSF)

CLIMATE ZONE 6A

EUI
35.4

Golden, Colorado

The approach taken by the National Renewable Energy Laboratory (NREL) for achieving a zero energy building was to write performance requirements into the contract for the design and construction of the building. This performance-based design-build approach shifted responsibility and control to the design-build team. The project had aggressive performance, cost, and schedule requirements. Successful execution required well-defined objectives by the NREL team. As it turns out, focusing on zero energy allows many of the other objectives to fall into place. The finished facility provides a living laboratory for best practices in zero energy performance.

KEY ENERGY-EFFICIENCY AND SUSTAINABLE FEATURES

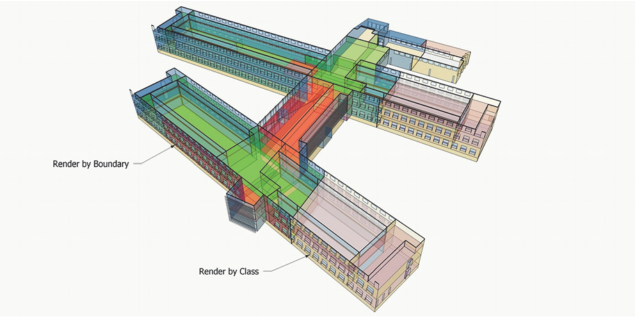
- H-shaped building plan with narrow (60 ft wide) east-west oriented wings
- 100% daylighted footprint with reflective louvered shade system to redirect sunlight
- Manual-ON, automatic-OFF lighting with photosensors, vacancy sensors, and time clock
- Operable windows with manual (67%) and automated (33%) operation
- Transpired solar collector with natural ventilation and night purging
- Dedicated cooling system for data center that exports useful heat to building
- Real-time energy dashboard

For more information, visit https://www.nrel.gov/docs/fy10osti/47870.pdf and http://www.hpbmagazine.org/Case-Studies/Department-of-Energys-National-Renewable-Energy-Laboratory-Research-Support-Facility-Golden-CO/.

NREL RSF
Photograph by Dennis Schroeder, NREL 17825

Daylighted Corridor
Photograph by Dennis Schroeder, NREL 17614

Caption
Photograph by Marjorie Schott, NREL 500006-C



Caption
Image by David Goldwasser, NREL 18547

Project Data

Building area: 220,000 ft^2
Number of floors: 4
Occupancy model: Owner occupied
Context: Suburban
Number of occupants: 822 (79%)
Year completed: 2010
Delivery method: Performance-based design-build
Construction cost: $57,400,000 ($259/ ft^2)

Energy Data

Predicted EUI: 35.1 kBtu/ft^2
Actual EUI: 35.4 kBtu/ft^2 with data center, 20.9 kBtu/ft^2 without data center
Actual net EUI: 11.2 kBtu/ft^2

Building Systems

LPD: 0.63 W/ft^2 (installed)

Plug-load power density: 0.35 W/ft^2
HVAC systems: Hydronic radiant slab ceilings and VAV reheat (non-office spaces)
Ventilation: DOAS with CO_2-based DCV

RE type and size: Four on-site PV systems totaling 1.6 MW
Energy storage: Transpired solar collector

Building Envelope

Roof type: Standing seam
Overall R-value: R-33
Wall construction: Precast wall and steel stud
Overall R-value: R-15
Foundation insulation R-value: R-10

WWR: 27%
View window type: Triple pane, low-e glazing
View window assembly U-factor: 0.17
View SHGC: 0.23
View VT: 0.43

Daylight window: Double pane, low-e glazing
Daylight window assembly U-factor: 0.29
Daylight SHGC: 0.38
Daylight VT: 0.70

Project Team

Owner: DOE and NREL
Architect: RNL
General contractor: Haselden Construction
Engineers: Stantec, KL&A, Martin/Martin
Energy consultant: AEC

Certifications

Certification/Year: LEED Platinum 2011; 100 ENERGY STAR score

Building Performance Simulation

4

INTRODUCTION

As discussed in Chapter 3, the energy use goal is critical to achieving zero energy. The performance of the on-site renewable system is also important. As a result, the design process should include mechanisms for assessing the energy performance of the proposed design with real-world operating assumptions. Not only must the tool used to assess the energy performance be capable of modeling the performance of the building systems, but also the operating assumptions must be relatively accurate predictors of how the building will be used. This latter requirement is much more stringent for designing to zero energy than for conventional design efforts because of the need to meet the zero energy benchmark when the building is occupied.

Many strategies can be used to achieve zero energy. The design process establishes goals and priorities for the project and identifies the strategies for achieving these prioritized goals. Specific strategies, best practices, and advice on their implementation are covered in Chapter 5. As discussed in previous chapters, achieving zero energy performance is only one of the reasons that owners build buildings. There are a number of performance goals that are included in the conventional design process. Using building energy modeling to meet specific performance goals requires using these tools to help guide the decision making process. Using these tools after design decisions often yields disappointing results as goals are not met even though energy modeling has been done.

Technological advancements have given designers the capability to almost instantly access feedback regarding the energy performance of a design and to optimize the project design through building performance simulation. The design and construction process for a zero energy building must provide for inclusion of feedback throughout the process so that the energy impact of each design and construction decision can be evaluated. The design team must provide accurate information concerning the components of the proposed design when they become available. As the design process progresses, the design team must encourage the owner to generate accurate projections concerning the building's use. Examples of this information include daily and monthly operating and occupancy schedules, occupant densities, owner-provided equipment power and utilization, and after-hour use including special or public events. The operating characteristics of the occupied building will have an impact on the building energy usage.

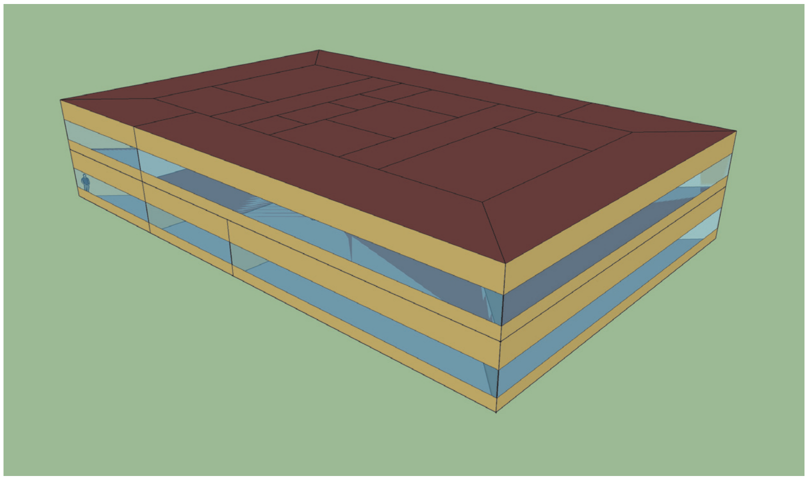


Figure 4-1 Office Prototype Building

The term *building performance simulation* encompasses the numerous forms of computational simulation that may be conducted during the design process. *Energy modeling* is often referenced among designers and remains an accurate description of the simulation process used to study energy performance of a building. While energy modeling generally looks at the whole building, additional specialty analyses may be needed for some technologies such as lighting, daylighting, and natural ventilation. While the energy impacts of these design strategies is certainly of interest, particularly in a zero energy building, they are not the only criteria that defines success. Lighting quality, thermal comfort, and indoor air quality (IAQ) are examples that should be modeled while meeting the energy goals.

The recommendations presented in this Guide are the result of numerous building energy simulation analyses using the prototype building shown in Figure 4-1. More information on the simulation specifics used in this Guide are detailed in the “Energy Modeling for the AEDG” sidebar.

TECHNICAL APPROACH TO ACHIEVE A ZERO ENERGY BUILDING

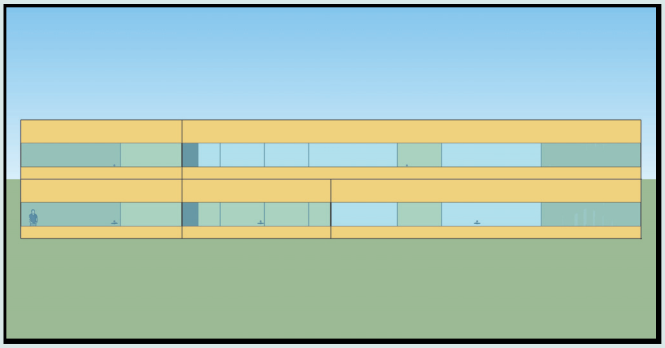
The building physics for achieving a zero energy building can be summed-up easily:

- Minimize the uncontrolled impact of exterior environment upon the interior environment of the building.
- Minimize the energy consumption by the owner-provided equipment to meet the functional requirements of the occupancy with compromise.
- Provide environmental conditioning (heating, cooling, ventilation, lighting) only when and where it is needed within the building. Minimize or turn off systems when no one is present, and condition only those spaces the require conditioning because they are occupied.
- Use climate conditions when appropriate to minimize the energy consumption for maintaining the required conditions in the interior environment (such as free cooling, passive solar heating, and daylighting).
- Maximize the efficiency of the HVAC and lighting systems in the ranges that they most often operate.
- Control the important parameters of the indoor environment separately, to avoid overconditioning when control of multiple parameters are controlled together (i.e., lumping cooling and ventilation into one control may result in overventilation on a hot sunlit day with no occupant in the space).

Energy Modeling for the AEDG

The analyses conducted to inform the design and equipment recommendations in this Advanced Energy Design Guide (AEDG) leveraged the OpenStudio® (ASE 2019) energy modeling platform, which uses EnergyPlus (DOE 2019) as the engine to simulate the thermodynamic heat transfer and fluid dynamics that drive building performance. This open-source software is available to public and private sectors and provides a range of functions for experienced energy modelers that are interested in replicating the analyses used for the AEDG in their own building projects.

The OpenStudio platform provides options for energy modelers to access and apply efficiency measures to a project's building geometry, location, and operational schedules. This can be done by accessing the Building Component Library (BCL) through a tool or service that supports the OpenStudio platform, such as the Parametric Analysis Tool (PAT).



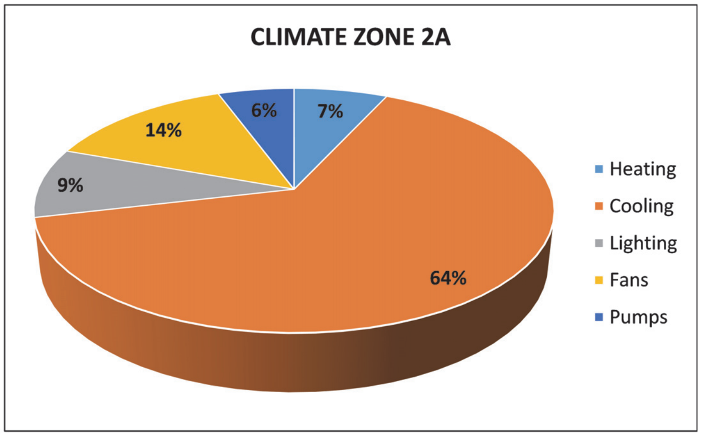
AEDG Zero Energy Office Prototype Building

The BCL includes "Measures," which are scripts that have been created to apply energy-saving measures to an energy model. For example, one measure adds overhangs to all south-facing windows in a model, while another measure easily changes the efficiency of HVAC equipment. More complex measures can strip out and replace entire mechanical systems in a model. The BCL also includes "Components," which describe detailed inputs of specific building elements such as construction assemblies or fan performance. Applications and services that support the OpenStudio platform can apply Measures and Components from the BCL to OpenStudio models. This enables building designers and modelers to easily add efficiency measures and packages of efficiency measures to project energy models for faster and more accurate evaluation.

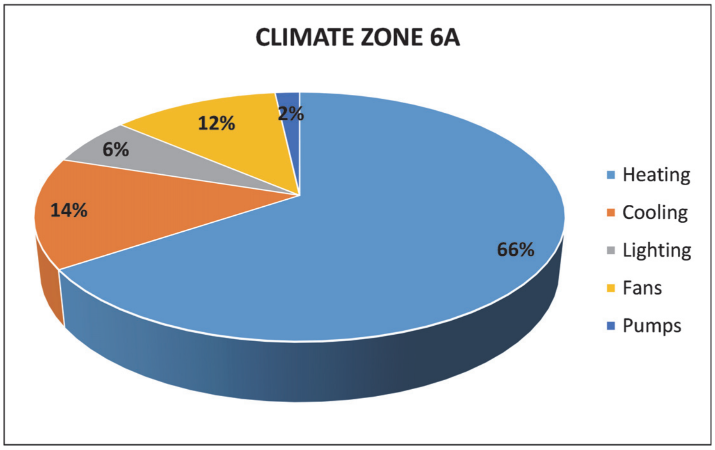
PAT enables energy modelers to create and run customized parametric analyses (of multiple energy efficiency measures) on local or cloud-based servers. PAT applies Measures to baseline building models to quickly compare the energy impacts of different energy-efficiency strategies, helping designers understand the energy impacts of design options. It also enables users to create and view various output reports and output visualizations to present results in clear, understandable formats. With PAT, modelers can perform detailed and powerful parametric studies in a reasonable amount of time for relatively low cost, facilitating a more comprehensive approach to achieving higher-performing buildings.

The OpenStudio platform uses a developer-friendly, open-source license and contains a lightweight command line interface that makes it easy for third-party organizations to incorporate the OpenStudio platform and BCL into their own tools and services. Furthermore, more sophisticated energy modelers can contribute to Component and Measure development within the OpenStudio modeling framework, while maintaining the license of content posted to the BCL. The user community may make contributions that add to or enhance existing components and measures to improve accuracy and help spread adoption of cutting-edge energy-efficiency measures. Additional information is available as follows:

- **OpenStudio:** http://nrel.github.io/OpenStudio-user-documentation/
- **Building Component Library:** https://bcl.nrel.gov/
- **Measures:** http://nrel.github.io/OpenStudio-user-documentation/getting_started/about_measures/
- **Parametric Analysis Tool:** http://nrel.github.io/OpenStudio-user-documentation/reference/parametric_analysis_tool_2/
- **AEDG models:** www.zeroenergy.org



(a)



(b)

Figure 4-2 Energy End-Use Components for Prototype Model using Typical Systems: (a) Tampa, Florida, and (b) Rochester, Minnesota

Buildings with different operating parameters in different climates have different energy use profiles. Building energy modeling in the conceptual design phase can identify the predominant energy end-use components for a specific project. Early identification of the primary energy end uses enables the design team to focus on the means to reduce the major users. Figure 4.2 shows the energy end-use components of the prototype office building used in evaluating the strategies for this Guide in climate zones 2A and 6A. Strategies for reducing cooling and dehumidification are required in climate zone 2A, while strategies to reduce building heat loss and increase heating efficiency are appropriate for climate zone 6A.

DESIGN PROCESS TO IDENTIFY AND IMPLEMENT STRATEGIES

The design team is composed of experts in many disciplines. The design process must be configured to facilitate communication and to provide opportunity at each stage to convey information between the design team members and major stakeholders. For a project with the performance metric of zero energy, conveying both the assumptions and the results of the energy modeling effort is necessary through the course of the design effort. ASHRAE

Standard 209 (ASHRAE 2018) has been developed to furnish guidance for how energy modeling should be used in the design process.

Building performance simulation may be completed by engineering firms, architecture firms, or dedicated specialists. Rather than focus on which consultant should provide the simulation scope, it is more important to focus on the skill set and knowledge required to make appropriate and informed recommendations that result from the simulation process. The design team must be positioned to use this knowledge to help inform the design. Variables that are accessible through the building simulation process include the following:

- Climate
- Form and shape
- Window-to-wall ratio
- Shading
- Envelope
- User behavior
- Equipment schedules and loads
- Lighting
- Natural ventilation
- Infiltration
- Daylighting
- Heating and cooling loads
- Mechanical systems comparisons
- Renewable energy systems

The responsibility for modeling in these areas will often be distributed among several team members, because it is challenging for one person to be an expert in all areas. All these factors can impact the energy performance and need thoughtful analysis during the design. Therefore, project leaders should ensure that their team has these capabilities available to support the design process and that these skills are brought to bear at the appropriate point in the design and construction processes.

A critical factor in the success of the building performance simulation process is making sure that the right information gets to the right people at the right time in the design process. The following subsections include some guidelines of required information and strategies for developing that information.

The best set of energy strategies for any zero energy building will be unique, based on the specifics of the project. Developing this best set of strategies involves understanding the energy and cost trade-offs for including or excluding any specific strategy. Energy efficiency and design elements interact with each other—the best strategies both enhance the design as well as save energy. Having a pathway to get to the energy target and types of strategies that are needed is critical for starting the discussion about how to achieve the goal. Energy-efficiency strategies can be added to the model sequentially to evaluate their impacts. The incremental impact of energy conservation measures is shown in Figure 4-3.

CONCEPT PHASE

During the concept phase the design team will determine the basic configuration of the building to meet the programmatic requirements and to adapt to the site. Modeling during this phase may include simple box modeling and conceptual design modeling, as discussed in Modeling Cycle #1 and Modeling Cycle #2, respectively, of Standard 209 (ASHRAE 2018). Building performance simulation can provide the following information by modeling simple boxes (simplified versions of different configurations):

- Impact of building massing and orientation building energy consumption
- Impact of window-to-wall ratio (WWR) on building energy consumption

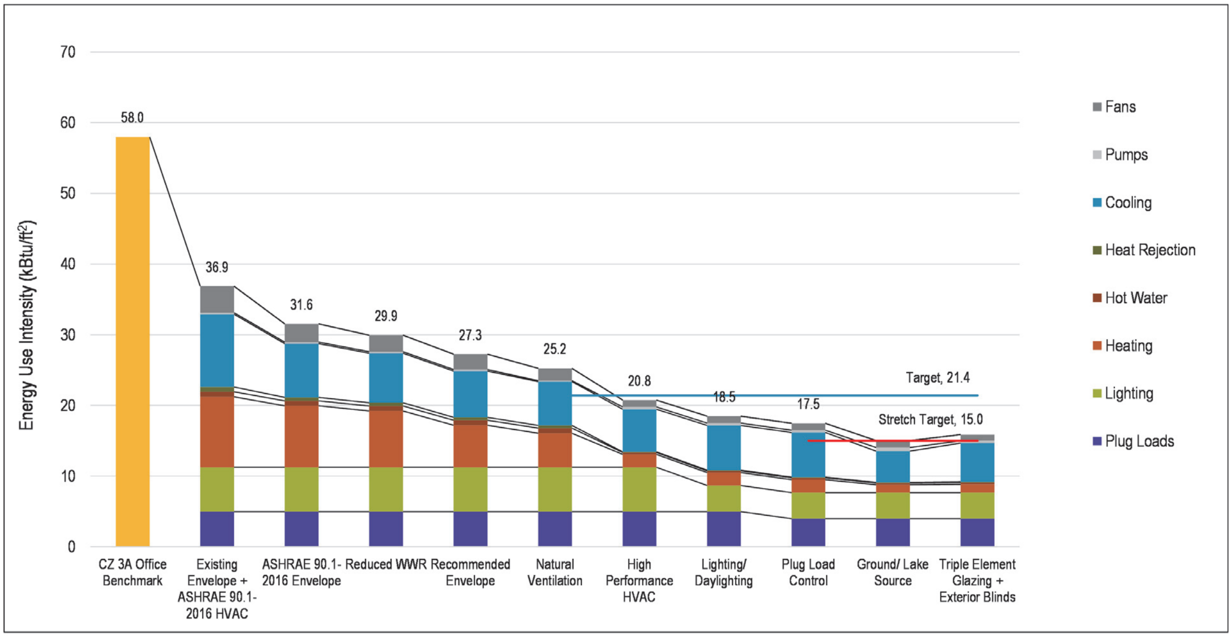


Figure 4-3 Incremental Impact of Energy-Saving Strategies for a Typical Office Building

- Availability of free cooling at the site
- Availability and importance of passive solar heating
- Potential energy savings from daylighting
- Potential energy impact of external shading strategies
- Potential for photovoltaic (PV) energy production
- General energy use patterns for the specific building use at this location
- Comparison of the energy use intensity (EUI) of this preliminary building with the energy targets shown in Table 3-1.

SCHEMATIC DESIGN

The goal of the schematic design phase is to develop a unified approach to the building configuration and systems, including floor plans, sections, and elevations, along with general recommendations for lighting systems and HVAC systems. Building performance simulations at this phase provide information on the difficulty of achieving the zero energy goal. These modeling efforts must begin to include the specific information about how the building will be used in order to assess the feasibility of the goal. Modeling during the schematic design phase should include elements of Modeling Cycle #3 and Modeling Cycle #4 of Standard 209 (ASHRAE 2018). During schematic design, the major energy- and comfort-related decisions include the following:

- General location of functional spaces
- Orientation of glazed areas and strategies for lighting and solar control
- Thermal control of walls and roofs
- Conceptual selection of mechanical systems

The comfort strategy during the schematic design phase is to provide input for selection of mechanical, electrical, and architectural systems that meet the programmed comfort requirements. The energy-conservation strategy should seek to maximize the potential for savings.

The schematic design phase does not solve the energy problem, but it does establish the potential for the solution. Parametric studies of optimal orientation are inappropriate at this phase because their direct impacts on energy conservation and interior comfort are much less than those of efforts later in the design process.

Different alternatives for these design elements should be evaluated in this phase via a detailed building energy model. Decisions concerning the fenestration and floor plan may be informed by daylight models.

DESIGN DEVELOPMENT

During the design development phase, a much greater level of detail is applied to the design decisions made during the schematic design phase. More specific information concerning building envelope elements, mechanical distribution systems, lighting design strategies, and operating assumptions are incorporated. Specific products or components, with specific performance parameters, are selected. For operable systems, sequences of control are identified. The internal operating conditions are further detailed. During this phase, detailed economic analyses may be performed to inform production selection. Modeling during this phase should be consistent with Modeling Cycle #5 of Standard 209 (ASHRAE 2018).

CONSTRUCTION DOCUMENTS

The primary role of building performance simulation in the construction documents phase is to further refine the model to incorporate changes or additional information added to the design development model. Simulations are performed using the actual sizes and capacities of the building mechanical elements rather than using the automatic sizing capability of the energy analysis program. Finalized operating schedules are incorporated. The impact of alternative component selections on building energy consumption should be evaluated with the results incorporated into the models. Examples of alternative components include different chiller selections, different air-handling unit (AHU) coil selections, and different cooling tower selections.

Energy modeling during the construction documents phase should include elements of Modeling Cycle #6 and may also include elements of Modeling Cycle #7 of Standard 209 (ASHRAE 2018) if accurate construction cost information support is available to the design team. At the end of this phase, the EUI must be compared with the target EUI value established before design as well as the renewable energy production.

While it is not directly part of the zero energy goal, a baseline energy model may be developed for energy code compliance. At the completion of the construction documents process, an as-designed energy model may be prepared following the description of Modeling Cycle #8 of Standard 209. The measures of success are that the energy model matches the construction documents and that the energy goal has been met.

CONSTRUCTION PHASE

The energy analyses are updated to reflect changes made in the design during the construction process, including change orders. Some of these changes may necessitate changes to the baseline design model for energy-code compliance. Modeling during the construction phase should include the evaluation of any implemented change orders as described in Modeling Cycle #9 of Standard 209 (ASHRAE 2018). At the end of the construction phase, an energy model representing the as-built condition of the building should be prepared, consistent with Modeling Cycle #10 of Standard 209.

OPERATIONS PHASE

During the operations phase a calibrated model can be developed using detailed testing or operational monitoring of individual systems. Actual performance parameters for the individual systems are entered into the energy model, replacing those used in the design phase, to model the actual operation of the building. This calibrated model can serve as a tool to assist with the operation of the building and can help identify malfunctions or faults in the operation of individual pieces of equipment. Postoccupancy modeling is described in Modeling Cycle #11 of Standard 209 (ASHRAE 2018).

This model is very useful in examining the actual energy data to identify when the building strays from its intended performance over time. In some cases, the results from the model are entered into the energy dashboard; these results can be compared with actual data in real time to identify issues. This comparison also provides valuable feedback to the design team for future projects. See the "Hire the Project Team" subsection in Chapter 3 for more information on how these comparisons can be used during the selection process for future projects.

BUILDING SYSTEMS STRATEGIES

The value and appropriateness of simulation types vary based on the stage of the project. Simulations can provide data for making better decisions at critical steps in the design. The earlier the decisions are made, the less overall project cost is incurred. While it may take additional time up front to prepare the simulations, these early decisions can streamline the design and operation of the building, saving the project time as it unfolds.

Decisions from simulations, on basic issues such as form and shape, are highly valuable at the early stages of a project. If left until later in the design process, such analyses are unlikely to change or inform the design. Likewise, certain studies, such as detailed plug-load studies, are probably more appropriate to analyze during the design development stage as equipment, audio/visual, information technology, and security needs have become more developed. This analysis should be done before the HVAC system is designed, as it may inform the sizing and type of HVAC equipment.

The following subsections describe in greater detail what is being analyzed as well as where some opportunities exist for a modeler to help provide valuable feedback to the design team.

CLIMATE

The location of the project dictates what climatic conditions represent opportunities or challenges. It is easier to achieve zero energy goals if the building uses the climate as a benefit rather than working against it; therefore, a thorough analysis of the site climate is done early in the design process using appropriate weather data. If long-term weather data are available from the building site, they should be used. A local weather station that reflects the local climate also has valuable information and weather files. When selecting a weather file, it is important to understand local climatic variations from that location. Ask local people about the weather patterns and confirm with data. Sometimes the best weather file is not the closest weather file—mountains, canyons, bodies of water, and cities all influence the microclimate. It is also important to understand the *typical* weather of the location—not the extreme weather days which may be used for sizing equipment. This is especially true of swing seasons. The weather files coupled with the energy model can help the design team understand the normal operating conditions that the building will experience and provide insights into achieving the EUI targets.

Projects with unique microclimate conditions may present additional challenges, particularly in the use of passive strategies such as natural ventilation or solar conditions. Review the available weather files to determine if they are appropriately representative of the actual site conditions (DeKay and Brown 2014; Olgyay 2016).

Climate analyses should be results oriented rather than just graphical renderings of raw climate data. Figure 4.4 shows an example of a results-oriented climate analysis that indicates the percentage of work hours during the year in New York City, during which various forms of free cooling are available.

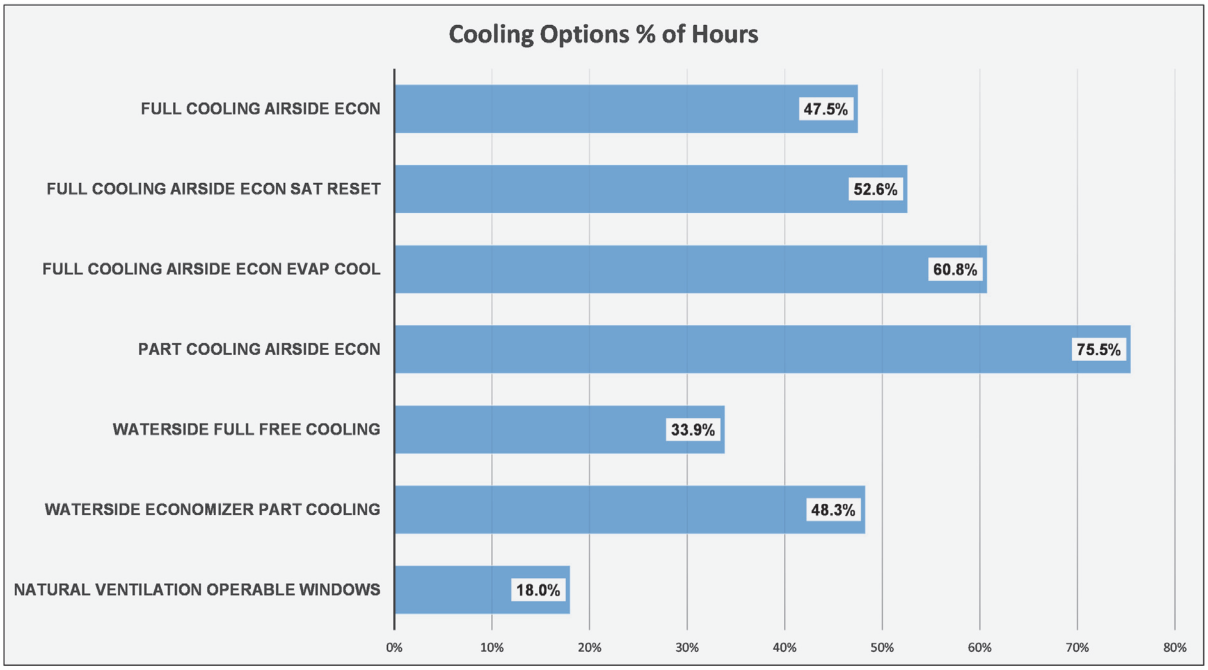


Figure 4-4 Climate Analysis of Free Cooling Availability

Lastly, because weather files use historical data, it may be worth considering future weather changes. Weather data files can be altered to test the sensitivity of building design elements. For example, a natural ventilation strategy may work for additional hours in a northern climate with higher ambient temperatures. One strategy is to use an alternative city that is warmer or colder to establish the sensitivities to changing weather patterns, for example, modeling a project in New York City using Baltimore weather data.

FORM AND SHAPE

A form and shape analysis examines the impact of a building's geometry on its energy performance, including the building's energy consumption and energy production from PV systems. From information, the building design team is able to understand quantitatively the total energy impact of many possible designs. The objective is to use the shape of the building to reduce the total energy loads. This information can add significant value to the overall discussion of which building form to select for the final building shape.

WINDOW-TO-WALL RATIO

Window-to-wall ratios (WWRs) can be analyzed by applying increments in percentage of windows to the entire model, different façade orientations, or selected rooms. When applying the windows, the options to select the height, width, and spacing for the windows are available to create an accurate model. Windows can also be segregated into those that primarily provide daylighting to offset electric lighting loads and those that provide views or visual access.

This analysis should reveal the optimum point between the increasing WWR versus the change in energy usage and peak loads while recognizing other building goals that require glazed areas. Most models show that there is an energy minimum where daylighting provides the most benefit yet solar gains are not excessive because of overglazing. Glazing types to be analyzed should be varied with respect to the solar heat gain coefficient (influencing solar gains), visible transmittance (influencing daylighting), and U-factor (influencing the heat

Exterior Building Enclosures—Functionality or Fashion

Magazines are full of images of office buildings with high quantities of vision glass in the exterior building enclosure—some exterior enclosures are up to 80% vision glass—closely followed by text touting green or sustainability or energy efficiency as a prime topic. Office interior environments are often presented as images of light-filled workplaces and highly glazed exterior enclosures. These are competing interests that owners, architects, engineers, and builders need to address to develop solutions for zero energy office buildings. Past and current trends in commercial office interior environments emphasize occupant health, wellness, and productivity in highly desirable office interiors. Additionally, commercial office spaces are financially successful when they are leased and occupied.

To better understand the consequences of these trends, here are a few simple questions and answers:

- Are enclosures with very high quantities of vision glass energy efficient? NO
- Do exterior enclosures require very high quantities of vision glass to provide high-quality interior environments? NO
- Do high quantities of vision glass use more energy? YES
- Are interior occupant views and well-being used to promote highly glazed exterior enclosures? YES
- Is daylighting an important design criterion? YES
- Should architects and the building industry care about energy efficiency? YES

Architects solve design challenges every day. Current fashion for many (not all) exterior building enclosures makes use of high percentages of vision glass. Exterior glass and the associated enclosure system—frames, gaskets, opaque/insulated areas, anchorages, etc.—represent one of the multiple building systems that contribute to energy efficiency or the lack thereof. All building systems must be considered together; there is not a one-size-fits-all response.

Energy efficiency, zero energy buildings, and high-quality interior environments must be equal design priorities. Do not separate these issues. Each commercial office project is its own unique design opportunity. Multiple studies and analyses using sites, programs, contexts, and climate zones yield results of approximately 30% maximum high-performance vision glass in thermally isolated window systems. There is no predetermined exact amount, but it is on the lower—not higher—end of the WWR. The challenge is how to design buildings in a holistic manner where environmental performance, function, and aesthetics work together to create solutions that address and solve each equally. This results in intelligent architecture that is enduring and timeless.

transmission). For additional information on WWRs, see the how-to strategy EN16 in Chapter 5.

SHADING

Closely coupled to the WWR analysis is the shading analysis. In a building zone where the mechanical plant is primarily cooling a space, the modeler should analyze the impact of shading to reduce solar heat gains. While reducing the amount of exterior glass can help with this problem, external shading devices or sunshades can also be effective. Conversely, in a heating-dominated climate, the modeler should review the impact of shading to ensure that it does not adversely impact potentially beneficial passive solar heating. With a model, the sizing and spacing of the exterior shading can be determined such that the shading benefits the energy use and simultaneously manages glare from the sun.

It is important to take occupant comfort into account when performing a shading analysis or relying on solar gains for passive heating. Solar heat gain must be able to enter through the building skin and be absorbed into the building mass to be of benefit. If this heat gain is in an occupied zone and falls directly onto an occupant or their immediate surrounds, occupant comfort could be compromised. Interior window treatments and light shelves can intercept and redirect solar gain before it can adversely affect either thermal or visual comfort. The combined solar heat gain coefficient (SHGC) of the entire window assembly, including internal window treatments, should be evaluated using a procedure such as AERC 1, developed by the Attachments Energy Rating Council (AERC 2017).

To be beneficial for passive solar gain, solar radiation cannot create excessive glare or overheating of spaces. Modeling can help determine this balance while using the solar gains to benefit the building. Modeling can also help evaluate alternative strategies, such as dynamic glazing, double envelope, or sunspace strategies, to better control solar heat gain.

Strategies related to shading techniques are discussed in how-to strategies BP5 and DL7 in Chapter 5.

ENVELOPE

The barrier between the outside elements and the indoors has a major impact on energy usage and peak loads. As the envelope's insulating properties decrease, energy usage and peak loads increase. Improvements to the building envelope have a point of diminishing returns, however, where the reduction in energy consumption no longer justifies further cost for envelope improvement. Because each building is impacted by many factors, including form, climate, internal usage, and glazing, each building's point of diminishing returns differs. But, for each building this point can be found through careful analysis.

Simply comparing the insulation to the EUI may not tell the full story. At high levels of insulation, it may be possible to downsize or even eliminate mechanical equipment, which may justify greater levels of insulation. This additional insulation also increases the exterior wall surface temperature, resulting in higher occupant thermal comfort.

By adjusting the constructions of the walls, roof, or windows in increments of one variable at a time, the calculated loads and simulations will show the optimal envelope values. Factors that should be analyzed include the construction assembly's mass, R-value, and impact on building air leakage.

A hygrothermal analysis may also be warranted, particularly with new or customized construction assemblies. Such an analysis will provide data on the heat and moisture migration through an assembly. This indicates potential condensation issues which could prematurely deteriorate the assembly and lead to biological growth.

Additionally, a hygrothermal analysis indicates assembly surface temperatures. Because the surface temperature influences occupant thermal comfort, this analysis can be used in conjunction with an ANSI/ASHRAE Standard 55 analysis (ASHRAE 2017a) to determine the impact of the studied assembly on occupant thermal comfort. A hygrothermal analysis also includes thermal bridging analysis. Modeling thermal bridging is critical to examine compromises in the thermal envelope, especially when materials change. These are also locations where condensation is likely to form.

USER BEHAVIOR

Estimating user behavior is an attempt to understand how building occupants may react to their workplace environment and also influence it with their active and passive behaviors. The objective is to mimic occupant usage with operational schedules such that lights and HVAC are operated during "occupied" hours. A common fault of models is that occupancy is underestimated, resulting in an energy model that underpredicts actual building energy usage, primarily extended evening work hours. Furthermore, occupant density changes during the day and week and must be accounted for to properly model internal heat generated from the occupants and their computer loads, ventilation requirements for buildings with demand-controlled ventilation, and lighting usage for systems with occupancy sensors and office equipment usage.

Surveys and interviews with operations staff can be used to determine the actual building occupancy and schedules of use. Actual usage can vary substantially from the official operating hours, which affects the accuracy of the model. In addition to hours of operation, the way the maintenance staff operates a building has an impact on the energy use. The model should be aligned with the building's specific operations policies as closely as possible.

EQUIPMENT SCHEDULES AND LOADS

Equipment schedules and loads are assumptions that help estimate the thermal gain and energy consumption. These include plug, process, information technology (e.g., servers), and all other loads that are connected to an energy supply that are not HVAC or lighting. Equipment loads play a role in the calculation of room loads, while equipment schedules play an important part in estimating building energy usage. It is not unusual for these loads to be over half of the total energy consumption of a zero energy building.

Estimated equipment loads and schedules are provided in *Standard 90.1 User's Manual* (ASHRAE 2017b) for different building types. When actual equipment loads are not available, these estimated loads are considered acceptable substitutes; however, the model should be updated as the actual information becomes available during the design process. It is important to note that plug loads should not be considered unchangeable; modeling can show that reducing these loads can have a big impact on achieving the energy target. Achieving the zero energy goal almost certainly will require review and significant reduction of standard office building plug loads. As stated previously, occupancy patterns may also have a significant impact on plug load patterns, such that buildings with unusual occupancy schedules should have plug load schedules that reflect their occupancy.

Initial estimates for equipment loading and schedules help determine peak loads and energy-use consumption. These values may be reduced through energy-efficiency measures, but the longer this process is delayed, the more challenging it is to rightsize mechanical systems within the design schedule. For additional information on rightsizing HVAC equipment, see how-to strategy HV32 in Chapter 5.

LIGHTING

Building performance simulation should be used to help develop overall lighting strategies. The modeler should coordinate with the design team to evaluate the energy impact of appropriate lighting strategies, including lighting power density (LPD), illuminance levels, daylight harvesting, and other controls options. For more information on these metrics, see the "Electric Lighting" section of Chapter 5.

NATURAL VENTILATION

If a project's climate analysis indicates that there are benefits to providing natural ventilation (including mixed-mode ventilation systems) for the project, further analysis may be required to determine the strategy's impact on energy usage.

Modeling software has various levels of sophistication with regards to modeling natural ventilation. Determine the feasibility of using natural ventilation with the fastest, most reasonably accurate simulation methodologies first. Only after the strategy has been deemed feasible and worth pursuing should more sophisticated analyses, such as computational fluid dynamics (CFD), be considered. A CFD analysis is time consuming and is a better strategy for optimizing the ventilation scheme, such as opening locations and sizes, rather than determining the feasibility of natural ventilation. Primarily a CFD analysis will determine whether comfort can be maintained during specific indoor and outdoor conditions. The results of the CFD analysis should be incorporated into the energy model, principally by incorporating simplified models that de-energize HVAC systems when external and internal conditions are such that comfort can be maintained as determined by the analysis. Figure 4-5 shows an example of an external CFD analysis assessing air pressure to inform ventilation. The scale indicates the range of pressure zones from negative (blue) to neutral (green) to positive (red). How-to strategies related to

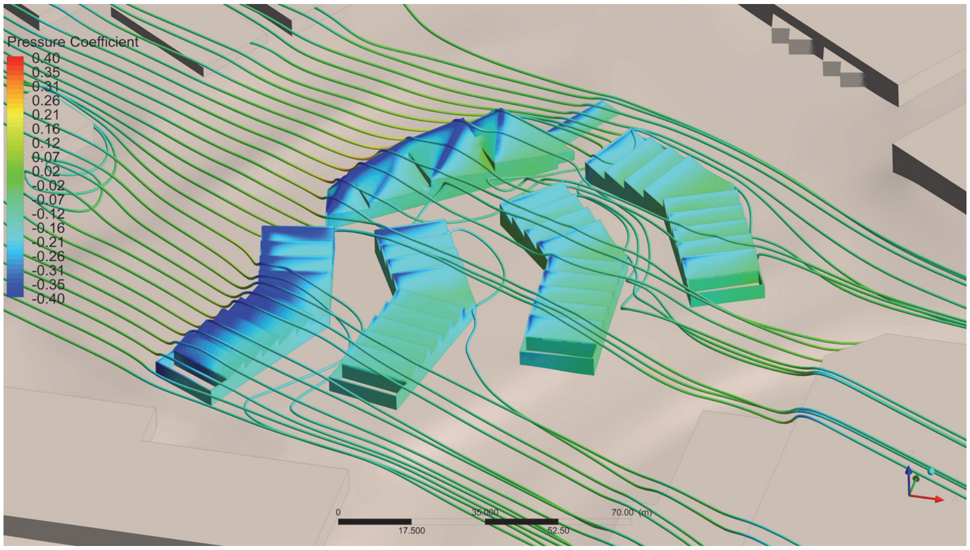


Figure 4-5 External CFD Analysis
Used with Permission, CPP, Inc. Wind Engineering Consultants

natural ventilation are covered in Chapter 5 (see BP1–BP11, EN15, EN16, EN23, DL2, DL5, DL8, HV34, and HV43).

INFILTRATION

Building performance simulation can be used to determine the merits of pursuing aggressive measures intended to reduce building air leakage. The modeler should discuss feasible air leakage rates with the design team, contractor, and envelope commissioning provider (CxP) and model strategies against conventional approaches to determine the value of pursuing these strategies.

Actual, tested air leakage rates should be obtained from the CxP and updated in the model to reflect the as-constructed conditions. See how-to strategies EN27 through EN29 in Chapter 5 for more information on infiltration and air leakage control strategies. Additional information on air leakage testing is provided in the "Commissioning for Zero Energy Systems" subsection of Chapter 3. For design purposes, using leakage rates from previous buildings is a good start. See how-to strategy EN29 for more information on target leakage rates. This parameter can be varied and its impact on the overall energy target determined. If a tighter envelope is needed to meet the EUI target, then a strategy can be developed to achieve that performance goal.

DAYLIGHTING

An effective daylighting system from an energy perspective is one in which the occupants do not want the lights on and do not want to cover over glazing to fix glare problems. To achieve this basic level of effectiveness, detailed daylighting analysis must be performed.

Climate-based daylight modeling is the study of how local daylight and sunlight patterns interact with fenestration, shading, and interior design to create layers and zones of daylight in a space on an annual basis. The results inform the selection and tuning of WWR, fenestration placement and visible light transmittance (VLT), and shading and redirection device selection and sizing.

Glare analysis is the study of how the amount and distribution of light is likely to impact occupant comfort and ability to work. Designs should be analyzed for critical times of day and year, if not on an annual basis, so that adjustments can be made to the design in order to reduce glare potential. Careful consideration of lighting quality can prevent overrides to fenestration systems that could result in the disruption of zero energy measures such as daylighting control or passive solar gain.

Information on daylighting design evaluation tools and metrics is provided in how-to strategy DL11 in Chapter 5. The numeric results of these studies should be fed directly into the energy model through matching of LPD schedules and daylighting system parameters (e.g., combined shading effect of glazing and redirection devices).

HEATING AND COOLING LOADS

Accurate estimation of heating and cooling loads is necessary to establish the first-cost trade-off between load reduction strategies and the HVAC equipment needed to meet the loads. Accurate energy modeling, furthermore, requires accurate input of the size and part-load performance of the equipment that conditions the building. Inaccurate input sizing of this equipment in an energy model can result in inaccurate estimation of energy consumption because the modeled equipment is not operating at the part-load range in which the actual equipment operates.

A fundamental energy savings strategy is rightsizing mechanical equipment. While some oversizing may result in energy savings, such as oversizing ducts or pipes, other overestimations may result in considerable energy waste, especially if equipment is forced to operate frequently at minimum part-load or to cycle. Therefore, it is important to align the calculated loads within the energy model and equipment sizing model if different software calculations are being performed. For additional information on sizing HVAC equipment, see how-to strategies HV4, HV18, and HV32 in Chapter 5.

MECHANICAL SYSTEMS COMPARISONS

A mechanical systems plant consists of the equipment that produces and distributes the heating and cooling, such as chillers, boilers, cooling towers, fans, pumps, and packaged heating and cooling equipment. In this comparison process, multiple heating and cooling options are evaluated to determine the most effective solution for a specific project. Modeling of candidate HVAC strategies should be performed early in the design phase, in conjunction with developing the building’s basic form and envelope configuration, in order to determine which strategy has the most potential to produce the require performance.

Later in the design process, modeling of HVAC systems can address performance of individual components, searching for the optimal trade-off between first cost and performance. The modeling can address even such detailed issues as the static pressure drop of the ductwork or piping system as designed, the impact of the zoning strategy implemented in the HVAC system design, and selection of fans and pumps. Alternative control strategies can also be addressed in these late-design-phase energy modeling efforts. Integration of the HVAC system with the dynamic behavior of the building, such as utilizing precooling of the building mass or early shutdown of the HVAC system prior to the end of the workday, can be tested by modeling.

RENEWABLE ENERGY SYSTEMS

Renewable energy modeling tools are used to assist in the design of the building so as to maximize on-site renewable energy production. Most on-site renewable energy is PV, as it is easily scalable and deployable in a wide range of situations. PV energy modeling can be done to determine the sizing accounting for shadowing, weather conditions, and panel degradation. The National Renewable Energy Laboratory (NREL) tools PVWatts® Calculator and System Advisor Model (SAM) are online, interactive tools that can be used to explore system sizing and output potential (NREL 2019, 2014). These tools model PV performance using inputs such as location, weather, panel types, and inverters and determine the solar production on a yearly basis. Hourly data can be retrieved for detailed analysis. One caution is that snow and ice coverage on PV panels is often overlooked by the modeling. Depending on local conditions, this can be a large factor and must be accounted for as an additional degradation factor.

Other on-site renewable energy sources such as wind generation, solar thermal technologies, or on-site-produced biofuel require modeling or evaluation tools specific to that technology. For the purpose of this Guide, the zero energy metric is based on the project output of an on-site PV system.

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THE 300 BUILDING

This project redefined the work environment for state agencies and established the value of the P3 (public-private partnership) delivery method for the Commonwealth of Kentucky. Each floor houses a specific cabinet for the government. Other building amenities include a large food-service area on the first floor, multiple collaborative spaces, walking trails, outdoor dining, and a technology-rich environment.

CLIMATE ZONE 4A

EUI
28.6

Frankfort, Kentucky

KEY ENERGY EFFICIENCY MEASURES

- 100% LED lighting
- 0.38 W/ft^2 overall LPD
- High-efficiency water-cooled chillers and condensing boilers
- Building automation system

For more information, visit http://www.eopa.com/work/frankfort-office-building/
and https://www.cmta.com/results/briefs/300-sower-office-building-frankfort-kentucky.

The 300 Building Exterior
Used with Permission of CMTA, © Phebus Photography

Project Data
Building square footage: 371,000 ft^2
Number of floors: 5
Occupancy model: Office
Number of occupants: 1400
Context: Urban
Year completed: 2016
Delivery method: Design-build with guaranteed maximum price (GMP); public-private partnership (P3)
Construction cost: \$150/ft^2

Energy Data
Predicted EUI: 26.9 kBtu/ft^2·yr
Actual EUI: 28.6 kBtu/ft^2·yr

Project Team
Owner: Commonwealth of Kentucky
Architect: EOP Architects
General contractor: DW Wilburn
Engineers: CMTA Inc.
Energy consultant: CMTA Inc
Construction manager: DW Wilburn

Building Systems
HVAC systems: Four-pipe VAV; VRF split systems to cool data and electric rooms: fan-powered VAV boxes on exterior zones
LPD: 0.38 W/ft^2

Certifications
Certification: LEED Silver, 100 ENERGY STAR score

CMTA INC. LEXINGTON OFFICE

This firm's core value of high-performance, sustainable design is well displayed in its Lexington office building. In addition to showcasing the technologies and strategies used in the design and construction of the building, the individually metered building systems provide real-world operating data that demonstrate the effectiveness of those systems. This provides a better understanding of available technologies and helps future building owners and clients make informed decisions.

KEY ENERGY-EFFICIENCY AND SUSTAINABLE FEATURES

- LED lighting in offices and lobby areas
- Solar-powered internally actuated diffusers
- Individually metered building systems (HVAC, lighting, receptacles)
- Insulated concrete form walls
- Ground-source heating and cooling with distributed pumping, adjustable ECMs
- Ground-source energy recovery water system

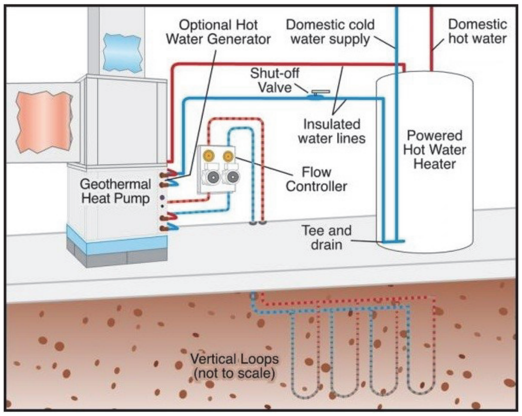
CLIMATE ZONE 4A

EUI
15.5

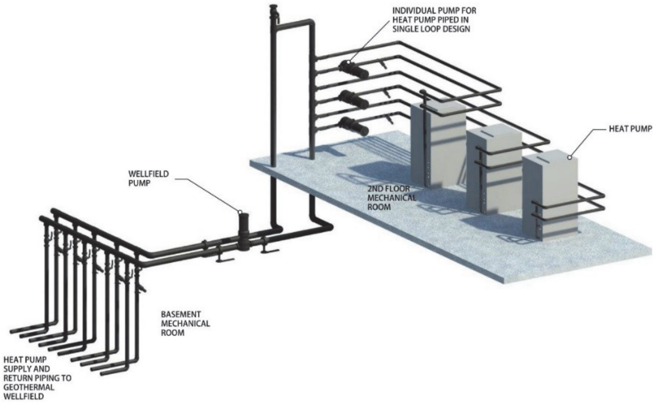
Lexington, Kentucky

The HVAC system for the building is a GSHP system that uses a single condenser loop with individual ECM pumps for each heat pump. The GSHPs are equipped with a domestic water desuperheater that uses waste heat from the heat pumps' refrigeration cycle. Rather than rejecting the waste heat back to the ground-source loop, the desuperheater uses that energy for domestic water heating, taking demand from the electric water heater.

For more information, visit https://dbda3zoqutugx.cloudfront.net/uploads/publications/44-53_Tech-Award_Cheek_CMTA_WEB.PDF and http://static1.1.sqspcdn.com/static/f/359317/26373940/1436303601117/CMTA+Lexington_Final.pdf?token=X8Iy4ETt1dE7yIk3V834mkXK3Wo%3D.



Domestic Water Desuperheater
Used with Permission, © CMTA Inc.



GSHP System
Used with Permission, © CMTA Inc.

CMTA Lexington Office Exterior
Used with Permission, © Batto Photo

Project Data

Building size: 11,750 ft^2
Number of floors: 2
Main building usage: Office
Occupancy model: Owner occupied
Context: Urban/suburban
Number of occupants: 38
Year completed: 2012
Construction cost: $254/$ft^2$ (includes site)

Project Team

Owner: CMTA Inc.
Architect: Sherman Carter Barnhart
General contractor: Buzick Construction Co.
Engineers: CMTA Inc.
Energy consultant: CMTA Inc.
Construction manager: Buzick Construction Co.

Building Envelope

Wall construction: insulated concrete form
Wall overall R-value: R-40
Window assembly U-factor: 0.32
SHGC: 0.27
Measured airtightness: 1730 cfm

Building Systems

LPD: 0.56 W/ft^2
HVAC systems: Geothermal
RE type and size: 8.58 kW monocrystalline solar PV system

Energy Data

Predicted EUI: 19.5 kBtu/ft^2·yr
Actual EUI: 15.5 kBtu/ft^2·yr

Certifications

Certification/year: LEED Platinum; 100 ENERGY STAR score

How-To Strategies

5

There are many pathways to achieve a zero energy building, and more are becoming available as new technologies are developed, as existing technologies improve, and as renewable energy technologies rapidly advance. This chapter outlines strategies to move a project towards zero energy, but success will come by finding synergies through the integrated design of all components that impact the energy consumption of the building. The objective is to achieve a low energy use intensity (EUI) as specified in this Guide (see Table 3-1) and balance that with renewable energy. Even if renewable energy is only planned into a project, the decisions about energy efficiency will create a building ready for a future zero energy status. Technologies are changing fast enough that a prescribed list of technologies will quickly become out of date. Many of the strategies needed to reach these low EUI targets are performance based, rather than prescriptive based, and the EUI targets are overall performance-based targets. As a result, energy simulations play a key role in determining which appropriate technologies to use.

The differences between office sizes, construction classifications, climate sensitivities, and regional practices make it impossible to address all the conditions that may be encountered in a typical office building project. The how-to information in this chapter is intended to provide guidance on strategies and good practices for achieving a zero energy office building. The guidance also includes cautions to help designers and other stakeholders avoid known problems and obstacles to energy-efficient construction.

Tables with recommended values are included throughout this chapter. These values may be used by designers and modelers as starting points for zero energy projects. The strategies and recommendations for the chapter are summarized in Table 5-1 and include the corresponding how-to information and table numbers. The far right columns can be used to keep track of recommendations that a building design includes (✓column) and components that the design does not contain (**x** column).

Also throughout this chapter, icons are used to highlight strategies that contribute to four different categories of information as follows:

⚡ Reducing peak demand and increasing alignment with the electricity grid
🔒 Energy resilience
$ Capital cost savings
🔧 Building retrofit strategies

Table 5-1 Summary of Strategies and Recommendations

	Component	How-To Tips	✓	x
Building and Site Planning	Site design strategies	BP1–BP2		
	Building massing	BP3–BP6		
	Comparison of building shape options	Table 5-2		
	Building orientation	BP7–BP8		
	Building design strategies	BP9–BP11		
	Planning for renewable energy	BP12–BP19		
	PV percent area of gross floor area	Table 5-3		
Envelope	Thermal performance of opaque assemblies	EN1–EN14		
	Envelope construction factors	Table 5-4		
	Insulation applications by envelope component	Table 5-5		
	Thermal performance of fenestration and doors	EN15–EN26		
	Fenestration and doors assembly criteria	Table 5-6		
	SHGC multipliers for permanent projections	Table 5-7		
	Air leakage control	EN27–EN29		
	Thermal bridging control	EN30–EN37		
Daylighting	Design strategies	DL1–DL11		
	Minimum surface reflectance	Table 5-8		
	Recommended annual daylighting design criteria	Table 5-9		
	Space-specific strategies	DL12–DL16		
Lighting Controls	Design strategies	LC1–LC10		
	Typical control characteristics	Table 5-10		
Electric Lighting	Interior lighting	EL1–EL2		
	Design strategies	EL3–EL7		
	LED specifications	Table 5-11		
	Space-specific strategies	EL8–EL16		
	Interior lighting power densities	Table 5-12		
	National average space distribution	Table 5-13		
	Exterior lighting	EL17–EL20		
	Exterior lighting power densities	Table 5-14		

Table 5-1 Summary of Strategies and Recommendations *(Continued)*

	Component	How-To Tips	✓	x
Plug Loads	General guidance	PL1		
	Plug load management	PL2–PL7		
	Equipment selection	PL8–PL15		
	Building process loads	PL16–PL17		
	Power distribution systems	PL18		
Service Water Heating	System descriptions	WH1		
	Design strategies	WH2–WH6		
	ENERGY STAR® criteria for dishwashers	Table 5-15		
	Gas water heater performance	Table 5-16		
	Electric resistance water heater performance	Table 5-17		
	Heat pump water heater performance requirements	Table 5-18		
	Parameters for recirculation pump loss calculation	Table 5-19		
HVAC Systems	System descriptions	HV1		
	Minimum efficiency recommendations by system type	Table 5-20		
	System A—Rooftop multizone VAV with hydronic heating	HV2		
	Recommendations for rooftop multizone VAV systems	Table 5-21		
	System B—Air-source VRF heat pump with DOAS	HV3–HV6		
	Recommendations for zone terminal systems with DOAS	Table 5-22		
	System C—Water- and GSHP with DOAS	HV7–HV13		
	Recommendations for zone terminal systems with DOAS	Table 5-23		
	Thermal properties of different soil types	Table 5-24		
	System D—DOAS with sensible fan-coils and chillers with waterside economizers	HV14–HV16		
	Recommendations for zone terminal systems with DOAS	Table 5-25		
	DOASs	HV17–HV31		
	Recommendations for DOAS	Table 5-26		
	DOAS unit control modes	Table 5-27		
	Example frost point for energy	Table 5-28		
	HVAC tips for all system types	HV32–HV41		
	Recommended control for air-side economizer	Table 5-29		
	Thermal mass	HV42–HV43		
Renewable Energy	Common terminology	RE1		
	Design strategies	RE2–RE8		
	Implementation strategies	RE9–RE12		

BUILDING AND SITE PLANNING

OVERVIEW

Early-phase design decisions have a profound impact on future building energy usage. With timely analysis and integrated planning, project teams can radically alter the trajectory for building energy usage by making smart and informed decisions that establish a solid framework for subsequent decisions and conservation measures.

During the early design phases, practitioners should employ a climate-responsive design approach that strives to design for efficiency while simultaneously satisfying or enabling the achievement of all project goals. The optimization process uses energy modeling and other tools to iterate design solutions and reconcile competing conservation measures.

SITE DESIGN STRATEGIES

BP1 Select Appropriate Building Sites

There are many factors that affect the selection of potential building sites. Some site aspects directly affect building energy use or renewable energy production; these issues should be prioritized when planning for a zero energy building. Include design professionals in the site selection process to ensure all relevant considerations are evaluated appropriately, including the opportunities and energy penalties associated with proposed sites. The following list summarizes factors that should be evaluated for a zero energy office site:

- Property configuration and zoning
    - Massing for passive design and low energy
    - Orientation for passive design and low energy
    - Integration of renewable energy systems
- Sunlight and shade
    - Renewable energy (solar electric and solar thermal)
    - Daylighting
    - Passive solar heating
    - Controlling heat gain and glare
- Wind and breezes
    - Renewable energy (wind power if feasible)
    - Natural ventilation
- Topography, ecology, geology, and hydrology
    - Slopes that impact solar access
    - Slopes that impact wind patterns
    - Slopes that impact building massing and/or orientation
    - Slopes that allow ground-coupling of building
    - Large water features that impact local temperature and wind patterns
    - Large landscape areas that impact local temperature and wind patterns
    - Soil conductivity for potential geo-exchange system

BP2 Optimize Building Siting Combined with Landscaping and Site Features

The design of landscaping and site features can enhance the positive aspects of a site while working to decrease the impact of negative aspects for a zero energy office. The following list summarizes potential site design and microclimate strategies to improve energy efficiency and renewable energy generation for a project:

- Use dense evergreen trees and landscaping to reduce undesirable winter winds, which will reduce building infiltration.

- Use trees and landscaping to funnel desirable breezes toward a building for cooling or ventilation.
- Use deciduous trees to provide beneficial shading of the sun in summer. But, be careful that the trees will not shade solar panels as they grow to full height. Even when trees lose their leaves, shading from branches impacts passive solar gains.
- Use bodies of water to provide beneficial changes in temperature or humidity to the immediate microclimate or to discharge heat.
- Note the effect of landforms and plant forms on wind speed and wind quality relative to natural ventilation and wind power.
- Understand that for sloped sites, cool or nighttime air flows down. For low-slope sites, identify predominate wind direction to determine whether to incorporate or mitigate in the design.
- Note the effect of landforms and plant forms on solar access and daylighting.
- Reduce the amount of paved surfaces (particularly dark, solar-absorbing colors) to reduce local heat island effect.
- Recognize the beneficial effects of plant-based evapotranspiration on thermal comfort.
- Consider the beneficial effects of earth-coupling on reduced cooling loads.

BUILDING MASSING

BP3 Optimize Surface Area to Volume Ratio $

Both energy use and building first costs are correlated to the efficiency of a building's massing, which can be measured by the ratio of surface area (envelope) to volume, also known as the shape factor A/V (area to volume). The efficiency can also be measured by the ratio of surface area to floor area, known as shape factor A/A (area to area).

Shape factor should be considered because it quantifies the area of envelope compared to the quantity of conditioned space. The envelope is a source of a variety of thermal loads to the perimeter zones of office buildings, including heat gain and heat loss via transmission, infiltration through the envelope, and solar heat gain via windows. In this case, the envelope is an energy liability, and by reducing the envelope area to a given area of conditioned space the envelope loads can be reduced, therefore saving energy. A sphere has the smallest ratio of surface area to volume. In more practical building terms, a cube has the smallest ratio and would minimize thermal losses through the building envelope. Also, multiple-story buildings have less roof area and therefore a more compact shape. It can also be beneficial to consider novel three-dimensional shapes, which can be designed so that the building is self-shading.

The envelope is also the interface for passive strategies such as natural ventilation and daylighting. (For more information on natural ventilation, see BP6, EN15, EN16, EN23, DL5, and HV34; for more information on daylighting, see DL1–DL16.) In this case, the envelope is an energy asset. By increasing the envelope area to a given quantity of conditioned space, more space can be passively conditioned, therefore saving energy. The increase in envelope area to optimize passive strategies is accomplished by elongating the building form in the east-west direction.

Optimizing the shape factor balances the benefits of reducing envelope thermal loads and increasing passive conditioning capacity. Compact and elongated shapes each have their pros and cons, which must be weighed for each project. These are listed in Table 5-2 and illustrated in Figure 5-1.

With these pros and cons in mind, there is a unique opportunity for elongated shapes in cold climates. By designing 100% passively cooled buildings in climates with low summertime temperatures, mechanical cooling can be eliminated from a project. This allows for both a reduction in first cost and a reduction in overall energy use—a potential winning strategy for a zero energy building.

It is also important to consider an office building's program and site when evaluating shape factor, especially related to passive design potential. First consider if the office building's

Table 5-2 (BP3) Comparison of Building Shape Options

<table>
<tr><th colspan="2">Compact Shape</th></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>• Often effective in cold climates (climate zones 7 and 8).
• Reduced quantity of envelope results in reduced heat loss and heat gain via transmission.
• Reduced quantity of envelope can reduce construction cost.
• Small compact footprints can still be effectively daylighted and naturally ventilated.</td><td>• West and east façades are equal in area to other façades and represent a significant liability for solar heat gain when glazed.
• Large compact footprints are challenging to daylight and naturally ventilate and restrict views for occupants.</td></tr>
<tr><th colspan="2">Climate-Responsive Shape</th></tr>
<tr><th>Pros</th><th>Cons</th></tr>
<tr><td>• Often effective in milder and warmer climates.
• All sizes of offices can be effectively daylighted and naturally ventilated.
• More spaces can have access to views.
• Elongated east-west shapes have reduced west and east façade areas and increased south and north façade areas, offering effective opportunities for significant solar control.</td><td>• Increased quantity of envelope results in increased heat loss and heat gain via transmission. However, strategically increasing the thermal performance of the envelope can effectively minimize this liability.
• Increased quantity of envelope can increase construction cost.</td></tr>
</table>

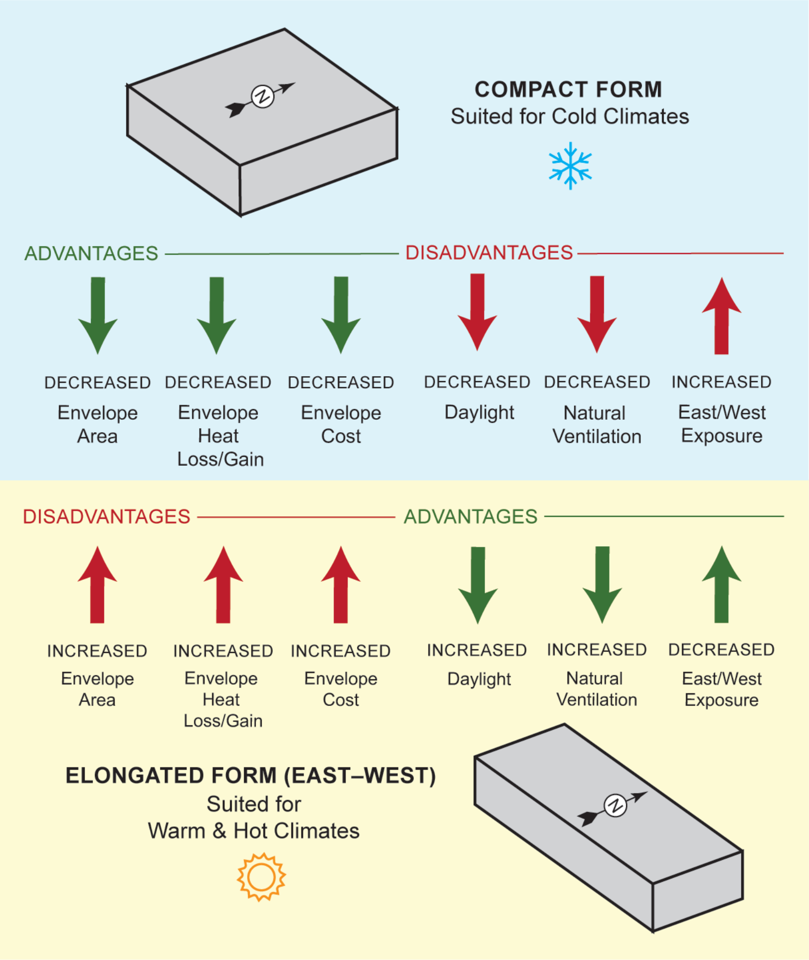


Figure 5-1 (BP3) Pros and Cons of Compact and Climate-Responsive Shapes

program is conducive to passive strategies or can be made passive friendly. Can the offices be open, rather than private? Open-office environments are easier to naturally ventilate and daylight. Will the occupants be engaged in using operable windows and daylight to meet their indoor environmental needs? They may be responsible for operating windows and/or controlling interior blinds in conjunction with weather conditions and indoor environmental needs.

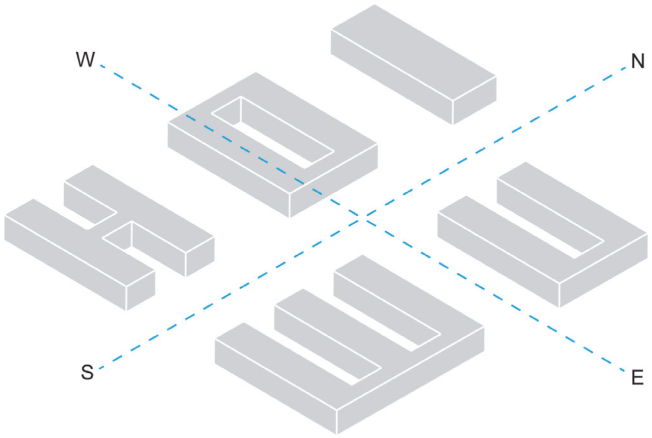
Next consider if the office building's site is conducive to passive strategies. Does the site have access to daylight and to usable outdoor airflows? Are there sources of exterior noise or poor outdoor air quality that would limit the application of natural ventilation?

BP4 Climate-Responsive Building Shapes

For larger buildings, where a passive design approach dictates, configure the building as a series of connected elongated shapes. These elongated shapes have a narrow plan depth to permit cross natural ventilation and full daylighting. In office buildings that are optimized for daylight and natural ventilation, these floor depths can be as low as 30 ft or as high as 60 ft. These elongated shapes need to be oriented properly, typically 20° plus or minus of east/west for the elongated axis (see BP9). The resulting shapes are sometimes referred to as *letter buildings* and resemble the shapes of letters such as C or E or H, as shown in Figure 5-2.

BP5 Minimize and Shade Surfaces Receiving Direct Solar Radiation for Cooling

Performance can be optimized by designing each façade based on its exposure to direct solar radiation. Minimize surfaces receiving direct solar radiation, especially during the cooling season. Prioritize the reduction of direct solar on glass because of the direct solar gain in the space. Opaque envelope assemblies in hot climates can also benefit from shading or solar reflectance because solar radiation can drive heat flow through opaque assemblies in addition to heat transfer via indoor and outdoor temperature differences. Prioritize the control and reduction of orientations that receive the highest solar gains during the cooling season. Horizontal surfaces (roofs) receive the most solar radiation, which can be problematic for horizontal components of skylights but also for roofs in hot climates. West- and east-facing façades receive the most solar radiation during the summer, compared to south or north orientations, and a good solar control strategy is to eliminate or significantly reduce east and west glazing. The graphs in Figure 5-3 show solar incidence per orientation at several latitudes. These graphs show hourly average solar radiation by orientation for three U.S. cities with diverse latitudes: (a) Cut Bank, Montana; (b) Denver, Colorado; and (c) Houston, Texas.



LETTER BUILDING SHAPES

Figure 5-2 (BP4) Letter Building Shapes

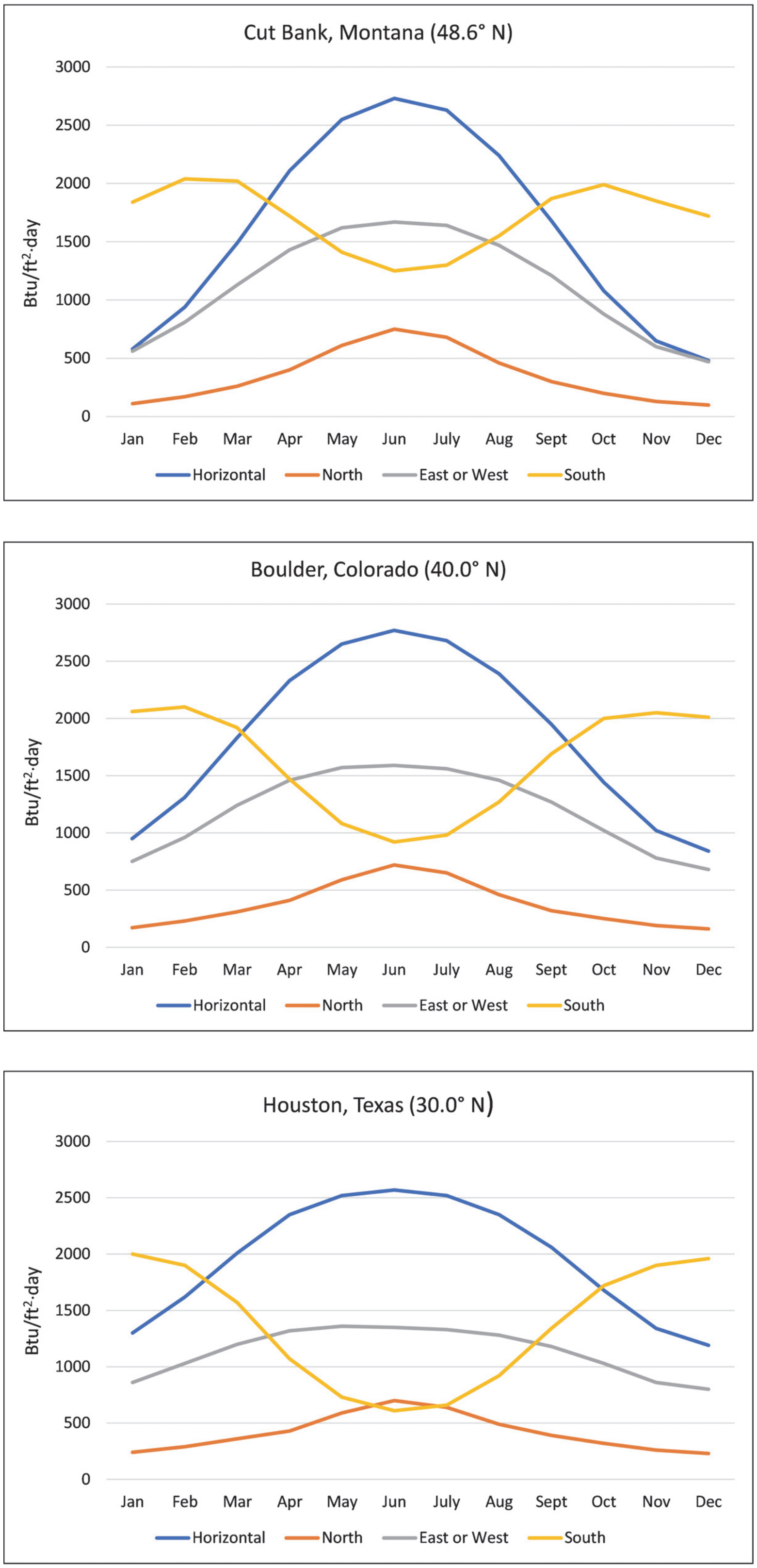


Figure 5-3 (BP5) **Daily Average Incident Solar Radiation by Orientation for Diverse Locations: (a) Cut Bank, Montana; (b) Denver, Colorado; and (c) Houston, Texas**

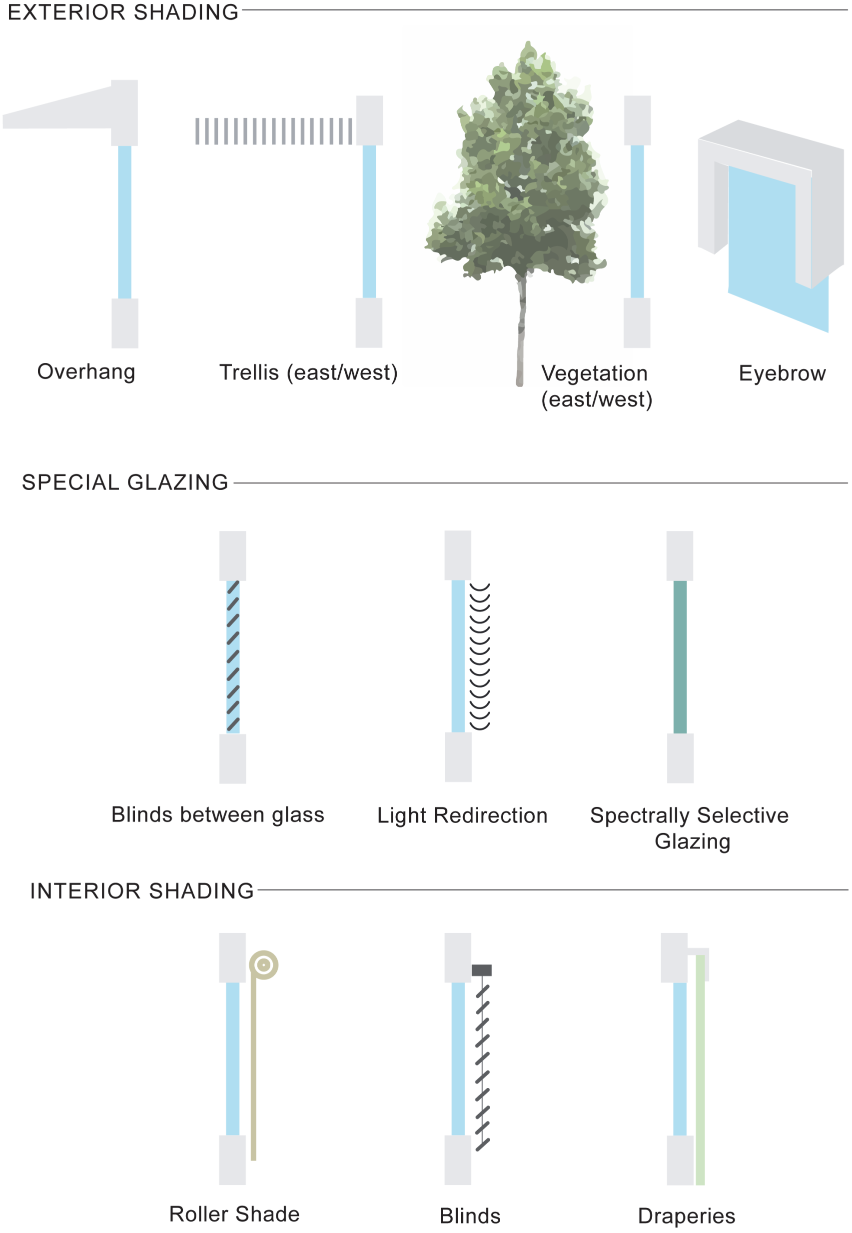


Figure 5-4 (BP5) Fenestration Shading Examples

There are a variety of ways to provide shading for glazing and other envelope components including overhangs, shade structures, screens, double-skins, exterior blinds, and landscaping. Exterior shading strategies are more effective at reducing solar heat gain than interior mounted solutions, because they prevent solar radiation from entering through the glazing. To understand the effect of combining solar shading and solar heat gain coefficient (SHGC) for glazing, refer to EN19. Shading also plays a significant role in daylight design and glare control (see DL7). Examples of shading strategies for glazing are shown in Figure 5-4.

BP6 Optimize the Building for Natural Ventilation

When appropriate, design building massing to make beneficial use of the wind for natural ventilation. In many climates there are significant time periods during which natural ventilation can play a role in cooling and bringing fresh air to offices and other spaces. Research has shown that in naturally ventilated buildings, occupants more readily adapt to a wider range of indoor temperatures, based on the outdoor air temperature. ANSI/ASHRAE Standard 55 (ASHRAE 2017) incorporates an adaptive comfort method for achieving occupant comfort in occupant-controlled naturally conditioned spaces. Buildings can integrate both natural ventilation and active cooling and ventilation as a hybrid solution called *mixed mode*. Mixed-mode buildings can use natural ventilation or mechanical systems depending on the conditions. See HV34 for additional information on natural ventilation and integration with HVAC systems.

As noted in BP3, providing a narrow-depth floor plan (high surface area to floor area) and an open office environment are key first steps for integrating natural ventilation. Consider the variety of techniques for inducing natural ventilation through a space. Cross-ventilation is a common strategy that moves outdoor air through a space due to the pressure differential of the windward side (intake) and the leeward side (discharge). Stack ventilation moves air through buoyancy created by a temperature difference, with air moving upward from cooler to warmer temperatures. This can be accomplished through the use of atriums, ventilation towers, or similar vertical openings, allowing outdoor air brought in from windows to move through the office space and be discharged at the top of the atrium. The use of a solar chimney, which strategically uses solar radiation to further increase the temperature at the top of the discharge point, can increase the effectiveness of stack ventilation. Note that even low windows on the windward side and high windows on the leeward side can induce some stack, which can be effectively combined with cross-ventilation. A less effective, but still usable, technique is single-sided ventilation, which uses a high window and a low window on the same exterior wall to ventilate a shallow space, such as a private office.

Design guidance for natural ventilation can be found in a number of industry resources and technical reference books, including application manuals *AM10: Natural Ventilation in Non Domestic Buildings* and *AM13: Mixed Mode Ventilation* from The Chartered Institution of Building Services Engineers (CIBSE; 2005, 2000). Design for natural ventilation can be assisted with the use of modeling including computational fluid dynamics (CFD) and bulk airflow modeling. CFD modeling can provide detailed analysis of air and heat flows within a space for a specific scenario. Bulk airflow modeling provides a broader view of natural ventilation design and quantifies annual hourly airflows in and out of windows and between spaces.

> ***Caution:*** Considerations need to be made for security, ambient exterior noise levels, outdoor air quality (see the U.S. Environmental Protection Agency [EPA] National Ambient Air Quality Standards [NAAQS] [EPA 2015]), outdoor air temperatures, humidity, operable window air leakage, pests, and allergens.

BUILDING ORIENTATION

BP7 Optimize Orientation

Building orientation is the practice of locating a building and its associated shape, massing, and volume to maximize certain aspects of its surrounding site, such as views (interior and exterior) and visibility from public ways, and to capitalize on natural factors such as topography, solar access, wind patterns, and water use/conservation. Orientation influences passive solar design considerations such as daylighting, shading, and thermal mass as well as solar access for on-site energy generation. These criteria should also be considered for hardscape and landscape features. Office building design is iterative, and while it is traditionally driven by interior layouts and building floor plate efficiencies, siting and orientation are also critical design parameters. Building energy use varies directly with building orientation, and orientation should be optimized during the early design process. Strategies for orientation relative to the solar path are well understood; however, a comprehensive optimization also considers the effects of prevailing and seasonal winds relative to energy consumption without neglecting concerns relative to exterior-borne noise and acoustics and reverberation time.

For optimal solar orientation in all climate zones in the northern hemisphere, select building sites and orient the building such that a rectangular footprint is elongated along an east-west axis. Solar azimuth and altitude vary depending on the time of the year. In the summer the sun rises slightly north of east and sets north of west and in the winter rises slightly south of east and sets south of west. Depending on the geographic location and the local climate, the building's east-west axis can vary up to 20° of south without substantial energy impacts. This orientation has the following advantages:

- Minimizes unwanted and difficult-to-control radiation on east- and west-facing surfaces
- Maximizes access to beneficial solar radiation on the south side and diffuse sky conditions on the north side
- Facilitates shading strategies on the long, south-facing surface

For buildings where extensive east-west exposure is unavoidable, more aggressive energy conservation measures may be required with other building components to achieve energy goals.

Another natural factor to consider in orientation is prevailing breezes. Considering wind direction when determining building orientation can allow the building to take advantage of summer breezes for cooling and to be shielded from adverse winds in winter. Cold winds generally originate from the north and west, while coastal locations generally experience on-shore flows. If the site has a unique microclimate, the orientation should take that into consideration, specifically wind directions per season.

Figure 5-5 illustrates the effect of solar path and prevailing breezes on a building.

BP8 Fenestration Orientation

In most climate zones, windows should be located in south-facing surfaces, where solar radiation is readily controlled with proper overhangs; however, low-angle winter light may be a problem in northern climate zones and cause glare concerns. Openings in east- and west-facing walls should be optimized through iterative energy simulation, as this radiation is very difficult to manage. Glare and summer heat gains are the predominant issues, and shading strategies are more challenging on the west in the late afternoon (see also DL7.)

North-facing fenestration can be used in all climate zones, but glazing specifications should be optimized and differentiated from glazing facing other directions. North-facing fenestration is ideal for daylighting and avoids solar heat gains. For more information on glazing specifications, see EN15–EN22.

Daylighting, ventilation, and potential heat gain should all be studied with energy simulations to properly size windows and specify the window glazing type. Fenestration orientation should be optimized through an iterative energy simulation process.

BUILDING DESIGN STRATEGIES

BP9 Space Programming for Low Energy Use

During the space programming phase of a zero energy office building, consider and plan for the aspects of space types that have direct impacts on energy use, including the following:

- Setting lighting power density (LPD) targets for each space.
- Setting daylighting goals and requirements for each space.
- Setting equipment power density targets for each space.
- Setting occupancy density and internal heat gain values for each space.
- Setting acceptable indoor air temperature ranges for each space.
- Setting heating and cooling load targets for each space.
- Setting natural ventilation goals and requirements for each space (if applicable or if desired).

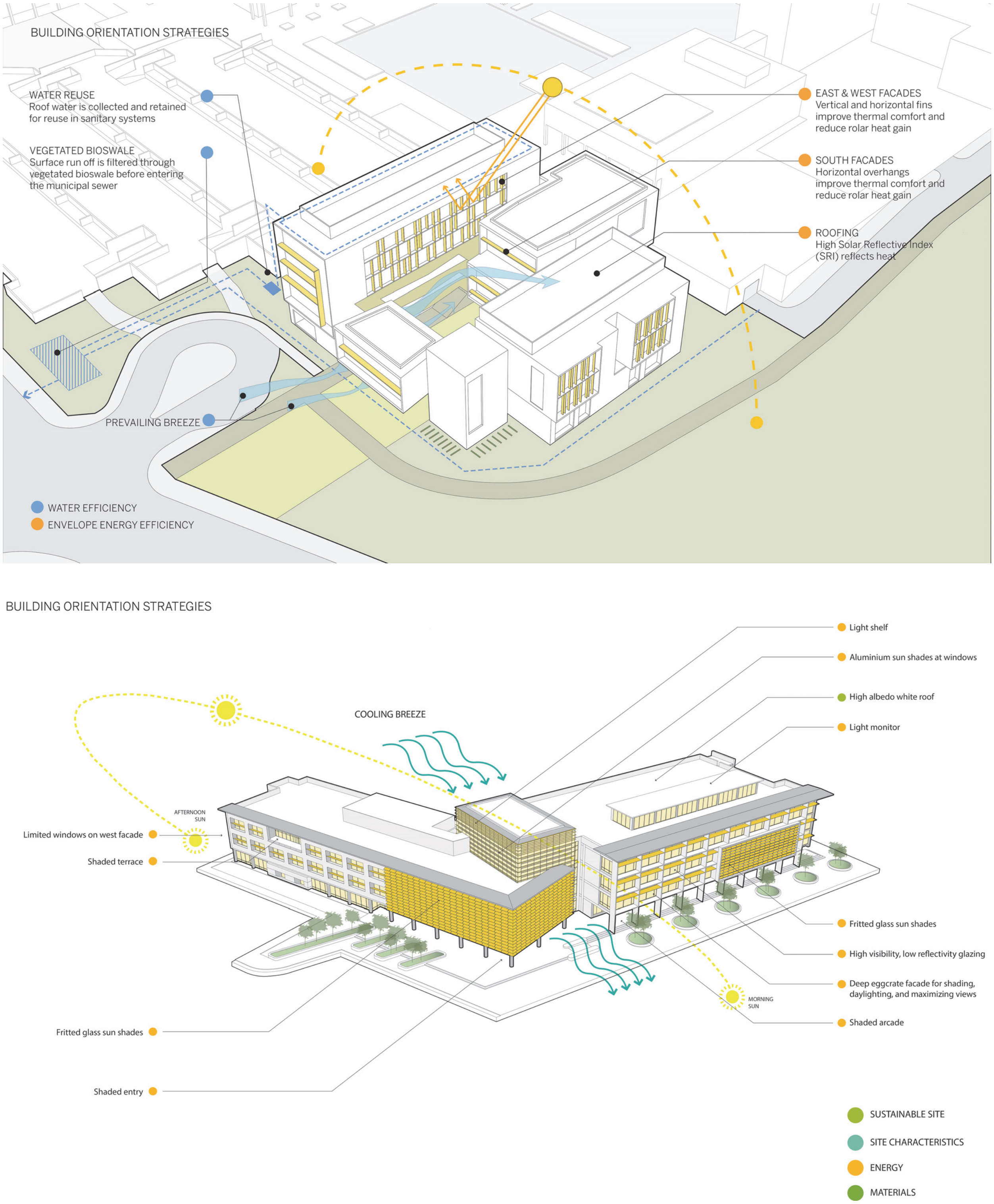


Figure 5-5 (BP7) **Building Orientation with Solar Path and Prevailing Breezes**
Images Courtesy of Skidmore Owings & Merrill LLP

BP10 Space Planning for Low Energy Use $ 🔧

Space planning for daylighting and views. Occupant access to daylight and views is a cornerstone of a healthy, zero energy office. The programming and space planning for a zero energy office should prioritize the location of regularly occupied spaces so they are within 30 ft of exterior walls with windows (refer to DL3 and DL4). When enclosed offices and rooms are located on the perimeter they can constrict access to daylight and views for adjacent spaces. It is best practice to locate open spaces, such as open office areas, on the perimeter of an office floor plate, with the enclosed spaces and core spaces toward the center to maximize daylighting and views for all occupants. Though this is best practice, there are many creative ways to design and space-plan an office to optimize daylight and views for all occupants.

Space planning for heating and cooling. Early space planning for heating and cooling considerations can reduce energy use and improve thermal comfort. Establishing equipment and LPD reduction goals for each space can reduce energy for lighting and plug loads and will also reduce internal heat gains and cooling loads for each space. Further, establishing internal heat gain values in combination with heating and cooling load targets for each space allows for energy-saving synergies in planning for space adjacencies and the development of the envelope design. For example, spaces with high internal gains should be located such that they avoid locations that could be subject to high solar heat gains. Also, spaces with high internal gains can be grouped together to more effectively zone them for space conditioning. Spaces with low internal heat gains and a flexible range of allowable temperatures could be good candidates for natural ventilation and be planned for locations with good access to natural ventilation.

BP11 Basic Office Design for Low Energy Use 🔒

Basic office design decisions can help optimize low-energy space-planning principles.

Floor-to-floor heights have an impact on energy in a variety of ways that need to be balanced and optimized. Increased floor-to-floor heights increase the area of exterior envelope, which can increase the envelope-related heating and cooling loads. However, increased ceiling heights can improve daylighting, views, and natural ventilation strategies if they are employed. Careful planning of structural and mechanical systems can work to reduce the floor-to-floor height while increasing the ceiling height.

Openings between floors can help connect office workers in a company, but they can also play a role in facilitating improved daylighting and natural ventilation. Openings can serve as light wells, bringing light from a roof monitor or other toplighting strategy to floors below. Openings can also serve as air wells, creating a stack effect that allows outdoor air from windows to be moved through a space and exhausted at the roof.

Workstation, enclosed office, and meeting room design should consider ways to enhance the effectiveness of daylighting. For workstations, lower cubicle partitions allow better penetration and distribution of daylight and can also aid the effectiveness of natural ventilation. If taller partitions are needed, locate them so they are perpendicular to the windows. In open offices a circulation space against the exterior wall can be a welcome buffer from potential glare and thermal comfort issues related to windows.

Enclosed offices and meeting rooms that are not located on an exterior wall can benefit from glass partitions to bring borrowed daylight into the space. If these spaces are located on an exterior wall, the same glass partition can bring borrowed light into adjacent spaces.

For all spaces, surfaces and finishes using light colors with high reflectivity can also improve the effectiveness of daylighting and the electric lighting system—generally, the ceiling being the most important surface and the floor being the least important. Refer to DL9 for additional guidance.

PLANNING FOR RENEWABLE ENERGY

BP12 General Guidance for Renewable Energy Planning

While other forms of renewable energy exist, solar systems or photovoltaic (PV) systems are the most prevalent and work in most building locations. PV systems are composed, in part, of PV panels or arrays. Ideally, PV arrays are located on the roof to minimize their overall footprint. Planning for an array must begin with project conceptualization to ensure that an adequate roof area is reserved for renewable energy generation.

There are also other opportunities for PVs, including building-integrated PVs (walls, sun shades, etc.), PV canopies over parking, and ground-mounted PV systems. A more detailed discussion on the use of PVs including mounting options (RE5) is provided in the "Renewable Energy" section of this chapter.

Other renewable technologies, such as wind power and micro hydroelectric generation, may make sense on some specific sites. Wind power systems can be attached to the building, but structural and vibration considerations must be designed into the system. Wind power should also be evaluated for noise considerations.

BP13 Roof Form

PV panels may be mounted on flat roofs or pitched roofs. For maximum production the orientation should be within 30° of south with a roof pitch ranging from latitude minus 30° to latitude plus 10°. However, the cost of PVs has decreased so significantly that non-ideal roof orientations may not be a significant design concern, especially if additional panels are added to account for the difference. Single-sloping shed roofs are preferable to gable roofs since large portions of gable roofs have reduced solar access. See RE3 for information on calculators for estimating solar production.

Flat roofs provide a lot of flexibility for laying out PV arrays. It is easiest if the roof has large rectangular areas free from obstructions such as plumbing vents and mechanical equipment. The angle of PV panels has decreased over time as the cost of PV installations has gone down. This is because the cost of the mounting system increases with angle due to the infrastructure required to support PV panels at higher angles. Many systems today are at a 5° to 10° angles and use a ballasted mounting system with minimal penetrations. The cost of this system is less than that of more expensive mounting systems with fewer PV panels, with both systems producing the same amount of energy. In some cases, systems facing east and west (see Figure 5-6) provide similar outputs to south-facing systems. The east-west dual tilt prevents module self-shading, provides a higher power density per roof area, and is still relatively efficient for individual module energy generation.

Mounting options for rooftop systems are discussed in the "Renewable Energy" section (see RE5).

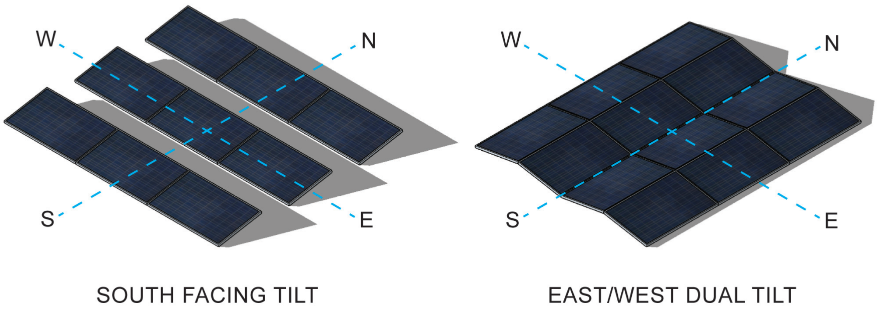


Figure 5-6 (BP13) Solar Panel Layout Options

BP14 Determine Required Roof Area for PV

Based on the modeled data developed by National Renewable Energy Laboratory (NREL), the approximate roof area needed for PV panel installation can be calculated in each climate zone. This area should be confirmed during the planning stages for the specific goals, project, and climate zone.

Table 5-3 indicates the required PV area for a modeled prototype office building in each climate zone. The PV area derived from Table 5-3 represents the required PV collector area, which needs to be multiplied by an upgrade factor of 1.25 to account for spacing, aisles, and other installation requirements found on a typical office project. The table demonstrates that in many climate zones, for offices over three or four stories, it is difficult to achieve zero energy with only rooftop solar panels.

> ***Caution:*** Individual projects may need to adjust the upgrade factor to account for the elements on the roof and how they are configured. Snow on the panels will also reduce output and is often not accounted for in the models.

Early in a project, verify the goals relative to the PV area required. Recognize that a building roof is never 100% available for PVs; space is required for roof access, toplighting, plumbing vents, rooftop equipment that cannot be located elsewhere, and other miscellaneous elements. It is possible to arrange these elements to maximize the PV area, sometimes approaching 80% of the roof area. (See also BP18.)

Table 5-3 (BP14) PV Percent Area of Gross Floor Area

Climate Zone	Target EUI, kBtu/ft^2·yr	PV Area as Percentage of Floor Area
0A	23.2	31.4%
0B	27.6	25.1%
1A	23.4	22.4%
1B	25.7	28.0%
2A	22.2	22.0%
2B	22.8	20.0%
3A	21.4	21.2%
3B	21.1	17.5%
3C	16.0	15.5%
4A	21.7	22.1%
4B	20.6	16.8%
4C	17.3	21.6%
5A	23.2	22.9%
5B	22.9	18.7%
5C	17.5	20.0%
6A	27.7	24.0%
6B	24.7	22.8%
7	30.3	27.1%
8	36.0	39.4%

Note: Table percentages are for the PV system only and do not include the upgrade factor for aisles and other elements on the roof. The PV modules are assumed to be 19% efficient at a 10° tilt facing south, with 14% total system losses.

The PV system should be sized using the actual EUI, fuel mix, and PV assumptions for the specific project based on *A Common Definition for Zero Energy Buildings* by the U.S. Department of Energy (DOE 2015). Table 5-3 provides an early planning guide. Using Table 5-3, the required percentage of roof area required for PVs can be calculated as follows:

Gross floor area × PV area % (Table 5-3) × upgrade factor = roof area required for PVs

Area required for PVs / gross roof area = percentage of roof area needed

For example, the calculations for a two-story, medium-sized office building in climate zone 5B are as follows:

$$\text{Gross floor area} = 100{,}000\ \text{ft}^2$$

$$\text{Gross roof area} = \text{gross floor area / stories} = 100{,}000 / 2 = 50{,}000\ \text{ft}^2$$

PV area % (from Table 5-3) = 18.7%

Upgrade factor = 1.25

$$\text{Roof area required for PVs} = 100{,}000\ \text{ft}^2 \times 0.187 \times 1.25 = 23{,}375\ \text{ft}^2$$

$$\text{Percentage of roof area needed} = 23{,}375\ \text{ft}^2 / 50{,}000\ \text{ft}^2 = 46.8\%$$

Some projects will not have the required roof area available for the PV system size needed for zero energy. Possible resolutions for this scenario include the following:

- Lower the target EUI for the project.
- Specify a higher-efficiency PV panel/system.
- Supplement the rooftop array with a parking canopy array, a ground-mounted array, or another form of on-site renewable energy. (See RE5 for more information on alternative mounting options.)
- Supplement the rooftop array with vertical-mounted PVs on appropriate exterior walls.
- Reevaluate the massing and roof area assumptions to increase the building roof area (while simultaneously analyzing increased envelope loads and construction costs resulting from less efficient building massing). This can include reducing the number of stories or adding large roof overhangs.
- Perform a more detailed analysis that looks at available roof area and production needs.

If financial resources are not available for PVs, assessing the potential PV system size and corresponding energy production output can inform building design and result in a PV system solution at a later time. Note that it is useful to plan for conduit and inverter space for future installations.

See the "Renewable Energy" section for additional information on PV systems.

BP15 Maximize Available Roof Area

Building infrastructure and building systems should be conceived in a coordinated way that minimizes the amount of rooftop equipment and number of roof penetrations. Toplighting strategies need to be balanced with project goals and weighed against the need for maximizing the area for renewables. For example, conventional toplighting approaches sacrifice roof area and reduce the rooftop solar capacity. Where sufficient daylighting can be provided from building vertical surfaces, roof area can be effectively dedicated to renewable generation. In general, the most cost-efficient PV systems have large areas of contiguous panels. An example of a roof-mounted PV system is shown in Figure 5-7.

Figure 5-7 (BP15) Roof-Mounted PV System

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Consider the following strategies for maximizing available roof area:

- Minimize rooftop daylight monitors. Monitors occupy valuable space and cast shade on adjacent roof areas, so use them sparingly and for maximum impact. Consider north-facing monitors so that the monitor roof can be used for PV mounting. Use the lowest-height monitors practicable to avoid shadows.
- Use tubular daylighting systems strategically. As with monitors, deploy in critical or high-impact areas. Consider clustering units and relying on the flexibility of the light tubes to direct light to the locations needed. Arrange units such that they fit in between modules.
- Limit or avoid skylights, which, in addition to the concerns noted above, also increase cooling loads.
- Require rooftop coordination drawings from the construction team, starting with the solar shop drawing and including all equipment, penetrations, roof drains, and other miscellaneous items. Adjust items to maximize the solar panel locations.
- Avoid rooftop equipment to preserve roof space and to avoid shadows. Locate equipment on the ground, in mechanical rooms, in ceiling spaces, or in attics. Note that this strategy frequently necessitates the dedication of greater floor areas to mechanical spaces. This is also a preferred solution for maintenance personnel for improving serviceability of the equipment, which increases its overall service life and efficiency.
- Avoid rooftop intakes and exhausts. Relocate to walls, if possible.
- Evaluate strategies for aggregating equipment and aligning equipment installations to minimize disruptions to the PV layout.
- Coordinate equipment locations to fall along edges of or in the aisles between PV arrays to minimize disruptions to the PV layout.
- Locate equipment in locations shaded by other building or site features that could not be otherwise used for efficient PV generation.
- Locate equipment items on the northern edge of the roof or in other locations that will not cast shade on the PV installation.

BP16 *Roof Durability and Longevity*

Because the panels will generally rest on top of the roof surface and preclude easy roof replacement, specify the most durable and long-lasting roofing the project goals can support. To host a solar PV system, a roof must be able to support the weight of PV equipment.

Also important is determining whether the roof installation carries a warranty and if the warranty includes contract terms involving solar installations. Consider roof warranties that are at least as long as the life expectancy of the PV array, and be aware of the factors that distinguish roof durability and roof warranty (which are not always synonymous).

Consider including third-party roofing inspectors on the commissioning (Cx) team to ensure roof installation quality and reduce the need for roof repairs after the PV installation is complete. Other considerations include the following:

- **Access.** Provide walk-out or stair access to all roof areas with PV system components, whether code required or not.
- **Weight.** Incorporate the PV system weights into the structural assumptions for the roof areas—even when an array is not expected to be installed immediately. A common assumption for solar array weight is 3 to 6 lb/ft^2.
- **Usage.** Develop planning assumptions for any roof areas that will have frequent visitors to demonstrate or study the PV system. Areas intended for these visitors require greater structural capacity.
- **Wind Loads.** Analyze wind loads to ensure the roof structure and PV equipment are rated to withstand anticipated wind loads.

BP17 *Roof Safety*

For safety purposes, PV panels should not be mounted within 8 to 10 ft of the roof edge, depending on local jurisdictions and fire department requirements. Be aware of applicable code requirements, fire department access requirements, and worker safety regulations (per Occupational Safety and Health Administration [OSHA] as well as any client requirements). Roofs may require fall-protection railings for roof-mounted equipment. Any required guardrails or guarding parapets will cast shade and thus directly affect the location and placement of PV collectors. Conversely, roofs without guards or parapets will need to maintain significant clear areas around roof edges and will thus sacrifice roof area that could be otherwise used for solar-electric generation.

BP18 *Maintain Solar Access*

Pay particular attention to the many instances of conventional practice that sacrifice solar access and in turn reduce the production of solar electric power. Even small amounts of shading can reduce the output from solar PV systems, so locate the building and PV array so that they are entirely clear of shade from adjacent site features and surrounding vegetation, particularly on the south-facing side of the building. Note the following strategies:

- Always calculate and analyze the solar path diagram, especially when working in unfamiliar locations. Pay particular attention in latitudes between the equator and 23.5° north (in the northern hemisphere), where direct sun will come entirely from the north for part of the year.
- Anticipate the buildable envelope of adjacent parcels. Secure solar easements or locate PV arrays entirely clear of the projected shade path.
- Anticipate the maximum/mature height of trees. Locate PV arrays entirely clear of the worst-case projected shade path. Do not rely on deciduous trees having dropped their leaves—plan the building/array location to receive unobstructed winter sun.
- Avoid towers, chimneys, and other appurtenances on the building that would impede solar access.

- Avoid shade thrown by parapets, monitors, stairwells, mechanical equipment, and other rooftop items.

Most three-dimensional modeling software used for architectural design can model shadows for specific locations at any time of the year. As a general rule of thumb, maximize the shade-free roof area at 9:00 a.m. and 3:00 p.m. on the winter solstice.

In addition to maintaining solar access for PVs, accommodate the maintenance of the PV system, including access to modules, hose bibs for PV cleaning, and rooftop power.

B19 Alternatives to Roof-Mounted PVs

There are times it will be advantageous to look at alternative locations to supplement or replace a roof-mounted PV system. Some projects may lack enough shade-free roof space for a properly sized system. Some may include a green roof, which limits the area available for PVs. In addition to many practical reasons for looking beyond the roof, some building owners want the PVs to be visible to the occupants and public. Ground-mounted and parking-canopy-mounted PV installations are the two most common alternative locations. These mounting options are discussed in the "Renewable Energy" section of this chapter (see RE5).

Another alternative is building-integrated photovoltaics (BIPVs), which can offer many creative applications. The concept of BIPVs is to use PVs in place of (or integrated into) standard exterior building materials. This can take the form of roofing, wall panels, glazing, canopies, roof shades, and other applications. Beyond the advantage of being more visible to occupants, this also creates the advantage of having exterior building components serve additional functions (building skin and energy producer). BIPV installations use a wide variety of PV technologies, including thin-film PVs, which have significantly different energy generation characteristics compared to conventional PV modules. If the BIPV system has an overall efficiency less than 19%, then the sizing approach in BP14 cannot be used. See Figure 5-8 for an example of BIPVs.

Figure 5-8 (BP19) Building-Integrated Photovoltaics (BIPVs)

Photograph Courtesy of Morgan Creek Ventures; Credit: Bruce Damonte

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ENVELOPE

OVERVIEW

The building envelope serves aesthetic and performance functions. The envelope must be well detailed, constructible, and installed correctly to provide durability and accommodate performance requirements including the control of transmission of water, water vapor, air, thermal energy, light, and sound, as well as other project-specific performance requirements. This section identifies strategies to properly insulate the building envelope and provide low air leakage rates. The how-to strategies are organized around the following four topics:

- Thermal performance of opaque assemblies
- Thermal performance of fenestration and doors
- Air leakage control
- Thermal bridging control

The thermal optimization of the envelope is tied to the building's climate. Figure 5-9 presents heating and cooling loads by climate zone. This information can be quite useful as an intuitive

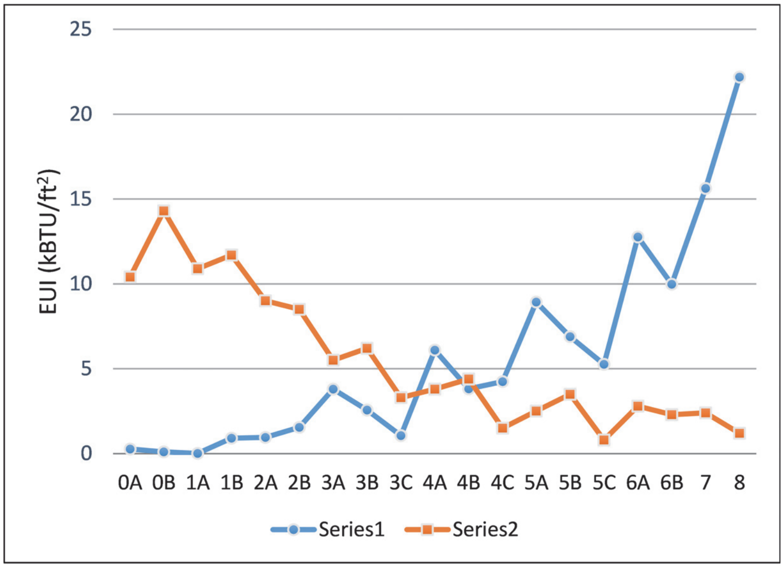

Figure 5-9 (EN) Heating and Cooling Loads by Climate Zone

starting point as one starts to evaluate appropriate building envelope strategies and, more specifically, the balance of solar gain control, thermal transmittance control, and air leakage control.

Installation and Cx are instrumental to the success of a high-performance building envelope and by extension the success of a zero energy building. Further discussion of building envelope Cx and other quality-control efforts is provided in the "Support Zero Energy in Ongoing Operation" section of Chapter 3. Consulting with a building envelope expert or commissioning provider (CxP) during design can improve the performance of the envelope and address potential hygrothermal issues. In addition, projects benefit from consultation with a structural engineer regarding the structural coordination for envelope details.

Cautions:

Adhere to applicable building codes and the underlying reference standards for building envelopes. These standards impose limits on the extent and application of combustible materials, in particular on foam plastic insulation products.

In many cases, specific tested assemblies may be required, and slight variances may require engineering judgment from manufacturers to satisfy the authority having jurisdiction.

THERMAL PERFORMANCE OF OPAQUE ASSEMBLIES

EN1 Building Insulation General Guidance

There are numerous insulation products available, and there are multiple criteria used to evaluate insulation, including R-value, moisture resistance, recycled content, recyclability, combustibility, and outgassing. Structural components and cladding attachments often decrease the effectiveness of the insulation, causing thermal bridges. Continuous insulation can help reduce thermal bridging. For zero energy buildings, it is critical to develop systems that meet the targeted clear-field U-factor for the envelope. The clear-field U-factor represents the overall U-factor of an opaque assembly including regularly spaced thermal bridges from studs and attachments.

Increasing insulation beyond recommended levels will save energy; however, this benefit may be minimal. While there is a diminishing return on energy savings by further increasing insulation levels, higher insulation levels may result in a reduced peak heating and/or cooling load that could reduce the size and cost of the heating and/or cooling plant. Project teams should start with the recommended insulation levels shown in Table 5-4 and model to see if additional insulation is effective at reducing the energy use and peak loads.

These recommendations were selected by reviewing the criteria in existing energy-efficient-building construction documents including ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2016), IgCC/189.1 (ICC 2018), and *Advanced Energy Design Guide for K-12 School Buildings: Achieving Zero Energy* (ASHRAE 2018). The most energy-efficient criteria for each of the envelope construction features were selected in each climate zone. Appendix A presents alternative constructions that have equal to or even better U-factors or F-factors for the appropriate climate zone.

Table 5-4 (EN1) Envelope Construction Factors

	Recommendations by Climate Zone								
Component	0	1	2	3	4	5	6	7	8
Roof U-factor	0.039	0.048	0.039	0.039	0.030	0.030	0.030	0.027	0.027
Frame walls above grade U-factor	0.124	0.077	0.077	0.064	0.061	0.052	0.047	0.047	0.035
Mass walls above grade U-factor	0.171	0.107	0.098	0.075	0.069	0.058	0.052	0.052	0.039
Slab F-factor	0.730	0.730	0.730	0.730	0.494	0.494	0.485	0.400	0.400

Units for U-Factor are Btu/h·ft^2·°F.

Table 5-5 (EN1) Insulation Applications by Envelope Component

Component	Insulation Material	EN2	EN3	EN4	EN5	EN6	EN7	EN8
		Roofs	Walls, Mass	Walls, Framed	Walls, Below Grade	Floors, Mass	Floors, Framed	Slab-on-Grade
Rigid boards	Extruded polystyrene	X	X	X		X		
	Expanded polystyrene	X	X	X	X	X		X
	Polyisocyanurate	X	X	X		X		
	Cellular foam glass	X	X	X	X	X		X
Semi-rigid boards	Mineral wool	X	X	X		X		
	Fiberglass	X			X	X		
Spray-in-place	Polyurethane	X	X	X				
Loose fill	Fiberglass			X				
Batts	Fiberglass			X			X	
	Mineral wool			X		X	X	

Table 5-5 outlines common commercial insulation material applications for the envelope components discussed in this Guide (refer to EN2 through EN8).

EN2 *Insulation of Roofs*

Insulation entirely above the structural deck is recommended. Carefully consider the consequences of the specified installation method in association with the roofing system. Mechanically attached insulation layers and systems increase thermal bridging losses, and fasteners can penetrate the roofing system air barrier (in assemblies where the roof membrane is not being used as the continuous air barrier). Penetrations in an assembly's air barrier can increase the susceptibility of the roofing layers to condensation.

Adhered layers (including insulation, substrate boards, and cover boards) eliminate thermal bridges and leave the air barrier intact. When relying on adhered systems, carefully weigh the energy-efficiency improvements against the potential increased volatile organic compounds (VOCs) inside the building envelope and the potentially degraded recyclability of the roof. In addition, confirm that the adhered installation meets related technical requirements defined by building codes and third-party stakeholders (such as insurers).

To minimize thermal losses and infiltration, board insulation should be installed in at least two layers staggering the joints. Refer to Table 5-5 for common insulation materials for roofs.

If PV panels are mounted to the roof, the roofing system must be able to accommodate the dead load and uplift from the panels. Attachments for PV panels must minimize thermal bridging through the insulation. Ballasted PV systems could be considered, as they do not penetrate the roofing membrane or roof insulation.

EN3 *Insulation of Mass Walls—Concrete and Masonry*

For mass walls, continuous exterior insulation is preferred over interior insulation as it can aid in the continuity of the air barrier and insulation and better accommodates the use of the thermal mass (when exposed to the interior) for energy efficiency. Exterior walls should meet the U-factor recommendations in Table 5-4.

Refer to Table 5-5 for common insulation materials for mass walls. In addition to the wall insulation options discussed above for mass walls, alternative or hybrid structures, such as insulated concrete forms (ICFs) may also be used as long as the actual U-factor complies with the values in Table 5-4.

For additional strategies relating to thermal mass see EN9 through EN11 and HV42 through HV43.

EN4 Insulation of Steel-Framed and Wood-Framed Walls

Cold-formed steel framing members are thermal bridges. Continuous insulation on the exterior of framed walls is the recommended method to minimize thermal bridges created by the framing. While wood studs are less conductive than steel, thermal bridging through the wood also decreases the effectiveness of stud cavity insulation; therefore, continuous exterior insulation is also recommended for wood-framed stud walls.

Alternative combinations of stud cavity insulation and continuous insulation can be used, provided that the proposed total wall assembly has a U-factor less than or equal to the U-factor for the appropriate climate zone construction listed in Table 5-4, and provided that analysis demonstrates that vapor will not condense in the wall. Wall sheathing with integral insulation can provide exterior continuous insulation that simplifies wall construction.

Refer to Table 5-5 for common insulation materials for framed walls.

EN5 Insulation of Below-Grade Walls

Continuous exterior insulation is recommended for below-grade walls (portions of the first floor or basement that is below grade). Certain closed-cell foam insulations are suitable for this application. Continuous exterior insulation can aid in the continuity of the air barrier and insulation (where the above-grade primary thermal insulation or air barrier layers are outboard of the exterior wall construction) and better accommodates the use of the thermal mass. Below-grade walls must be insulated for their full height. When heated slabs are placed below grade, below-grade walls should meet the insulation recommendations for perimeter insulation according to the heated slab-on-grade construction (EN8). Refer to Table 5-5 for common insulation materials for below-grade walls.

EN6 Insulation of Mass Floors

Mass floors (over unconditioned space) should be insulated continuously beneath the floor slab. Because columns provide thermal bridges, the insulation should be turned down the column to grade for crawlspaces. For columns extending to below-grade parking, insulation should be turned down to the extent possible without presenting a durability issue with vehicles. Note that this is in reference to supported mass floors; slab-on-grade floors are addressed in EN8. Refer to Table 5-5 for common insulation materials for mass floors.

EN7 Insulation of Framed Floors

Insulation should be installed between the framing members and in direct contact with the flooring system supported by the framing member in order to avoid the potential thermal short-circuiting associated with open or exposed air spaces. Refer to Table 5-5 for common insulation materials for framed floors.

EN8 Insulation of Slab-on-Grade Floors—Unheated and Heated

Where slab edges or the enclosing stem walls are exposed to the exterior, rigid insulation, suitable for ground contact, should be used around the perimeter of the slab and be continuous to the footing (see EN37). For heated slabs, or for slabs in climate zones 4 or higher, continuous insulation should be placed below the slab as well. For thermal comfort, evaluate slab surface temperatures and adjust insulation levels until interior surface temperatures are within 9°F of the indoor air temperature. Refer to Table 5-5 for common insulation materials for slab-on-grade floors.

EN9 Thermal Mass General Guidance

Thermal mass is a property of a material that allows it to store and release thermal energy. Thermally massive materials have high densities and high specific heat capacities. They also have medium thermal diffusivity, which means the rate of heat flow through the material is moderate and can often match a desired time delay for storing and releasing energy within a daily cycle. Materials with high thermal mass include masonry, stone, rammed earth, concrete, and water. The advantage of thermal mass is its ability to absorb thermal energy and temporarily store it before releasing it, thereby creating inertia against outdoor temperature fluctuations.

Two primary strategies for incorporating mass in the building structure include internal thermal mass and external thermal mass. External mass is located outside of the insulation layer of the envelope and is directly exposed to the exterior. Internal thermal mass can take many forms, but it is inside of the thermal envelope and it is directly exposed to the space. Internal thermal mass can be exterior walls (inside the insulation layer), interior walls, slabs, and/or columns and beams. Thermal mass does not require deep floor or wall assemblies to be effective, but it is more effective if it is distributed throughout the space. While these two approaches are passive, thermal mass can also be made into thermally active surfaces. Refer to HV42 and HV43 for additional information on utilizing thermal mass.

EN10 Internal Thermal Mass

Exposed internal thermal mass within office spaces tends to mitigate temperature swings that might result from a mismatch between conditioning level and thermal load at any specific time, allowing conditioning to be applied to the space in a more energy-efficient manner and, sometimes, precluding the need for conditioning. While internal thermal mass tends to mitigate interior temperature swings, one must remember that heat transfer between the thermal mass and the air must be driven by temperature difference. Therefore, to "exercise" the thermal mass, to make use of its thermal storage capacity, the air must be warmer than the thermal mass to drive heat into it and must be colder than the thermal mass to extract heat from it. As a result, the cycling of the air temperature must necessarily have a greater amplitude than the cycling of the thermal mass temperature. For certain types of occupancies, cycling of air temperature may be acceptable; for others not, especially if the cycling extends outside of the comfort range.

Thermally massive elements in a space will dampen variation in space mean radiant temperature, improving comfort even with significant changes in space air temperature. If the thermal mass has significant area in the space, its relatively invariant surface temperature can reduce fluctuations in mean radiant temperature, resulting in improved thermal comfort. Interior thermal mass is particularly effective in spaces with significant solar gain, because it dampens the peak conditioning loads or temperature variations that might occur due to highly variable solar heat gains.

One additional advantage to internal thermal mass is that it can reduce the rate at which internal temperatures rise as cooling capacity for the space is reduced, facilitating adaption of the building to minimizing electrical demand during the 4:00 pm to 9:00 pm period when the utility generation profile includes fewer renewable assets. Upon receipt of a signal from the utility that their renewable generation fraction has fallen below a certain threshold, thermostat set points can be raised, with the realization that a thermally massive building will conform to the new temperature more slowly than a less massive one.

Examples of internal thermal mass utilization that may not require extreme cycling of air temperature are passive solar heating systems, in which short-wave solar radiation is transmitted through windows or skylights and directly heats internal mass. This heat is stored and over time is released into the internal environment, avoiding the need for high internal air temperature to charge the mass. Solar-heated thermally massive elements also exchange heat through long-wave radiation with other surfaces in the space. If those other surfaces are also massive, the rate of discharge of the absorbed solar energy will be further attenuated and extended over time. Designers using this strategy should be cautious of the thermal discomfort that can result from direct solar penetration into the space and the visual discomfort that can result from direct solar glare.

Over the course of a day, in an office building dominated by cooling, people arrive to work, computers and lights turn on, and sunlight enters through the windows. A portion of these heat gains can be absorbed by exposed thermal mass in the space and then released at night when the building is unoccupied. To release the thermal energy at night, the mass needs to be exposed to air cooler than the temperature of the mass. This works in climates with large diurnal temperature swings that go below the comfort zone, using a passive strategy known as *night flushing*. Night flushing can be accomplished passively or mechanically (with an air-side economizer). Using the strategy of night flushing, however, requires that the air temperature in the space vary as much as 15°F, possibly putting the space conditions outside of the comfort zone for part of that period. Night flushing with cool, high-humidity air, however, can cause moisture absorption by porous surfaces in the space, resulting in dehumidification cooling loads the following morning. Utilization of night flushing strategies should include controls to avoid flushing with high-humidity air.

Figure 5-10 shows an example of exposed thermal mass at the exposed ceiling (painted steel deck and concrete) and interior face of the exterior walls (concrete painted white) at the Research Support Facility on the NREL campus.

EN11 External Thermal Mass

External thermal mass reduces the total thermal loads over time when the impact of intermittent exterior conditions (sun or air temperature) can be stored to offset the impact of later conditions that might drive the space temperature in the opposite direction. Nighttime heat losses and daytime heat gains to some extent cancel one another in their journey across the depth of the wall, resulting in a much smaller temperature swing on the interior surface of the wall that may well stay within the comfort band (see also HV42 through HV43). An example of such storage is the impact of a massive exterior wall on the building's internal temperature, when the diurnal exterior temperature oscillates across the building's balance-point temperature. If the ambient diurnal temperature cycle does not traverse the building's balance-point temperature, however, thermal mass will have little effect on the daily heat transfer across the building envelope and little effect on the total conditioning required. In all cases, however,

Figure 5-10 (EN10) Exposed Thermal Mass at NREL Research Support Facility

Photograph by Dennis Schroeder, NREL 19913

Phase-Change Materials

In low-mass buildings the use of phase-change materials (PCMs) can offer benefits for passive cooling that are similar to those of thermal mass, as discussed in EN11. While thermal mass absorbs and releases sensible heat (temperature changes with no change in material phase), PCMs absorb and release latent heat (changes in material phase at constant temperature) and have high thermal energy storage densities. The melting point is designed to be a specific temperature to absorb heat from a space that is warming and in need of cooling. When the space temperature drops below the material's melting point, the thermal energy is released back into the space. A common strategy would to be include night flushing to remove this heat during unoccupied hours.

PCMs such as paraffins, slat hydrates, and fatty acids are encapsulated to create a product that can be integrated into construction assemblies such as those for walls, ceilings, and glazings. A common example is a membrane encapsulated with pockets of PCM that can be laid over a ceiling in order to absorb and control internal heat gains.

additional mass reduces peak loads, both heating and cooling. Conventional masonry cavity walls and insulated precast panels are examples of this construction and offer the co-benefit of a very durable exterior finish. The mass can absorb and store thermal energy during the day and release it back to the cooler exterior air at night. This reduces the amount of heat gain that is conducted through the insulated portion of the wall to the interior environment. This can also delay the peak cooling demand. Refer to HV42 and HV43 for more information on integrating thermal mass effects with an active conditioning system.

EN12 Roofing General Guidance

There is a wide range of roofing choices available in the marketplace, and many factors affect the selection, specification, design, and detailing of a building's roofing system. Roofing material properties can have a significant effect on a building's envelope loads, energy usage, and microclimate (heat island effect). Architectural, engineering, and construction (AEC) teams should plan to optimize the roofing materials and assemblies through energy modeling and an understanding of how roofing choices influence overall project energy goals.

Rooftop PV arrays can complicate roof maintenance and future roof replacement. See BP16 for strategies on designing a long-lasting roof.

EN13 Cool Roofs and Warm Roofs

Cool roofs reduce the temperatures of roofs and can therefore reduce the urban heat island effect and reduce the cooling loads of buildings. To be considered a cool roof, a product must demonstrate a solar reflectance index (SRI) of 78 or higher. A detailed explanation of the SRI calculation is available by the Cool Roof Rating Council (CRRC) at https://coolroofs.org/resources/home-building-owners.

In the past, cool roofs were generally lighter colored and had a smooth surface. The product category has expanded with technical advancements, and cool roofing materials are now available in a wider variety of colors and textures. Commercial roof products that qualify as cool roofs fall into three categories: single-ply, liquid-applied, and metal panels. Additional information is available from the CRRC or the U.S. Department of Energy (DOE) publication *Guidelines for Selecting Cool Roofs* (DOE 2010).

Cool roofs provide energy reductions in climate zones 0 through 4. Warm roofs, in contrast, reduce energy use modestly in climate zones 7 and 8. Differences in energy usage between cool roofs and warm roofs are negligible in the remaining climate zones. Project teams can energy-model different roof types to confirm which provides the best energy benefit for a project.

One reason to consider a cool roof in most climates is that a cool roof can improve the efficiency of roof-mounted PVs. Elevated temperatures adversely affect solar production. PV modules are tested and rated at 77°F, and roof temperatures in the summer can significantly exceed this. White, reflective roofs can also be used in combination with bifacial PV modules, which can produce power from both sides of the module and achieve energy production gain from sunlight reflected from the white roof.

EN14 Green Roofs

Green roofs are roofs with a vegetative layer and soil and plants. Green roofs provide similar benefits as cool roofs, referenced in EN13. The EPA estimates that green-roof temperatures can be 30°F to 40°F lower than those of conventional non-cool roofs. Though they are more expensive than conventional roofs, green roofs offer unique advantages in addition to reduced heat island effect. These advantages include improved storm-water management, sound insulation, improved air quality, biodiversity, biophilia, and aesthetics.

THERMAL PERFORMANCE OF FENESTRATION AND DOORS

EN15 Building Fenestration General Guidance

Fenestration includes the light-transmitting areas within a wall or roof assembly, including windows (fixed and operable), skylights, and glass doors. Vertical fenestration is glazing with a slope equal to or greater than 60° from the horizontal. Glazing with a slope less than 60° from the horizontal is considered a skylight.

Effectively designing the fenestration is one of the cornerstones of creating a zero energy office. The best way to achieve low-cost daylighting, views, and natural ventilation is to integrate fenestration early in the schematic design phase. The most economic and effective fenestration design requires coordination with the structural, mechanical, and electrical disciplines. This includes designing fenestration to help reduce peak cooling loads, which can result in scaled-back mechanical systems providing first-cost savings.

Operable fenestration can be a source of natural ventilation that can reduce the need for mechanical cooling and ventilation in many climates and provide resiliency during power outages and other emergency events. On the negative side, fenestration is a significant source of heat loss and gain through a building envelope. Designers should seek a balance between the benefits of fenestration (daylighting, natural ventilation, and views) and the penalties (heat gain and loss) through iterative modeling and testing of fenestration strategies. Effective fenestration should provide more benefit from daylighting, natural ventilation, and occupant views than the adverse heat loss and gain from a diminished thermal envelope.

In general, an optimized energy solution is to rightsize the glass for daylighting and natural ventilation while realizing that additional glazing is often desired for views, which provide benefits to occupant health, well-being, and productivity. Balancing the amount of glass to meet architectural and energy goals requires careful energy simulations to evaluate the energy impacts, because they vary considerably by climate and fenestration orientation.

Energy modeling and cost analysis should be used to optimize fenestration design. The goal is to balance cost, thermal loads, natural ventilation, daylighting, and views. This modeling needs to be completed early in the design process to have the greatest impact on design decisions. See the “Building Systems Strategies” section of Chapter 4 for more information on energy simulation.

Structural performance, hurricane-impact-resistant requirements, and durability should also be considered because they will affect fenestration product selection and the resulting energy performance.

EN16 Window-to-Wall Ratio

The window-to-wall ratio (WWR) is the ratio of window area to above-grade exterior wall area (excluding parapets) for a building or a façade.

The WWR must be established early in the design process, as it has a significant effect on building energy performance. In many climates it may be one of the most important variables in delivering a cost-effective zero energy building. Setting a WWR for each façade is a key design consideration that can help meet the energy target and construction budget. The actual articulation of fenestration may be developed later in the design process.

Windows have valuable benefits, including providing views, daylight, natural ventilation, increased real estate value, and aesthetics. However, they also represent a liability in terms of overall thermal performance and first cost. High-performance glazing systems and additional shading and daylighting devices improve performance but also increase the first cost. With this in mind, it is important to consider the life-cycle value of glazing, weighing first costs and energy costs with productivity and occupant benefits as outlined in the “Occupant Satisfaction” section of Chapter 1.

Glazing systems are the weak points in the thermal envelope, having a significantly reduced R-value compared to high-performance opaque walls and accounting for the majority of an office building’s heat loss and virtually all of the solar heat gain for a building. Therefore, it is important to select high-performance glazing systems and rightsize the WWR.

In general, a good starting point for a WWR goal is 30%. This should be adjusted for climate zone, façade orientation, occupant views, and other design considerations. It is good practice to reduce WWR on the east and west elevations compared to the north and south elevations. It is difficult to control solar gains and glare on the east and west façades, and northern latitudes have higher incident solar radiation striking these façades during the summer.

Typically, only a relatively small area of well-positioned windows is needed to provide daylight and/or natural ventilation. Predominantly overcast climates may require higher WWRs for daylighting, but care must be taken to also design for sunny days in overcast climates. Providing for views usually drives the WWR higher than what is needed for daylight and natural ventilation. Refer to DL8 for a discussion of glazing for daylighting and views.

EN17 Select the Right Glazing

The selection of window glazing should be considered independently for each orientation of the building based on the requirements for each orientation. In addition, daylighting and view functions should be considered independently based on the requirements for their proper function. The three main performance properties for glazing that should be considered are as follows:

- U-factor
- SHGC
- Visible transmittance (VT)

Table 5-6 shows target values for U-factor, SHGC, and VT (as a ratio to SHGC). These recommendations were selected by reviewing the criteria in existing energy-efficient building construction documents, including ASHRAE/IES Standard 90.1 (ASHRAE 2016), IgCC/189.1 (ICC 2018), and *Advanced Energy Design Guide for K-12 School Buildings: Achieving Zero Energy* (ASHRAE 2018). The most energy-efficient criteria for each of the fenestration performance properties were selected in each climate zone. Fenestration products are available that exceed the minimum requirements in Table 5-6 and should be considered for zero energy office buildings. Project teams should model further improved performance properties to see if additional improvement is effective in reducing the EUI relative to other energy-savings strategies in order to provide the best energy-savings strategy for the project budget.

Table 5-6 (EN17) Fenestration and Doors Assembly Criteria

	Recommendations by Climate Zone								
	0	1	2	3	4	5	6	7	8
Maximum U-factor (fixed)	0.48	0.48	0.43	0.40	0.34	0.34	0.32	0.28	0.25
Maximum U-factor (operable)	0.59	0.59	0.57	0.51	0.43	0.43	0.40	0.34	0.30
Maximum SHGC (fixed)	0.21	0.22	0.24	0.24	0.34	0.36	0.36	0.38	0.38
Maximum SHGC (operable)	0.19	0.20	0.22	0.22	0.31	0.31	0.32	0.34	0.34
Minimum ratio of VT/SHGC	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Swinging doors U-factor	0.370	0.370	0.370	0.370	0.352	0.352	0.352	0.352	0.352

Note that the values in this table represent values for the overall fenestration assembly, not just the glazing. This is particularly important for the U-factor (see EN18). Units for U-factor are Btu/h·ft^2·°F.

EN18 U-Factor

The U-factor is the rate of thermal transmittance through a window assembly induced by temperature differences between each side of the window—the lower the value the better. The recommended fenestration U-factors in Table 5-6 are assembly U-factors that include the center-of-glass U-factor for the glazing, the type of edge-of-glass spacers, and the framing material and design.

The center-of-glass U-factor for glazing is dependent on the makeup of the glazing unit, including the number panes, type of low-conductance gas fill (air, argon, or krypton), use of low-e coatings, and/or use of suspended films. The edge-of-glass U-factor is dependent on the type of edge spacer used in the glazing unit. There are a number of "warm-edge" spacer technologies that have lower conductance compared with standard aluminum spacers. These warm-edge spacers include stainless steel, silicone foam, butyl, plastic composites, and other spacer technologies.

In cold climates, triple-pane windows should be used because double-pane insulated glazing will not typically meet the recommended or optimal U-factor. An emerging option is vacuum glazing, which has a very low U-factor and is now commercially available from a number of suppliers.

Window frames have higher U-factors than the glazing. To achieve a low U-factor, window frame material, construction, and design must all be considered. Aluminum is the most common window frame material for commercial offices due to its structural performance, lightweight characteristics, wide spans, design flexibility, durability, low maintenance, and recyclability. However, because aluminum is highly conductive, its assembly U-factors will be higher compared with other nonmetallic frame materials such as wood and fiberglass. Frame U-factor is improved by introducing one or more thermal breaks into the frame assembly to separate the interior exposed portion of the frame from the exterior exposed portion of the frame. New high-performance window framing includes advanced thermal break technologies such as double pour-and-debridge and wide thermal struts. Examples of advanced technologies for thermally broken aluminum frames are shown in Figure 5-11.

Window framing is typically the weakest link in the overall window U-factor, and care should be taken to avoid unnecessary framing and subdividing mullions that are not needed structurally. Balance the visual composition with the thermal and structural performance requirements of the window. Note that mullions are helpful to separate daylighting glass from view glass and can be used as a mechanism for attaching light shelves, sunshades, and blinds that can reduce glare without impacting the daylighting.

The method of detailing and installation of the window system, including factory-built windows, storefront, and curtain wall systems, must be considered and accounted for in the overall energy modeling. Clips and bearing plates are integral to the installation and can be a source of thermal bridging between the window system and the exterior wall construction. These thermal bridges should be minimized.

Verify that energy models, drawings, and specifications all reflect the window assembly U-factor. Avoid using the center-of-glass U-factors for comparisons. For manufactured fenestration, whether shipped assembled or site assembled, look for a label or label certificate that denotes that the window U-factor is certified by the National Fenestration Rating Council (NFRC). This label/certificate will also include the SHGC and VT. It is typically easier to establish U-factors for factory-built window units than for storefront or curtain wall glazing systems. During design, window manufacturers can be consulted for assembly U-factors, or the U-factors can be modeled using the WINDOW software (freely available from Lawrence Berkeley National Laboratory [LBNL 2019]). Manufacturer-provided online calculators can also be used.

In colder climates, select fenestration to avoid condensation and frosting. This requires an analysis to determine interior surface temperatures. Condensation can occur on the inner face of the glass whenever the inner surface temperature approaches the room dew-point temperature. This scenario is most likely in spaces with elevated humidity. Condensation risk is reduced for windows with low U-factors, as their reduced heat loss translates to a higher glass surface temperature. This also translates to improved thermal comfort. During the winter, if the interior surface temperature of glazing drops considerably lower than room temperature and the temperature of other interior surfaces, then a condition known as *radiant asymmetry* occurs. This can cause significant thermal comfort challenges, even when indoor air temperature is satisfactory.

EN19 Solar Heat Gain Coefficient (SHGC) 🔧

The solar heat gain coefficient (SHGC) is the fraction of solar radiation that is transmitted through glazing. Lower SHGC equates to better control for solar hear gain. As a starting point, the SHGC of fenestrations should comply with the SHGC delineated in Table 5-6. SHGC is ideally tuned to each elevation, with the lowest value typically for west-facing glass and the highest value typically for north-facing glass. Dynamic glazing can also be considered; it can actively change its SHGC to optimize energy performance and glare control throughout the day, month, and season and on different elevations (see EN26).

Overhangs work to effectively reduce the SHGC of vertical fenestration on the east, south, and west façades, but on the east and west there are many times during the day when sunlight

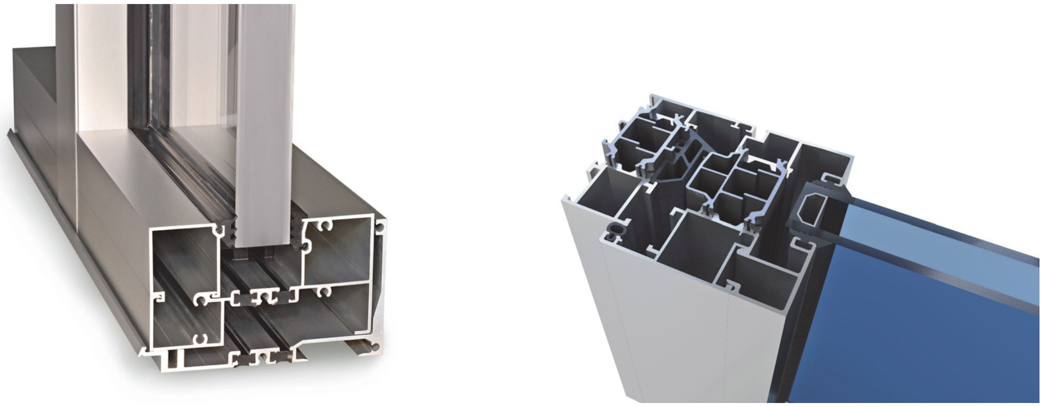
(a) (b)

Figure 5-11 (EN18) Thermally Broken Aluminum Frames: (a) Double Pour-and-Debridge and (b) Wide Thermal Struts
Photographs Courtesy of Azon (left) and Technoform (right)

will shine under the overhang, causing glare and discomfort. The size of an overhang is commonly characterized by its projection factor (PF), which is the ratio of the distance the overhang projects from the window surface to its height above the sill of the window it shades.

The multipliers in Table 5-7 may be applied to the SHGC of the assembly to calculate the effective SHGC. For instance, if the NFRC-rated SHGC is 0.40 and the window is shaded by an overhang with a PF of 0.75, the effective SHGC is 0.40 × 0.51 = 0.20.

EN20 *Visible Transmittance (VT)*

The visible transmittance (VT) is the fraction of the visible spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight. As the VT is coupled to the SHGC, the ratio of VT to SHGC is often used rather than using them as individual criteria. With advanced coatings, it is possible to block most of the radiation outside the visible spectrum while allowing visible light to pass through. Such glazing is known as *spectrally selective*, as it selectively allows visible light wavelengths to pass while blocking the infrared heat wavelengths.

The target value for VT/SHGC ratio as shown in Table 5-6 is 1.10 or higher. Most highly reflective glazing materials will fail to meet this requirement, as they typically have a VT lower than the SHGC. Clear, green, or blue glass with low-e coatings will almost always comply with this requirement. Bronze or gray tinted glass with mirror-like coatings will not. Relatively high VTs ensure that occupants can see out. The amount of daylighting that enters the building is directly proportional to the VT, so daylight apertures should have high VTs, but the size, position, and layout of daylight zones is equally important (refer to the "Daylighting" section of this chapter for more information).

EN21 *Dynamic Glass*

Dynamic glass can change its tint to respond to real-time solar conditions. This allows the energy performance and glare control to be optimized throughout the day, month, and season and on different elevations. Dynamic glazing technologies on the market including electrochromic and thermochromic. Each technology has a unique process for varying glazing tint and has its own advantages and disadvantages.

Electrochromic glazing can allow a VT range of approximately 0.01 to 0.58, corresponding to a SHGC range of 0.09 to 0.41. These wide performance ranges allow for glass to be quite transparent (when there is no need for solar control) or approaching opaque (where sig-

Table 5-7 (EN19) SHGC Multipliers for Permanent Projections

Projection Factor (PF)	SHGC Multiplier (South, East, and West Orientations)
0 to 0.10	1.00
>0.10 to 0.20	0.91
>0.20 to 0.30	0.82
>0.30 to 0.40	0.74
>0.40 to 0.50	0.67
>0.50 to 0.60	0.61
>0.60 to 0.70	0.56
>0.70 to 0.80	0.51
>0.80 to 0.90	0.47
>0.90 to 1.00	0.44

nificant solar control is needed) or anywhere in between; Figure 5-12 illustrates two extreme states. This type of flexibility can significantly reduce annual solar heat gain while still optimizing for daylighting and views. Dynamic glazing also provides glare control and can often eliminate the need for conventional window interior blinds.

For cold climates, dynamic glazing can be configured as triple-pane units to provide glazing with an improved U-factor while having the benefit of dynamic control of VT and SHGC.

EN22 Spandrel Panels

Glazing systems such as storefront and curtain wall systems accommodate a variety of building products that give designers aesthetic flexibility. These systems can incorporate spandrel sections where opacity is required (such as floor and ceiling edges). Opaque spandrel glass and panels are considered by energy codes to be opaque walls and must be insulated and thermally broken accordingly. Meeting wall-assembly U-factors with spandrels is extremely chal-

(a)

(b)

Figure 5-12 (EN21) Electrochromic Glass: (a) Fully Untinted and (b) Fully Tinted

Photographs by Dennis Schroeder, NREL 18736 (left) and NREL 18753 (right) lenging due to thermal bridging caused by the window framing and the metal backpans used to protect and install the insulation behind the spandrel. Often the effective assembly U-factor for spandrel panels can be four or more times the U-factor of the center of the insulated spandrel glass or panel.

If spandrel panels are important to include in a design, then make use of some of the best practices for improving their U-factor, including the following:

- Provide continuous insulation behind the spandrel panel and overlap insulation behind the curtain wall frame with the insulation behind the spandrel glass or panel.
- Provide a stud cavity wall insulated with spray foam insulation behind the spandrel.
- Use the highest R-value of insulation feasible in the assembly (use modeling to determine the point of diminished returns).
- Detail the spandrel assembly to maintain continuity of the insulation at the floor slab edge.
- Use low-U-factor spandrel glass (such as triple-pane glass) or insulated spandrel panels.
- Minimize the number of curtain wall framing members (while maintaining structural requirements) to reduce the quantity of thermal bridges in the assembly.
- Use improved thermally broken curtain walls, thermally improved deflection heads, and thermally improved connections of the metal backpan to the curtain wall.
- Consider structurally glazed curtain walls to reduce thermal bridging through the frame and metal backpans (see Figure 5-13).

Also consider new technologies, such as vacuum-insulated panels glazed into the curtain wall and aligned with the thermal break in the curtain wall frame.

EN23 Operable Fenestration

Operable fenestration offers personal comfort control and connections to the environment. Therefore, there should be a high level of integration between operable windows, envelope, and HVAC system design to maximize the energy benefits of this strategy. The envelope should be designed to take advantage of natural ventilation with well-placed operable openings. See BP6 for guidance on building and site planning as it relates to natural ventilation and HV34 for information on integration of natural ventilation with HVAC systems.

While screens may be used, note that they can significantly reduce the airflow (up to 40%) and air volume through fenestration openings. Screens also reduce the VT and SHGC and can impact daylighting.

EN24 Opaque Swinging Doors

Maximum U-factor values for opaque swinging doors are shown in Table 5-6. Where exterior swinging doors are provided, single doors should be used whenever possible. Use of double swinging doors without a center post should be minimized and limited to areas where width is important, such as for moving large equipment. In such situations, consider removable center mullions, which can be more tightly sealed than door astragals.

> ***Caution:*** Doors should be carefully inspected prior to final acceptance to ensure that all weather stripping is tightly sealed to the door and that all sweeps and bottom seals are tightly contacting the threshold or sill. Consider using double sweeps to improve airtightness.

EN25 Opaque Nonswinging Doors

When nonswinging opaque doors are functionally required, use doors that have a U-factor of less than 0.31 Btu/h·ft^2·°F, including edge effects and joints. A tight seal at the edges is critical to minimize infiltration.

Metal doors pose more challenges because they can have poor emissivity, resulting in a hot exterior surface from solar gains, which are transmitted through the door, increasing cooling

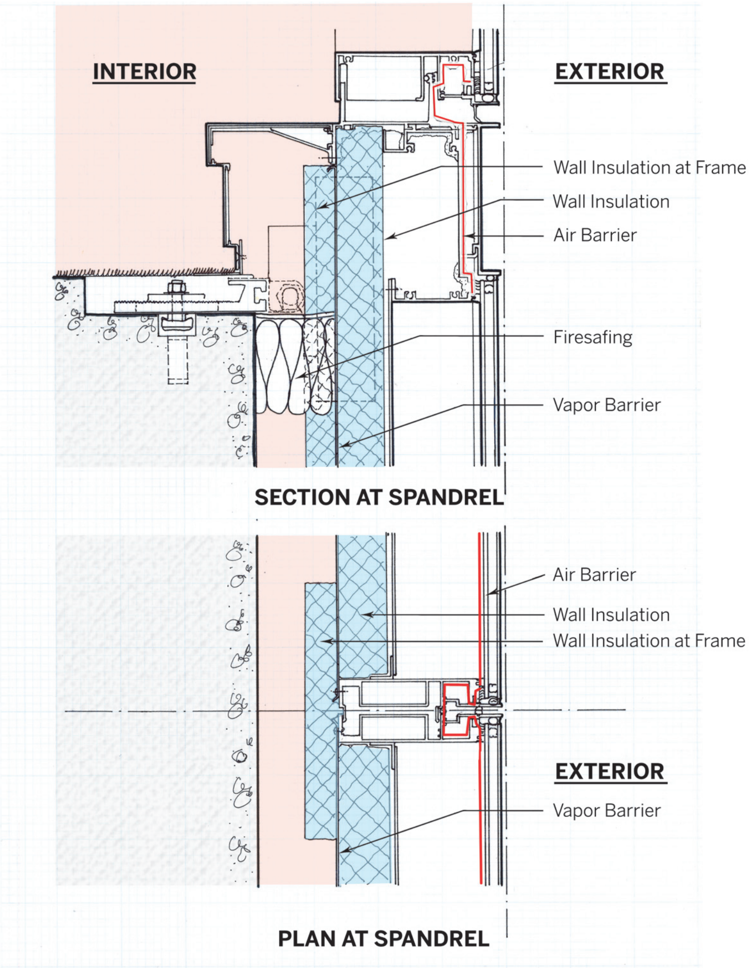

Figure 5-13 (EN22) Spandrel Insulation Continuity
Figure Created by Keith Boswell, FAIA

loads and magnifying thermal comfort issues. Where steel doors are functionally required and are exposed to solar radiation, a high-emissivity/reflectivity coating should be specified and proper solar shading should be provided. Specify insulated curtain slats and that the installed unit has seals contacting the curtain slats.

Minimize or mitigate thermal bridging and air leakage between the door assembly's perimeter components and the building framing.

EN26 Glazed Entrance Doors

Metal-framed glazed entranced doors should have a U-factor of less than 0.68 Btu/h·ft^2·°F.

In climates where infiltration is a concern, the use of entrance vestibules or revolving doors can reduce air infiltration from people entering and exiting the building. Vestibules and revolving doors should be considered on any doorway that is frequently used and are required by energy codes under certain conditions. Consider the following strategies.

Orientation and configuration. Orient entrances to avoid unwanted infiltration by prevailing winds. The inner and outer doors in vestibules are generally oriented in-line, for optimal pedestrian flow. Where practicable, configure the inner and outer doors at right angles to one another to further limit air infiltration during operation.

Vestibule depths. Vestibule depths are generally a function of safe and accessible ingress and egress. Deeper vestibules offer the advantage of improved indoor environmental quality because they increase the walk-off surface available and in turn reduce the amount of dirt and moisture introduced to the interior. Deeper vestibules also offer the co-benefit of limiting the instances of simultaneous openings of inner and outer doors during passage. Vestibules that are 10 ft or more in clear inside depth are recommended.

Vestibule construction. Configure vestibules such that the air, water, vapor, and thermal barriers are continuous from one side of the vestibule to the other (and from top to bottom), through the outer vestibule envelope, including openings. The inner vestibule envelope should be treated with equivalent concern for airtightness and insulation levels. This includes the door weather stripping. Fenestration in the inner vestibule envelope can generally be selected for U-factors equivalent to the exterior glass. SHGC values are not typically critical for the inner envelope glazing.

Vestibule conditioning. The vestibule should be a semi-heated space and not mechanically heated to above 45°F.

Revolving doors. Revolving doors can save energy but are often avoided by occupants in favor of traditional swinging doors located nearby. Consider adding signage to encourage use of revolving doors.

AIR LEAKAGE CONTROL

EN27 Air Leakage Control General Guidance $ 🔧

The building envelope has several functional layers to address vapor, water, air, and thermal control. From an energy perspective, this Guide is focused on the air and thermal control layers. Considerations for water and vapor control should be undertaken by a design and/or construction professional. Air barriers play a role in vapor control (depending on their vapor permeability), and some air barriers can also function as a water control layer. Therefore, the air barrier system needs to be considered in the water and vapor control design. In addition, the amount and location of thermal insulation plays a role in the temperature gradient through an exterior assembly and influences where the dew-point temperature (and possible condensation) occurs in the assembly based on interior and exterior temperatures. Because these control layers are so integrated, a hygrothermic analysis can be very useful in understanding the complex movement of heat and moisture through an envelope.

Air leakage through the envelope must be controlled to a determined maximum rate (see EN29). When air moves through the envelope, energy transfer occurs and either heating or cooling from the interior is lost (exfiltration) or exterior air is admitted (infiltration). Air infiltration and exfiltration are caused by pressure differences from wind, stack effect, and building mechanical systems and are controlled by the air barrier system. The air barrier system must be continuous over all surfaces of the building envelope, including at the lowest floor, exterior walls, and the roof, separating controlled interior environments from exterior and semi-conditioned or unconditioned spaces.

The air barrier system is composed of materials and details that work together to control building infiltration and exfiltration. There is a range of materials that can function as an air barrier. These materials need to be air impermeable (but not necessarily vapor impermeable) as well as durable and strong enough to perform for a long period in their application. Particular attention needs to be paid to the detailing of air barrier system joints, penetrations, and transitions.

The Building Science Corporation (BSC) article "BSD-014: Air Flow Control in Buildings" (Straube 2007) is a great resource for understanding air barrier systems.

EN28 Air Leakage for Fenestration and Doors

In addition to designing and installing a continuous air barrier utilizing appropriate materials, it is important to specify fenestration and doors that are part of the air barrier with tested and labeled air leakage rates (in accordance with AAMA/WDMA/CSA 101/I.S.2/A440

[AAMA/WDMA/CSA 2017], NFRC 400 [NFRC 2004], or ASTM E283 [ASTM 2012]) that are better than current energy code requirements. Window assemblies can be tied to the wall air barrier in a relatively straightforward way through the combination of flashing, self-adhering membranes, low-expansion foam insulation, and sealants.

EN29 Establish a Minimum Air Leakage Rate Target

The recommended target air leakage rate is 0.25 cfm/ft^2 (or less) of total envelope surface area at 75 Pa for all climate zones except 7 and 8. The recommended target for climate zones 7 and 8 is 0.15 cfm/ft^2 (or less) of total envelope surface area at 75 Pa. These targets are based on air leakage testing procedures per ASTM E779 (ASTM 2019).

THERMAL BRIDGING CONTROL

EN30 Thermal Bridging Control General Guidance

The design and construction of an energy-efficient building envelope requires a consistency in building assembles and construction sequencing that focuses on the continuous air barrier system and continuous-insulation strategies. Continuous insulation is greatly compromised by thermal bridging through the building envelope. Potential thermal bridges must be identified in design, well in advance of construction, to eliminate or at least mitigate thermal bridging.

Thermal bridging occurs when highly conductive elements (such as concrete, steel, and aluminum) "bridge" through the thermal barrier connecting internal and external surfaces. In general, this most often happens at studs, fasteners, assembly penetrations, and assembly interfaces or at transitions such as floor to wall, roof to wall, corners, and window openings. Uniformly distributed thermal bridges, such as studs or cladding attachments, need to be accounted for in the overall clear-field U-factors for those assemblies (see EN1 and EN34, as well as Figures 5-20 and 5-21). Likewise, thermal bridges from framing for building fenestration need to be accounted for in the overall U-factor for each window assembly (see EN18).

Point or penetration thermal bridges, such as a pipe penetration, and linear or interface thermal bridges, such as parapets, are the focus of this section and need to be quantified separately so that the building enclosure U-factors can be derated. This accounting for thermal bridging is important for energy modeling of zero energy buildings. Refer to Appendix C for information on methods for quantifying the impact of thermal bridges.

Strategies for minimizing thermal bridges can be categorized as follows:

- Mitigate thermal bridges to the greatest extent possible. This generally entails the provision of additional insulation inboard and/or outboard of the bridging component, including incorporating a layer of continuous insulation.
- Integrate nonconductive materials or spaces where conductive elements bridge the thermal barrier. Relatively nonconductive materials include fiber-reinforced plastic (FRP), some ceramic composites, and gypsum sheathing.
- Use the least conductive material when a bridge must be used. For example, stainless steel can be used in place of carbon steel for fasteners, brick ties, and structural clips. Plastic pipes can be used in lieu of metal pipes. Use Table C-1 in Appendix C for comparing envelope materials.
- When bridges are unavoidable, use fewer, larger bridges. This might include further spacing for structural or stud elements. Use modeling to compare scenarios.

EN31 Roof Penetrations

Roof drains and the substantial connecting pipes are a source of thermal energy loss (and internal building condensation) at the roofing assembly. The following strategies are recommended:

- The inboard side of the drain assembly should be thoroughly insulated where it penetrates the thermal envelope.
- Where metal rain leaders are used, the leaders should be insulated inside the building to the point where they penetrate the floor below (see Figure 5-14).

Generic penetrations of the roof, such as plumbing vents, can also be thermal bridges. These penetrations should be sealed, with all gaps around the penetration filled, as illustrated in Figure 5-15. When metal pipe is used, the pipe should be insulated to the top of the vent before being flashed. On the interior side, metal pipe should be insulated for a minimum of 10 ft.

Structural and pedestal penetrations of the roof and roof insulation are common on commercial construction projects. Examples include guardrail supports, rooftop screens, PV panel support attachments, and custom equipment platforms. All such penetrations must be carefully detailed to minimize energy losses. Rely on thermally broken structural connections, where a nonconductive plate is placed in the joint. The nonconductive plate should be located in the center of the roof insulation depth, if possible, to avoid complications with flashing and waterproofing.

EN32 Roof Curbs

Roof hatches are another substantial source of unintended energy loss. Roof hatches can vary greatly by manufacturer and have conventionally been significantly underinsulated. Recent innovations have included thermally broken hatches that decouple the exposed outer portions of the unit from the base mounting. During design, consider roof access that does not require roof hatches. If roof hatches are required, follow these recommendations:

- Select hatch covers with the maximum available insulation. Covers with at least R-18 are commercially available.
- Understand how the cover is structured and whether the cover is thermally broken.
- Select curbs with the maximum amount of insulation available. Curbs with at least R-18 are commercially available.

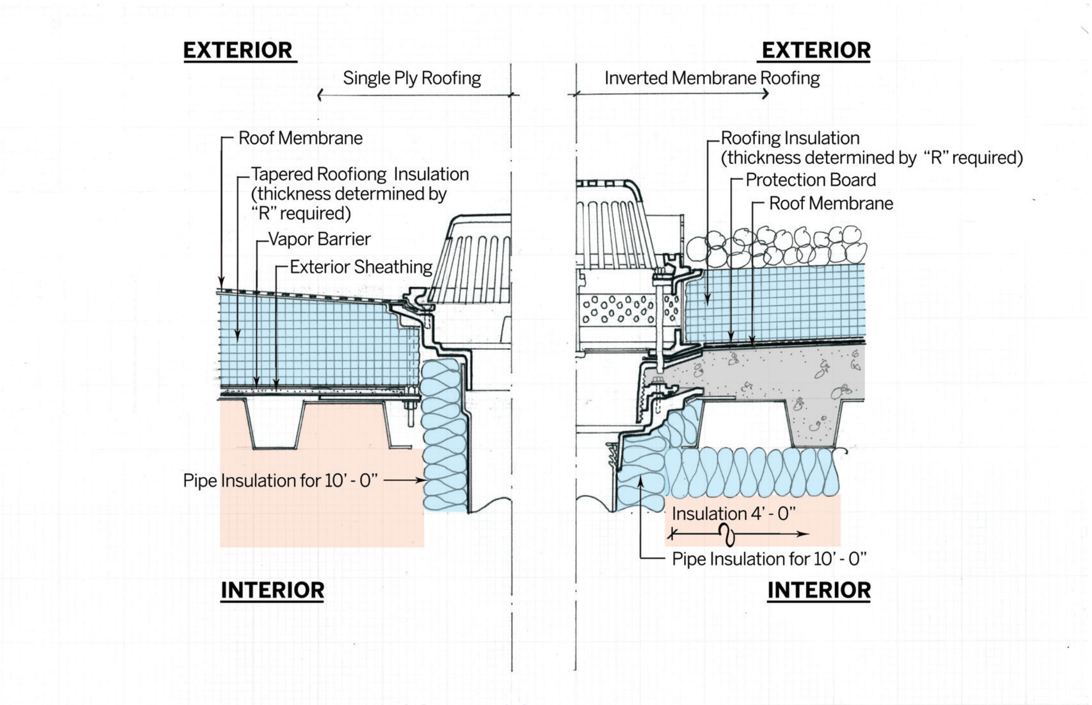

Figure 5-14 (EN31) Roof Drain Insulation

Figure Created by Keith Boswell, FAIA

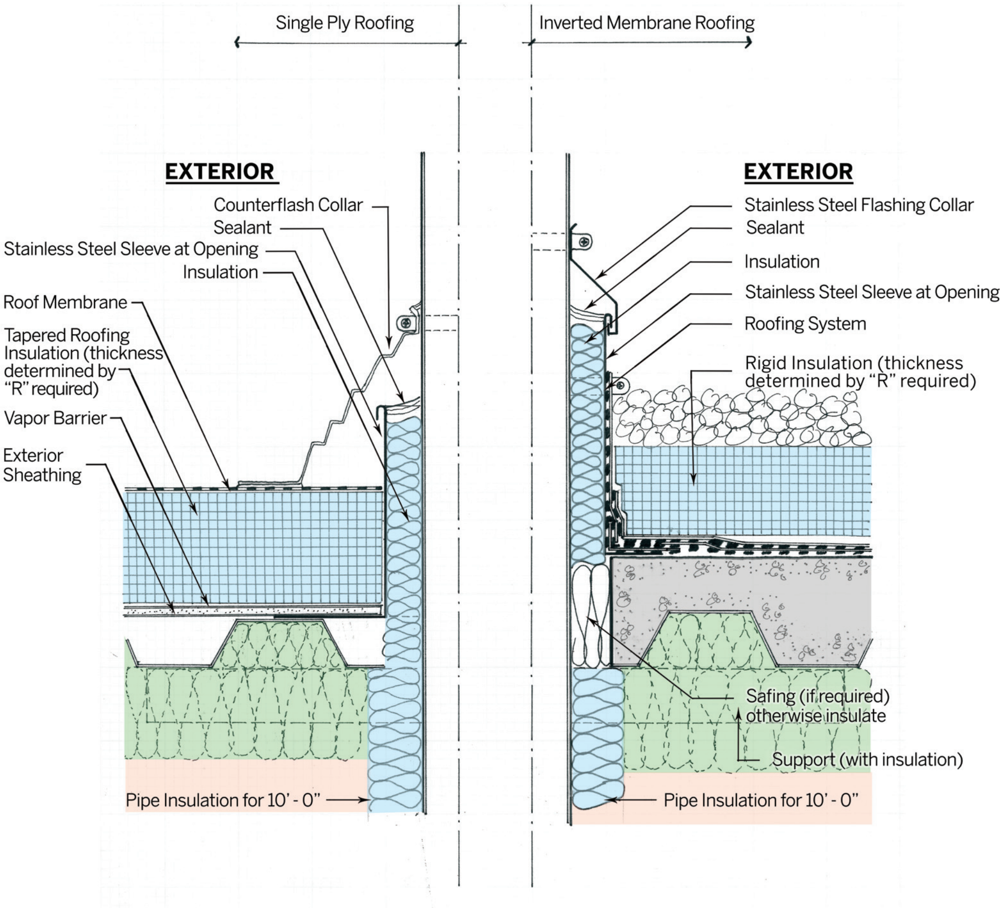

Figure 5-15 (EN31) Plumbing Vent Insulation

Figure Created by Keith Boswell, FAIA

- Select thermally broken curb mounts.
- Consider whether supplemental insulation can be added to the outside of the curb in conjunction with the roofing system and whether such an application affects the manufacturer's warranty.
- Consider the quality of the hatch cover weather stripping (air seal).

Mechanical curbs should follow the principles outlined above to optimize the design, installation, and performance of each condition. Recognize that both conventional detailing and appropriate product availability are impediments to high-performance detailing or curbs. Strive for airtightness and specify the highest level of insulation available for curbs. Also consider field-applied supplemental insulation on the outside of the curb.

Skylights are sometimes mounted on premanufactured curbs, which generally offer limited insulation levels, few insulation material choices, and few thermally broken options. If skylights are included in the design, consider the following strategies:

- Insulate the curb wall to at least the level required of opaque wall assemblies. Better, insulate to the level of the roof assembly.
- Apply additional insulation outboard of the curb, if possible, without creating condensation problems or voiding product warranties.
- Specify or detail thermally broken curbs, anchoring, and attachments.

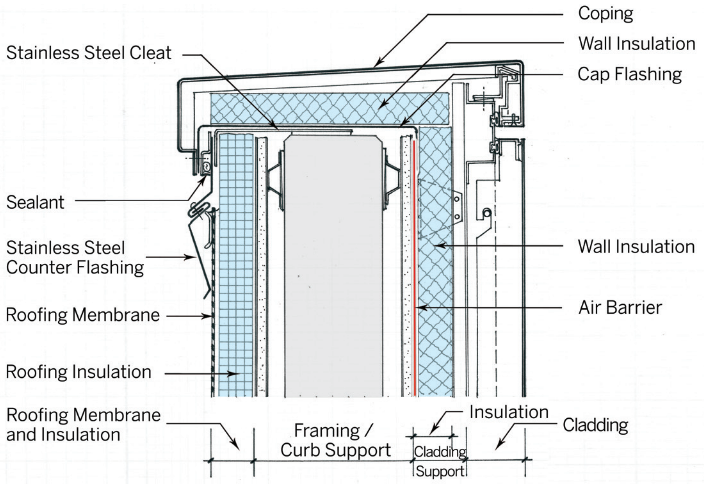

Figure 5-16 (EN33) Parapet Insulation
Figure Created by Keith Boswell, FAIA

EN33 Roof Parapets

Roof parapets require continuous air barriers and continuous insulation. Install insulation continuously on the outer face of the wall to the top of the parapet, horizontally beneath the parapet coping, and vertically on the back side of the parapet connecting to the roof insulation, as illustrated in Figure 5-16. In practical terms, this can involve multiple insulation types to meet the individual requirements for the various assemblies.

Roof edges, gravel stops, and similar conditions require continuous insulation from the roof to the wall below (as well as air, water, and vapor control). Wood nailers and/or metal cleats can be continuous or intermittent components to facilitate connection of fasteners for copings or flashings. Depending on the system detail and coping attachment strategy, insulation may continue behind nailers and cleats with minimal disruption to insulation continuity or outboard of nailers and cleats with nonconductive shims or standoffs. The objective is to attach the coping and flashing securely and insulate as continuously as possible.

Through-wall scuppers penetrate the envelope twice: once on the front and once on the back of the parapet. To maintain continuity, insulation and the air barrier should wrap the entirety of the opening and provide a continuous connection to the insulation on both faces of the parapet, as illustrated in Figure 5-17.

EN34 Walls

Wall interfaces at floor edges should allow the continuous exterior insulation of the wall to be continuous through the entire transition. Masonry walls typically require shelf angles at floor edges to support the masonry and are an especially problematic source of thermal energy transfer through the building envelope. Conventionally, shelf angles are attached directly to the building structural frame or floor edge. Shelf angles must be detailed and installed to minimize the interruption in the thermal barrier. In practice, shelf angles in high-performing envelopes are held off the building structure by clips or proprietary structural components that allow insulation to pass between the shelf angle and the building structure, as illustrated in Figure 5-18.

Clips or components carrying the shelf angle can be substantial in thickness and, because they penetrate the thermal barrier, they too should be selected to minimize the thermal bridging. Select such components to minimize conductivity through the envelope. Stainless steel can be an effective choice because carbon steel is approximately two and a half times as conductive as stainless steel. Carefully research and address material compatibilities as envelope cladding systems are developed.

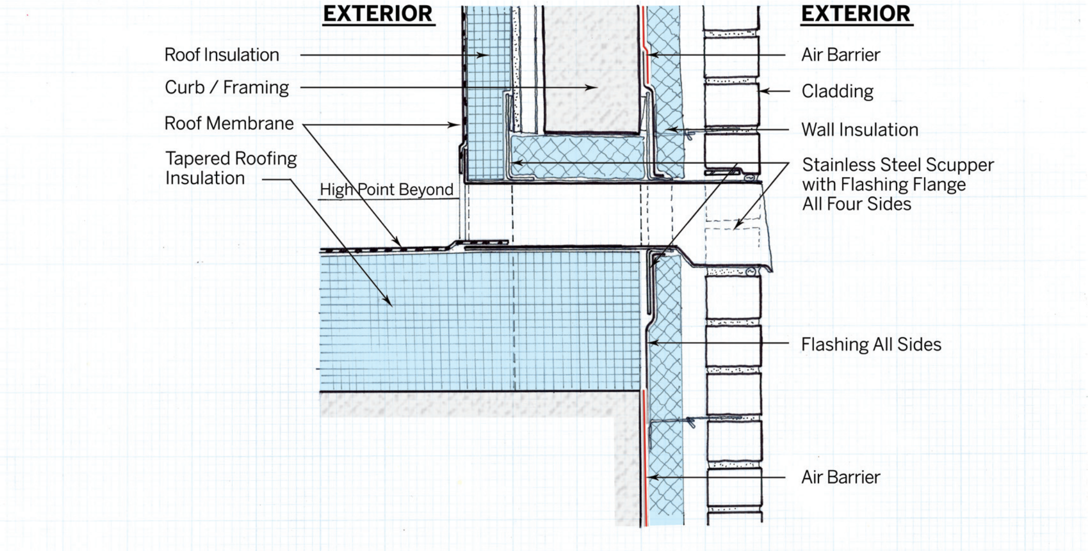

Figure 5-17 (EN33) Through-Wall Scupper Insulation

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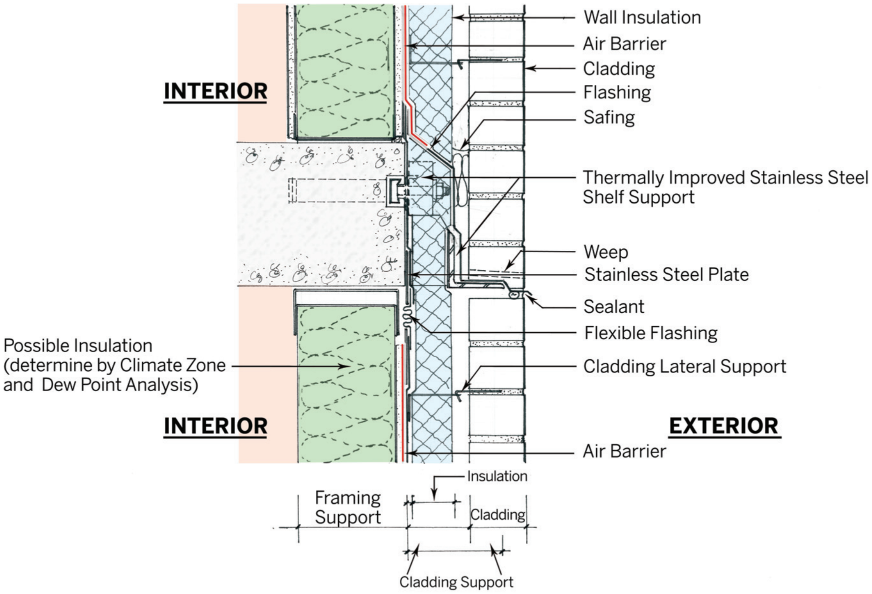


Figure 5-18 (EN34) Shelf Angle Installation at Floor Edge

Figure Created by Keith Boswell, FAIA

To support the building cladding, attachments need to be connected to exterior wall framing. These attachment points can be sources of thermal bridging because they penetrate the exterior wall insulation. Attachment systems should be evaluated based on their ability to meet the load requirements without compromising the thermal integrity of the envelope. Note that thermal bridging from cladding attachments should be incorporated into the overall clear-field U-factor for the assembly, just as the thermal bridging from the studs are accounted for in the assembly U-factor. See Figures 5-19, 5-20, and 5-21 for examples of cladding and masonry attachment details.

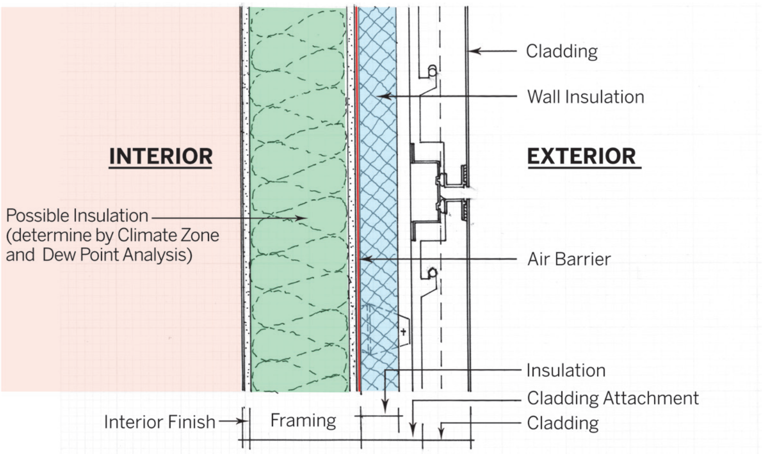


Figure 5-19 (EN34) Wall Cladding Attachment

Figure Created by Keith Boswell, FAIA

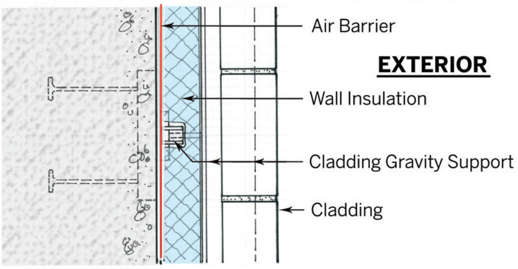


Figure 5-20 (EN34) Wall Masonry Attachment—Cladding Gravity Support

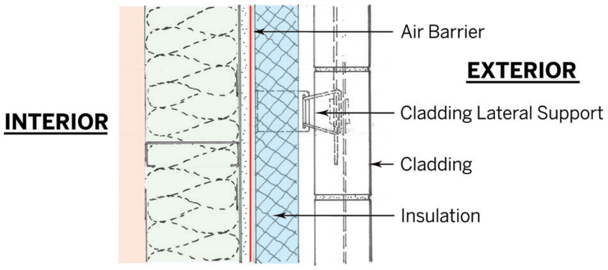


Figure 5-21 (EN34) Wall Masonry Attachment—Cladding Lateral Support

Figure Created by Keith Boswell, FAIA

For exterior wall cladding attachments, consider the following:

- Avoid the use of continuous girts that penetrate the exterior insulation, causing thermal bridges and thereby increasing the U-factor of the wall assembly.
- Use nonconductive clips at penetrations. Where nonconductive clips are not an option, use the least conductive option available (such as stainless steel or thermally isolated galvanized clips in lieu of carbon steel or aluminum).
- Design attachment systems to minimize the number of attachment points and thermal bridges.
- Ensure that all cladding attachment systems are structurally sound.

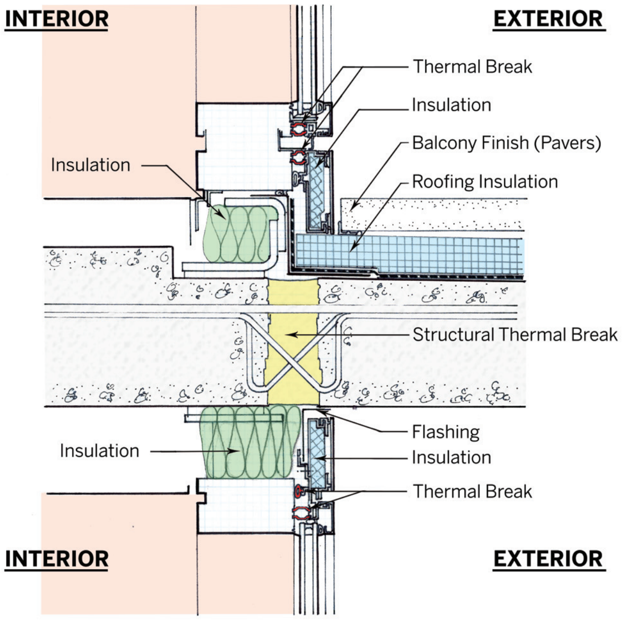


Figure 5-22 (EN34) Wall-to-Balcony Transition
Figure Created by Keith Boswell, FAIA

Wall-to-balcony transitions represent serious thermal bridges. Conventional engineering practice has relied on a cantilevered extension of the primary structural floor to support the balcony. This creates a significant thermal bridge along the entire length of the balcony. Envelopes in buildings in cold climates should include an effective thermal break between the balcony and the building wall in the plane of the wall insulation. While such a break can be engineered on a project-by-project basis, proprietary thermally broken structural components are available to serve this specific purpose (see Figure 5-22).

Exterior walls above roofs require continuity of the continuous roof insulation and the exterior rigid insulation of the exterior wall above (see Figure 5-23). Where the higher wall is a masonry cavity wall, conventional practice allows the cavity wall veneer to bear on the roof structure. In this condition, the cavity wall veneer is likely to introduce a thermal discontinuity between the wall insulation and the roof insulation. To maintain a continuous insulating barrier, the higher cavity wall veneer should be carried on a stand-off shelf angle that allows the wall insulation to meet the roof insulation without a thermal bridge.

EN35 Wall Openings

Window transitions in walls should align the insulated glazing unit, the window frame's thermal break, and the continuous exterior insulation (see Figure 5-24) to minimize thermal pathways around the frame. Further, the exterior insulation should extend to the window frame at the head, sill, and jamb. This requires special coordination with the structural engineer and window manufacturer for the connection of the window in the window opening.

Door transitions in walls require details similar to those outlined above for windows. In the same way, insulated exterior doors or thermally broken framed doors with glass need to fall entirely within the exterior building insulation plane, as illustrated in Figure 5-25. At door sills, the foundation insulation should extend all the way to the sill and the exterior walking surface must be held back to accommodate the insulation. (*Note:* the insulation is covered by the threshold.)

Louver penetrations in walls require careful coordination between architectural and HVAC detailing. Ensure that the duct or plenum is insulated and that this insulation is tied into the

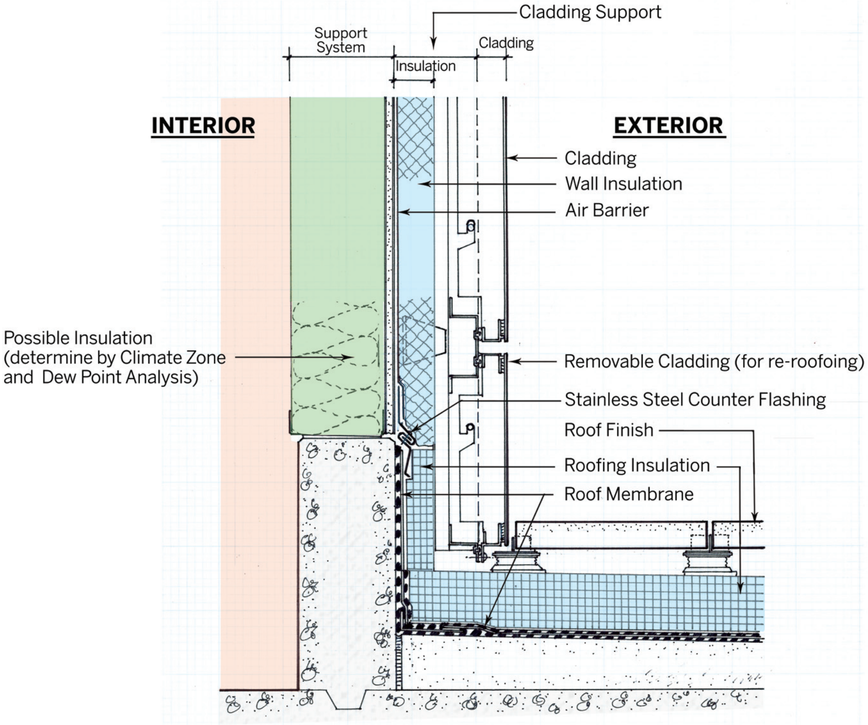


Figure 5-23 (EN34) Exterior Wall Above Roof

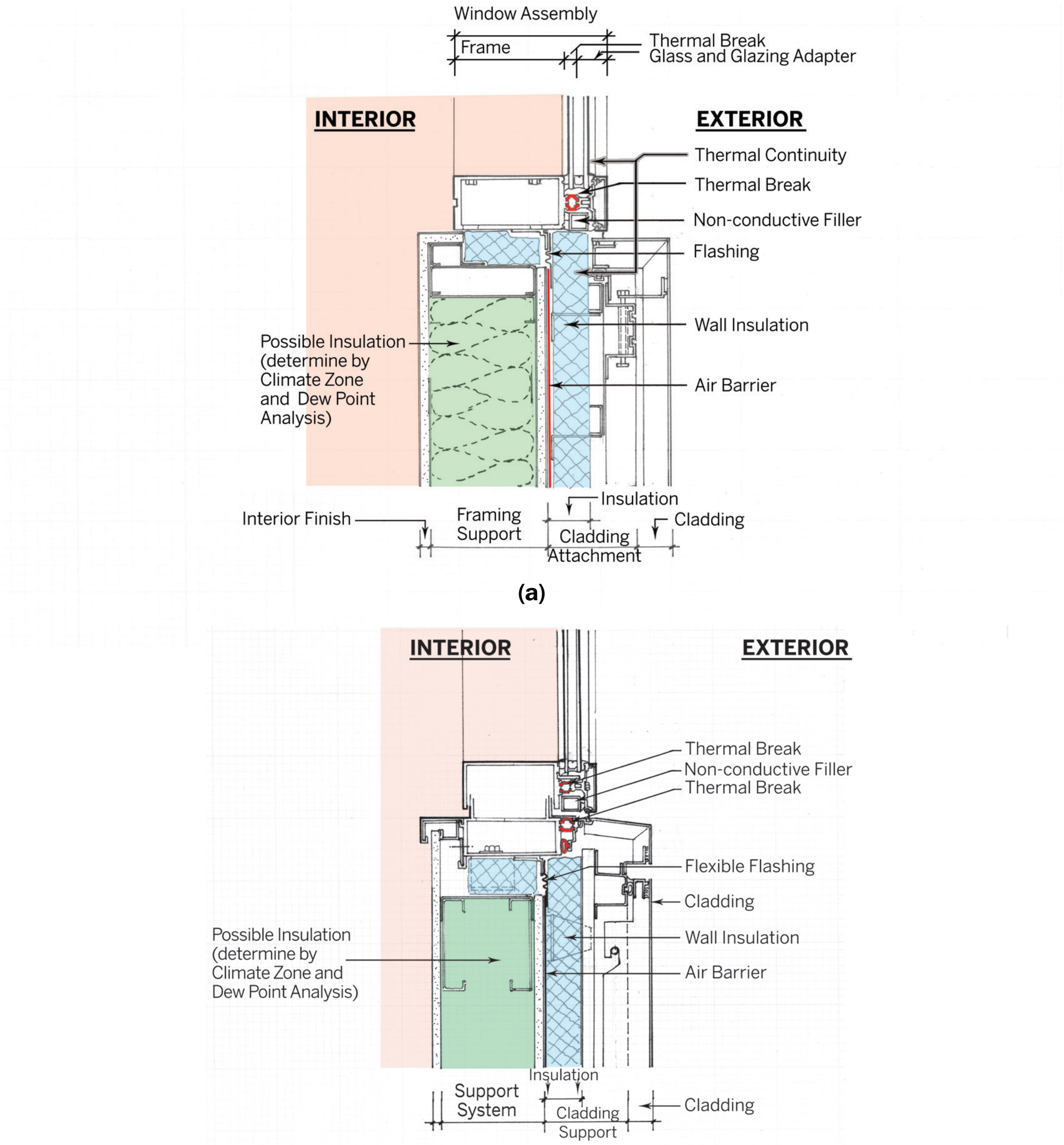
Figure Created by Keith Boswell, FAIA

insulation in the exterior wall. Additional insulation and detailing around the window frame are required.

EN36 Canopies and Sunshades

Canopies, like balconies, represent significant compromises to the building envelope when assembled in conventional fashion. Practitioners must carefully consider alternatives based on the specific circumstances of each project. See Figure 5-26 for a canopy support example. To maximize building energy savings, consider the following:

- Evaluate whether canopies can be supported by other than structural penetrations of the building envelope. Cantilevered canopies require significant amounts of highly conductive steel to penetrate the envelope and should be avoided. Ground-supported canopies, however, can eliminate the need for complex insulating and sealing strategies.
- Where cantilevered canopies are unavoidable, thermally broken structural connections should be used. For smaller canopies, high-strength bolts can sometimes provide sufficient capacity to accommodate continuous insulation between the interior and exterior structural members. Where the structural loads are more extensive, nonconductive plates should be placed between the interior and exterior structural members and located in the plane of the wall insulation.
- Where non-thermally-broken structural connections are used, building insulation should be wrapped around the entirety of the projecting canopy. This is most effective for smaller projections. When using this approach, all penetrations in the canopy need to be sealed and all recessed light fixtures should be fully enclosed and air sealed.
- As a last resort, where none of the strategies above are implemented, insulate the penetrating/cantilevering structural member inboard and outboard of the wall envelope. Insulation should be extended a minimum of 6 ft on interior members (and connecting interior mem-



(a)

(b)

Figure 5-24 (EN35) **Window System to Opaque Wall Connection: a) Plan @ Jamb and b) Section @ Sill**
Figures Created by Keith Boswell, FAIA

bers). Insulation should be extended a minimum of 6 ft or the full length of the member (whichever is less) on exterior members. Sprayed polyurethane foam is the most practical insulation for such an application, though other more labor-intensive materials may also be used.

Vertical and horizontal shade supports and other similar structural penetrations may be common in zero energy offices to accommodate exterior shading structures. Evaluate all such penetrations to determine the best strategy to balance the requirements of each penetration. First, evaluate alternative support strategies that would eliminate the need to extend a conductive structural member through the envelope. Where penetrations are unavoidable, use the least

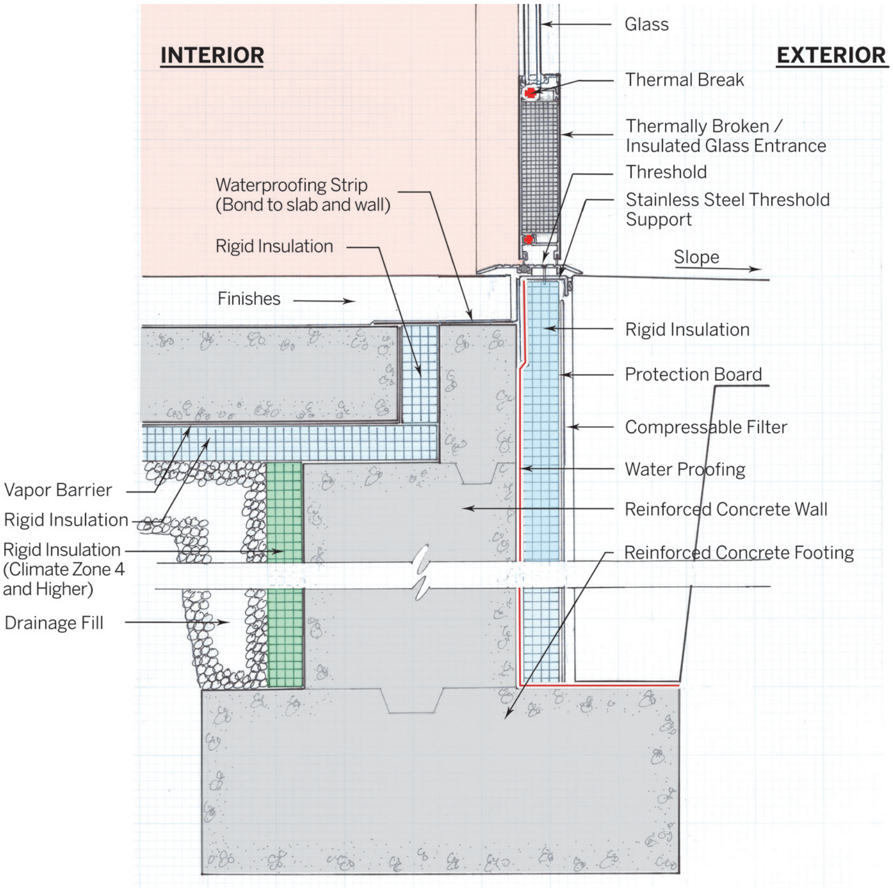


Figure 5-25 (EN35) Exterior Door Insulation Installation
Figure Created by Keith Boswell, FAIA

amount of penetrating material that meets structural requirements and use thermally broken structural connections. For smaller loads, high-strength bolts can sometimes provide sufficient capacity to accommodate continuous insulation between the interior and exterior structural members. Where the structural loads are more extensive, place nonconductive plates between the interior and exterior structural members and locate them in the plane of the wall insulation (see Figures 5-27 and 5-28).

EN37 Foundations and Floors

Foundation and slab-edge transitions require continuity of exterior wall insulation and insulation of the slab edge/foundation (see Figures 5-29 and 5-30). Also refer to EN8 for the insulation of slab-on-grade floors, EN3 and EN4 for the insulation of above-grade mass and framed walls, and EN5 for insulation of below-grade walls.

Transitioning of masonry cavity walls requires special consideration and careful detailing. Cavity insulation should be carried in the same plane above and below grade and extended to the footings. The masonry can be extended below grade to the same depth or, alternatively, an at-grade shelf angle may be used to minimize the extent of below-grade masonry.

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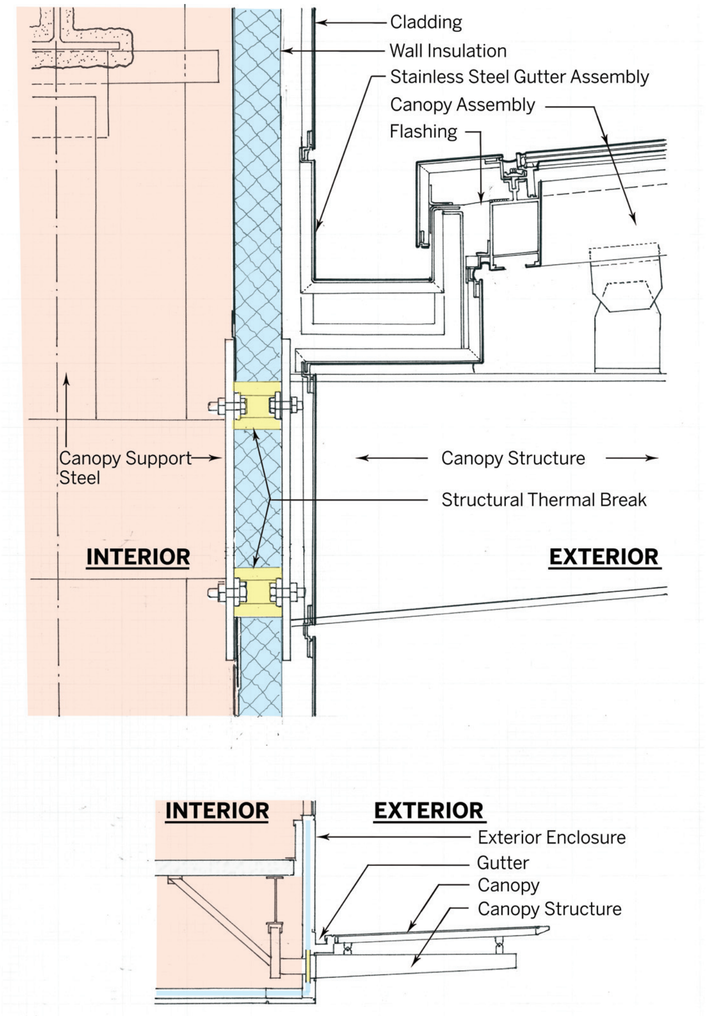

Figure 5-26 (EN36) **Canopy Support**

Figure Created by Keith Boswell, FAIA

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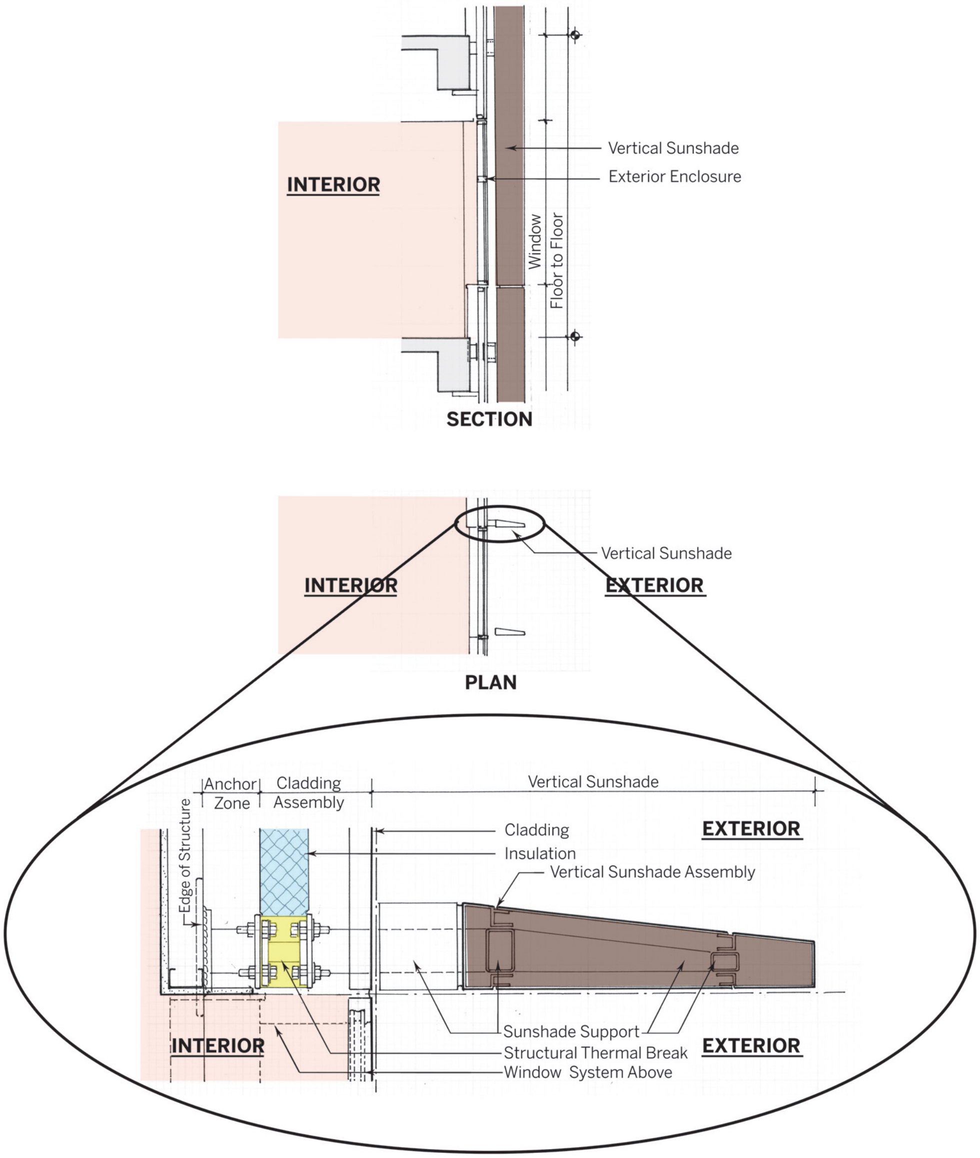

Figure 5-27 (EN36) **Vertical Sunshade Support**

Figures Created by Keith Boswell, FAIA

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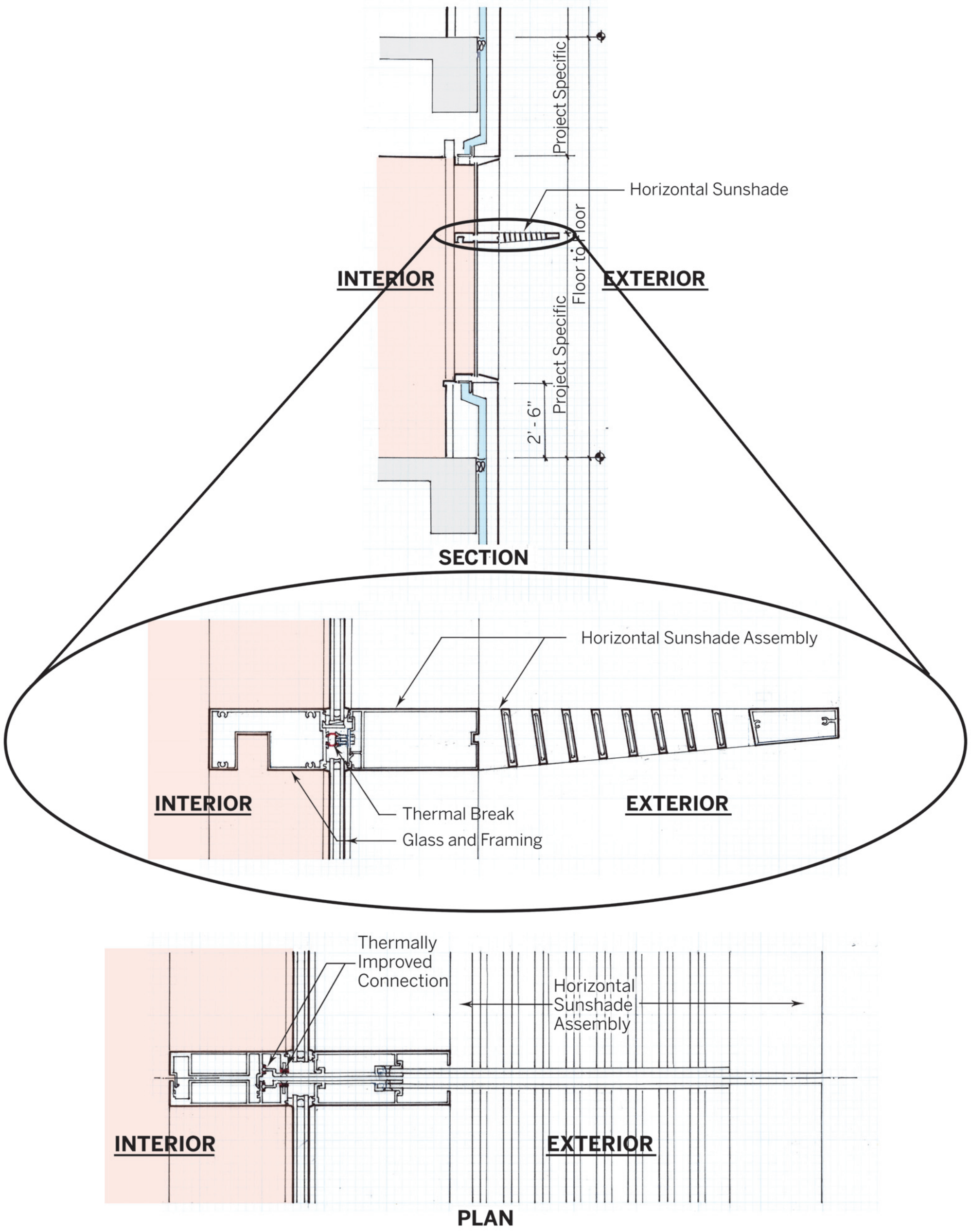

Figure 5-28 (EN36) Horizontal Sunshade Support

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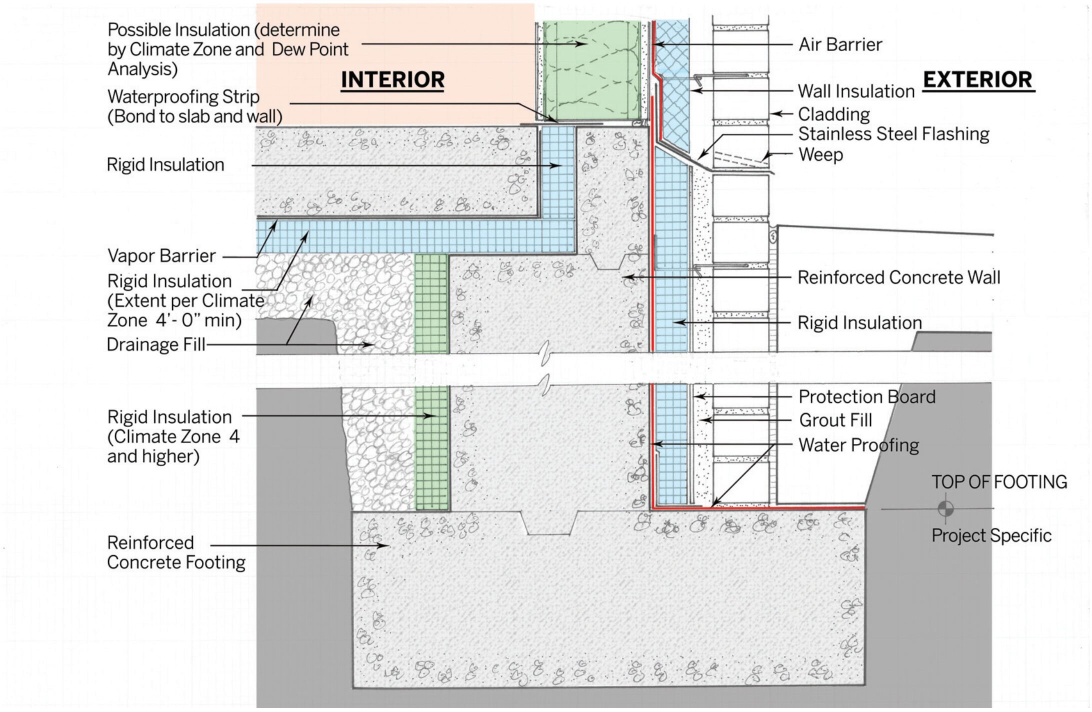

Figure 5-29 (EN37) **Wall Transition with Insulation Continuous to Foundation**

Figure Created by Keith Boswell, FAIA

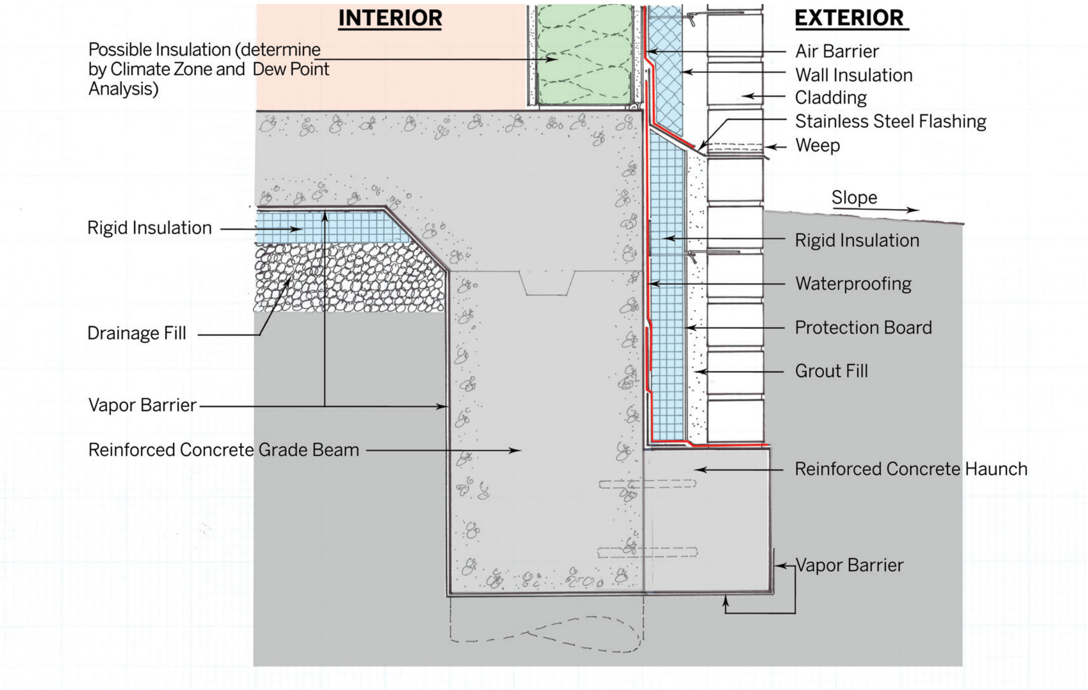

Figure 5-30 (EN37) **Wall Transition with Insulation**

Figure Created by Keith Boswell, FAIA

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DAYLIGHTING

OVERVIEW

Daylighting is an occupant well-being, building resiliency, and energy-efficiency design measure. In the context of occupant well-being, daylighting provides people with a connection to the outdoors through high-quality views, intensity variation over space and time, and access to a full range of visible wavelengths. In the context of building resiliency, daylighting offers a layer to the lighting system that can be used to support demand-response load reductions and wayfinding during prolonged grid outages.

In the context of zero energy office building energy efficiency, daylighting can lower the electric lighting EUI by about 25% by reducing lighting power in response to useful daylight. For example, the model developed for this Guide, which is grounded in real high-performance lighting load profiles, results in an electric lighting EUI of 1.2 kBtu/ft^2/yr for a mid-latitude location. Without daylighting, the lighting EUI result would be 1.6 kBtu/ft^2/yr. Compared to the whole-building EUI target of approximately 20 kBtu/ft^2/yr for the same location, daylighting reveals itself as a nontrivial but lower priority of the energy measure portfolio. This relative lessening of the impact of daylighting as an energy-efficiency measure is due to a recent increase in lighting system efficacy and higher-resolution occupancy control. Additionally, WWR and solar heat gain (for hot climates) top the list of important zero energy design considerations, after plug loads and infiltration. Overglazing is not a cost-effective option for zero energy design. That said, glazing should and will be used on buildings for a variety of reasons, and electric lighting use should decrease with the available resource as one of the many steps needed to reach zero energy.

To achieve a successful zero energy design, it is ever more important to consider daylighting as a measure which should be thoughtfully applied with equal consideration of energy use, environmental quality, and resiliency.

DESIGN STRATEGIES

DL1 Daylighting Design Methodology

The following tenets describe a daylighting design driven by multiple performance goals, zero energy being one. The methodology informs the specific recommendations given in the subsequent how-to strategies.

- Each window provides a function, if not multiple, including providing high-quality views and providing daylighting to replace or supplement electric lighting use during daytime hours.
- Occupants are provided with access to ambient daylight and views through the use of a shallow floor plate and clear lines of sight. For example, all occupants are located within 30 ft of a perimeter window, and low partition heights at workstations and view-preserving partition glass between office spaces are typical.

Nonvisual Benefits of Daylighting

Daylighting is most often considered a design strategy in relation to humans' image-forming visual system. It is considered an option to offset electric lighting with the intent of providing occupants with sufficient light to perform a task. It is also considered a lighting strategy to add surface luminance balance or visual interest/relief through views, in part contributing to occupants' overall visual comfort and performance in the space. Distinctly nonvisual effects of a lighting system are its ability to support circadian rhythm entrainment, prevent circadian disruption, and enhance alertness. These potential effects are not uniquely tied to daylighting but should be considered in the design, since for a zero energy building daylighting can serve as an efficacious light source for accomplishing nonvisual goals due to its typical spectral composition, time of availability, and spatial distribution.

Circadian stimulus is one metric currently used to describe the relative effectiveness of a lighting scene in suppressing melatonin. Nocturnal melatonin suppression is not the only measure of light's effect on the human circadian system, but empirical data are available for engineers and scientists to evolve the understanding of the nonvisual impacts of light exposure (Rea and Figueiro 2018). As understanding of the impact of light exposure to health and well-being grows, the performance metrics might change but will likely be grounded in the same considerations of spectral content, time of exposure, and quantity at the retina (versus at the workplane, which is typical for lighting design for visual task performance).

Lack of consensus exists as to whether a designer should accept the responsibility of designing for nonvisual effects without the physiology background, the degree to which other environmental factors interact with or outweigh lighting's influence on occupant well-being, and the appropriate design metrics. Regardless, circadian lighting metrics are being developed for use in building design and performance verification. One such metric, equivalent melanopic lux (EML), can be related to photopic measurements/calculations. Vertical illuminance measurements or calculations at eye level can be converted to EML and evaluated for quantity and duration to show intent to consider physiological effects of the lighting design (IWBI™ 2019).

Steps a daylighting designer can take to address circadian lighting opportunities and risks include the following:

- Lead the team in a conversation about what is and is not known about nonvisual effects of lighting to establish the exploratory nature of current circadian lighting design efforts.
- Take early and simple design steps to increase vertical daylight illuminance at the eye without presenting glare by locating daylighting media at useful places for vertical surface illumination and view (versus adding overhead daylighting that can create harsh shadows and limit vertical irradiance). One study on hospital lighting shows the ability for a simple sidelighting scene in a typical patient room with a window to provide sufficient circadian stimulus according to a preselected threshold, at the vertical plane, for a majority of the room, using a 40% WWR (Acosta et al. 2017).
- If a more robust design process is appropriate, calculate the vertical irradiance (sensor as proxy for irradiance at the eye in a typical working view direction) from a base daylighting design and use the information to subsequently calculate a prevailing circadian lighting metric such as circadian stimulus. Evaluate daylighting design alternatives that can meet proposed thresholds for the metric and weigh the energy and cost implications of meeting the threshold through electric lighting and daylighting. It is likely that daylighting has an inherent and energy-efficiency role to play if lighting designs tend toward a response to nonvisual lighting effects.

- Façade, interior, and electric lighting design decisions are made with an integrated system design approach. For example, workstations are retracted from windows and corridors are placed at the perimeters of open office areas so that the walkway and exterior shading elements work together to provide a buffer for occupant glare and heat control.
- The design is glare free on an annual basis since glare can negate all positive energy and occupant well-being effects. Glare from the sky and sun, as well as reflections off of building equipment, are considered. Start the design process by considering the use of passive

shading and filtering strategies in each space type, then consider automatic devices in critical working areas for which static devices cannot mitigate glare year round for a given interior layout or for climates where static devices block valuable daylight resources for much of the year.

- Surface luminance balance is considered for a range of daylighting and electric lighting with daylight scenarios. Vertical surface lighting can enhance vertical illuminance at the eye and the perception of spaciousness; however, adjacent surface luminance ratios should be kept to a maximum of 20:1 relative to the daylight glazing to maintain visual comfort.
- Electric lighting near glazing dims during daylight hours. A more considered control strategy that includes daylight dimming of predefined electric lighting zones is incorporated in design, but a basic check for lights off near all glazing such as entry doors, corridors, and stairways is an ingrained part of the setup and Cx process.
- Electric lighting supports daylight distribution through workstation task lights or surface lighting that is controlled, manual-ON by occupants when needed, allowing flexibility for various occupant preferences and tasks, not requiring the system to automatically turn on to meet an illuminance criterion at the darkest location in the space, which is often not necessary throughout a day or year. (See the “Lighting Controls” section for a more general controls methodology.)

Figure 5-31 identifies two office buildings that exemplify many of the daylighting design tenets for zero energy. The photograph of NREL’s Research Support Facility in Golden, Colorado, shows a static solution of exterior hoods and optical louvers that redirects sunlight onto the ceiling, which is appropriate for predominantly clear skies and an elongated building on an east-west axis. The photograph of the Bullitt Center in Seattle, Washington, shows a dynamic solution of automated louvers and tall spans of high-transmittance glazing, which is appropri-

(a) (b)

Figure 5-31 (DL1) Examples of Zero Energy Daylighting Design: (a) NREL Research Support Facility and (b) Bullitt Center

Left: Photograph by Pat Corkery, NREL 17410; Right: Photograph Used with Permission, © Nic Lehoux ate for predominately overcast skies and a square building oriented off-axis in plan. These examples show just two of the many possible workable configurations and offer two solutions known to contribute to the success of operating zero energy buildings.

The daylighting design approach might also differ for a speculative versus a build-to-suit office building. For speculative office space, the daylighting design need not provide the full task illuminance in all spaces. Daylight is used as a general layer of light for occupants to achieve a base task such as wayfinding and conversing with colleagues for as many spaces as possible. Focus on balancing surface luminance and allowing access to high-quality views. As tenants move interior partitions over time or use spaces for various visual tasks, the base daylight layer may need to be supplemented with electric light.

For a built-to-suit office, focus on full daylighting for areas with high illuminance/LPD requirements or high occupant use/density areas. The occupants of these areas can benefit from a continuous, higher saturation of daylight. The potentially higher WWR for one or two façades can be balanced with a lower WWR on other façades or other energy-efficiency measures.

DL2 Project Phase Tasks

Successful use of daylighting requires attention to the building design at every scale, from building footprint to occupant task orientation, as well as attention to integrated design decisions during each phase of the acquisition process. One or more team members must champion the expected daylighting outcomes by generating design ideas and validating expected outcomes throughout the process.

Predesign. During predesign, focus on building configuration studies and the shaping of the floor plate. The goal is to minimize floor-plate depth and maximize access to daylight and views by strategically placing light wells, shafts, and atriums and orienting fenestration in a predominantly north- and south-facing direction. Maximize the amount of occupied space that has access to windows and minimize the distance from the building core to the perimeter.

The building footprint is the key factor for anticipating future design upgrades and improvements. A frequent challenge with existing buildings is their depth of floor plate, which prevents easy retrofits for daylighting, views, and natural ventilation.

Schematic design. During the schematic design phase, focus on spatial considerations such as ceiling height and articulation for clerestories, as well as on space layouts including occupants' primary working orientation. Place space types that benefit from daylight and views, such as open and private offices and conference rooms, near the perimeter. Develop a shading strategy to address heat gain and glare potential, considering a cut-off angle that will shade sun from equinox to equinox or by using a shading period that started at the transition from heating degree-day to cooling degree-day dominance for a given location. Try to achieve the selected cut-off angle with static building elements such as overhangs, fins, louvers, grates, and building self-shading.

Design development. During the design development phase, focus on envelope design to optimize quantity and quality of daylight while minimizing solar gains. Attempt first to achieve full glare control (no direct sun in occupants' working area during prime work hours) with static building elements and interior programming as initiated during schematic design, then consider automatic shading and glare-control devices such as exterior louvers, interior louvers, or shades to address challenging façade orientations or low winter sun. A comprehensive glare evaluation should take place at this stage. The late addition of manual shades or blinds is likely to mitigate the daylighting benefits that can be achieved with early and intentional design. Additionally, ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2016) and the *International Energy Conservation Code* (ICC 2017) require that daylight zones be identified on floor plans as part of the submitted documentation. This requirement is an opportunity to merge the conversation about daylighting and lighting controls early in the design process. The interior design focus is on surface reflectivity and optimizing furniture and partition layout to align with visual and thermal comfort requirements.

Construction documents. Coordinate electric lighting and controls, including the placement of manual-ON switches for occupant zones, and verify the placement of photosensors for automatically turning off or dimming lights in response to daylight. Verify glazing details such as visible light transmittance (VLT) for each façade and window type.

Construction administration (CA). Walk through the building from the perspective of an occupant and identify any glare conditions or otherwise uncomfortable lighting scenes to address the issue before occupants cover windows or otherwise override the design. Look for small opportunities to turn lights off in response to daylight, such as in vestibules or corridors with borrowed daylight from an adjacent office space.

DL3 Building Footprint and Façade Orientation

For the simplest daylighting design, the building should be elongated in the east-west direction, oriented within 15° of north and south directions. This allows for static shading solutions of reasonable size and daylight redirection devices that are most efficient during typical daytime working hours.

In new buildings with site constraints or in retrofits, east and west or off-axis façade orientations can work well with more sophisticated shading solutions to block glare and heat gain from low-angle sun. If care is taken to develop a glare-free east-west daylighting solution, then a benefit can be that electric lighting savings are realized during times of lower output from PVs, aiding in a grid-friendly building design.

Metrics to guide footprint form, which set the stage for successful daylighting and views, include the following:

- Locate the maximum amount of occupied space within minimum distance to the building perimeter, using 30 ft from occupant to perimeter as a guide.
- Locate 75% of the occupied space within 20 ft of the perimeter wall.
- Achieve a 60 ft floor-plate depth where possible.

DL4 Space Programming

In concert with the building orientation, identify the spaces that benefit most from daylighting (high occupant density and high LPD) and locate those spaces on the perimeter of the building. For typical offices, the first priority is to locate open office areas on the perimeter, preferably at the south perimeter, to take advantage of redirected south sun. Locate private office spaces on the east- and west-facing perimeters or on the interior at the boundary of the secondary daylight zone. For private offices not on the window wall, place glazing along the private office wall that is parallel to the perimeter wall, which allows views toward windows. Locate intermittently used, large conference rooms on the north or east façade corners to prevent the overlap of high occupant heat gain with high solar heat gain during afternoon peak load. An east or west façade location for conference rooms also frees up south and north façades for open office placement. Locate small huddle rooms, often the most used spaces in open office environments for group viewing of audio/visual materials for short periods of time, on north or west façades or at the core of the building. Figure 5-32 shows a southwest corner of a floor plate designed with daylighting and views in mind.

DL5 Fenestration Function

Daylighting apertures should be located as high in the space as possible to increase the ability to provide even, ambient illumination across the space. Daylighting apertures start at 7 ft or higher and extend to a minimum of 10 ft and maintain a high VT of 60% or higher. Figure 5-33 shows daylight windows on the right side of the image and north clerestory windows on the left. View windows should be located at eye level, although a sight line to daylighting apertures might be a necessary or desirable way to provide a view. View windows should have a VT of 30% to 60% depending on the brightness of the scene being viewed (e.g., dense vege-

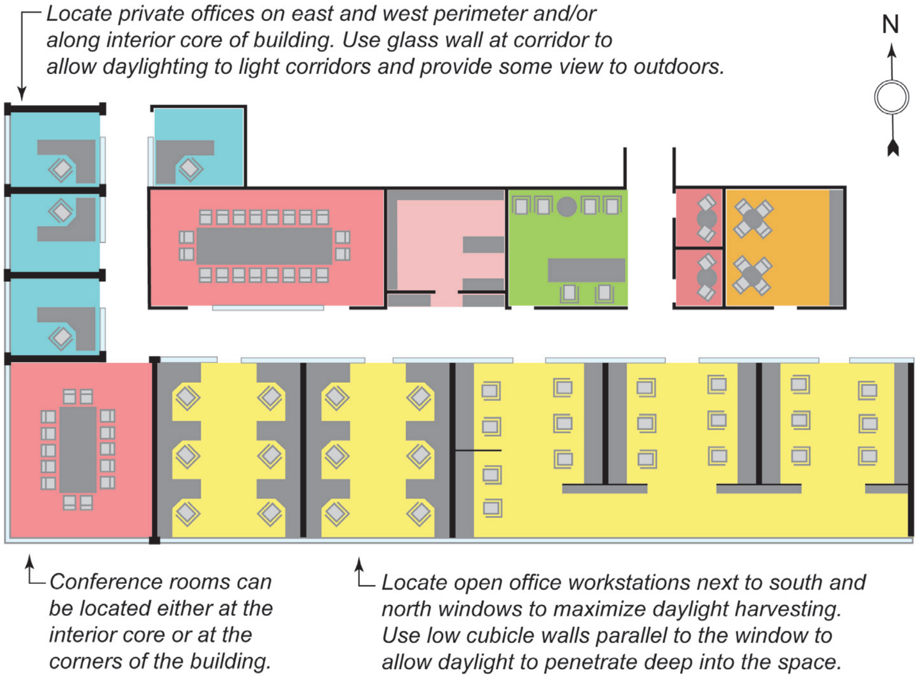

Figure 5-32 (DL4) Typical Southwest Corner Floor Plate for Daylighting and Views

Figure 5-33 (DL5) Example of Clerestory (left of image) and Daylight Windows (right of image)
Photograph by Dennis Schroder, NREL 19452

tation versus light concrete buildings). Openings for natural ventilation need to be located both low and high in the space. For these reasons, fenestration should be designed to separately serve specific functions instead of having large spans of windows used solely for transparency or continuity.

The total WWR including both daylight and view windows should not exceed 40% for a zero energy office building. A WWR of 25% to 35% will enable sufficient daylighting and views in most office buildings while preventing excess heat transfer. Small increases in WWR have a relatively large impact on whole-building EUI relative to other design parameters. For

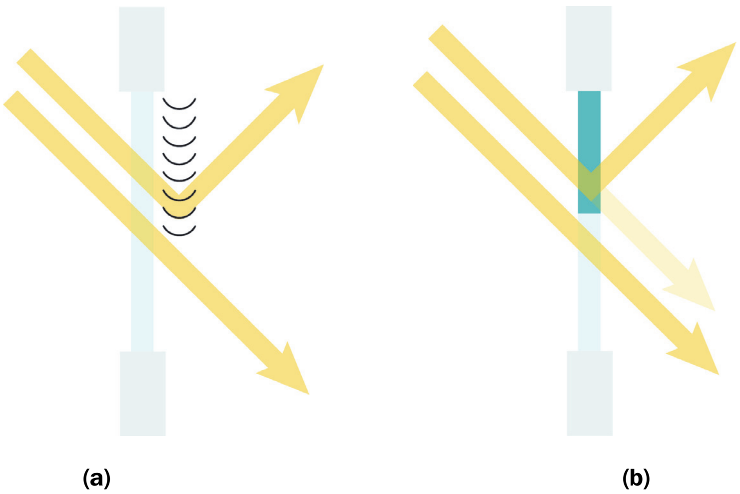

Figure 5-34 (DL6) (a) Optical Louvers and (b) Microstructure Applied Film

this reason, setting a WWR and working within that limit to achieve the maximum daylighting and views possible is an appropriate zero energy design approach.

DL6 Daylight Redirection

Diffuse daylight from an overcast sky or clear sky through a window starting at 7 ft AFF can be assumed to provide sufficient occupant illuminance for a depth of about one times the head height of the window to the space. Partial occupant illumination can be provided to a depth of about two times the window head height into the space. (This perpendicular measure from the wall is part of a daylighting zone calculation, commonly referred to in energy codes and standards.) To provide ambient daylight to a greater zone depth, such as the recommended 60 ft floor-plate depth, daylight redirection devices are needed. These devices use direct sunlight and redirect it upward to create a luminous ceiling. This strategy is most effective on south façades in sunny climates; however, all locations and east and west orientations can benefit from sunlight redirection.

Optical louvers, shown in Figure 5-34, which are specifically designed shapes for redirecting sunlight of a given input angle, can be highly effective for maximizing the depth of penetration of sunlight onto the ceiling and for preventing direct sunlight from being transmitted or redirected down to an occupant's visual field. If daylight windows are placed high on the wall and well out of the occupant visual field, as with clerestories or monitors, then treatments such as frit, etching, or translucent glass can be used to diffuse incoming sunlight. These treatments prevent glare from direct sun and redirect daylight to room surfaces, but they do not create daylighting zones of the size that is possible with redirection devices. Also, when placed too low in a space, glass treatments can, in some cases, increase glare potential relative to view-preserving glass.

For retrofits with curtain walls, consider applying a redirecting film or micro louvers to the portion above 7 ft and mount shades at 7 ft for the view portion of the window.

DL7 Shading and Glare Control

Uncontrolled solar heat gain is a major cause of energy use for cooling, particularly in warmer climates, and of thermal discomfort for occupants. Appropriate configuration of windows according to the orientation of the wall on which they are placed can significantly reduce these problems while simultaneously reducing or eliminating direct beam radiation that often contributes to unwanted heat gain and glare.

Unwanted solar heat gain is most effectively controlled on the outside of the building. Significantly greater energy savings are realized when sun penetration is blocked before it enters the windows. Horizontal overhangs at the tops of the windows are most effective for south-facing façades and must continue beyond the width of the windows to adequately shade them. As discussed in EN19, Table 5-7 shows factors to approximate the impact of various-size overhangs. Vertical fins can be effective for east and west façades and to aid in glare control for early morning and late evening summer hours on the north façade. Additional exterior shading strategies include building self-shading, filtering, baffling through soffits, trellises, awnings, external light shelves, and vegetation. See BP5 for information and Figure 5-4 for sections of some of these strategies. The combined SHGC of the window and shading system should not exceed 0.25 for warm climates and should not exceed 0.45 for any climate. Window SHGC is a sensitive building design parameter for achieving zero energy.

Shading, filtering, and reflecting materials can be integrated into the glazing to reject additional unwanted solar gain, particularly for low solar angles. These include glazing that employ special coatings/constructions with selective transmission, as well as diffusing or opaque elements integral to the glazing, fritted patterns, fiber-fill, aerogel, and interstitial louvers.

Interior blinds and shades are the least effective shading devices for limiting the window-driven cooling load in a space. However, these solutions are often employed as a cost-effective, controllable solution to mitigate glare and thermal discomfort for occupants on façades where static exterior shading is not possible and on façades that experience a wide range of solar angles not easily controlled with static shading devices. When using such solutions, consider the use of top-down shades for view glass or blinds with tilt angle limits for daylight glass to maintain functionality of the windows for providing some daylight distribution and views throughout the entire day.

The success of daylighted offices depends on how occupants interact with the daylighting system, particularly blinds and shades. If blinds are left closed, the daylighting and view potential will not be realized. If adequate glare control is achieved through static or automated shading elements, and if temporary darkening of a specific space is not functionally required, do not install shades or blinds. Unnecessary blind application can result in reduced daylight performance, increased first costs, and higher long-term maintenance expenses. However, blinds should not be excluded from the design if admitted direct sun, the sky dome, or reflections from exterior buildings will cause high contrast or induce glare during working hours. If blinds are necessary, consider including a mechanism to reset the shade position or the clear, view-preserving state at least once daily and, ideally, to the most efficient position when the space is unoccupied. This can be accomplished using a control system that collects and intelligently uses information about the current sun position and sky condition.

Figure 5-35 shows a combination of north-facing windows, hoods on south-facing view windows, sufficiently low visible light transmittance (VLT) to limit glare potential from the sky dome, and building self-shading on the west-facing windows, which enable a solution with no blinds, saving cost and maintaining views.

DL8 Fenestration Details

The specification and design details of daylight and view windows are important for realizing well-daylighted, comfortable interior environments. The window specifications of SHGC, U-factor, VT, and VT/SHGC (also referred to as *light-to-solar-gain ratio*) should be considered for thermal performance as described in EN17 through EN20 and as shown in the window diagrams in Figure 5-36. Additional considerations include the following:

- Place all view glass above 3 ft AFF. Windows below the task plane rarely offer sustained benefit to occupants in terms of view and provide minimal contribution to usable daylight distribution on the task plane or visible surfaces.
- Consider the use of continuous bands of daylight glazing. An unbroken window can improve overall U-factor, enable use of continuous shading and redirection devices, and limit areas of high contrast produced by window and wall junctions. Punched windows, as

Figure 5-35 (DL7) No-Blind Shading Solution
Photograph by Dennis Schroeder, NREL 20048

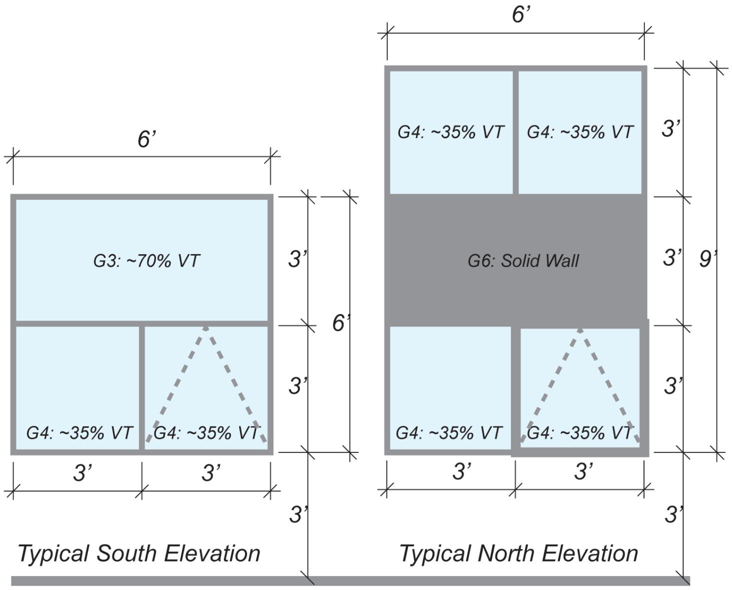

Figure 5-36 (DL8) Example Window Diagrams

shown in Figure 5-36, are appropriate in cases where prefabricated, modular construction is used as a way to cost-effectively achieve zero energy.

- Align windows with office partition walls and the ceiling plane. This can reduce contrast near the apertures by allowing daylight to wash the adjacent ceiling and wall, which will in turn reflect more light onto the perimeter wall, reducing luminance ratios across that surface.
- Consider frame color, window well color, and depth for reducing or enhancing contrast at the window wall.
- Screens for natural ventilation can decrease VT and view clarity. Compensate for the reduced daylighting efficacy through an increase in VT and by examining the screen effect in locations considered important for occupant views.

Table 5-8 (DL9) Minimum Surface Reflectance

Location	Minimum Reflectance
Wall segment above 7 ft	70%
Ceiling	70% (preferably 80% to 90%)
Light well or window well	80% to 90%
Floor	20%
Furniture	50%
Walls segment below 7 ft	50%

DL9 *Interior and Exterior Surface Finishes*

For interior surfaces, select light colors (white is best) with a matte finish for walls and ceilings to increase light reflectance, mitigate glare, and reduce lighting and daylighting requirements. Minimum surface reflectances are shown in Table 5-8. The colors of the ceiling, walls, floor, and furniture have major impacts on the effectiveness of the daylighting strategy.

Consider ceiling tiles or surfaces that have high reflectivity. Make sure that the ceiling tile reflectance includes the fissures within acoustical tiles, as these irregularities affect the amount of light absorbed. Do not assume that the color of a tile alone dictates its reflectance. When selecting a tile, specify a minimum reflectivity. Most manufacturers list the reflectance as if it were the paint color reflectance. The CxP should verify the reflectance. See EL4 for additional information on interior finishes.

Consider the reflectance of the roofs, sidewalks, and other surfaces in front of the glazing areas. The use of lighter colors can increase daylighting at the glazing and, in some cases, reduce the glass area needed for roof monitors or clerestories. Note that a light-colored walkway or roofs in front of view windows may cause unwanted reflections and glare. The color might be a good design choice for the overall heat load of the site, but additional glare control measures at the window or task location might be necessary.

DL10 *Electric Light Integration*

Consider the use of lighting fixtures with an indirect component that more closely represents the same surface lighting effect as daylighting. Indirect lighting spreads light over the ceiling surface, which then reflects the light to task locations; with the ceiling as the light source, indirect lighting is more uniform and can provide better glare control than fixtures with a predominantly direct component.

See the "Lighting Controls" section for recommendations on daylighting control design and Cx. Attention to these tips (LC1–LC10) is critical for realizing the energy-efficiency potential of daylighting.

DL11 *Daylighting Performance Metrics and Analysis Tools*

Energy and daylighting modeling programs make evaluating energy-saving trade-offs faster and daylighting designs far more likely to be successful and accepted by occupants over time due to adequate distribution and control of glare and heat gain. Tools designed specifically for daylight modeling allow an accurate look at performance indicators such as daylight distribution with interior finishes and glare potential as well as a prediction of daylighting control system performance based on realistic photosensor placement and response. Specific metrics used in daylighting design include spatial daylight autonomy (sDA) and annual sun exposure (ASE), which are detailed in the sidebar "Annual Metric Descriptions."

In terms of daylight quantity, daylighted spaces should provide a minimum of 300 lux for at least 50% of the operating hours. This illumination is then supplemented as needed by electric lighting. The sDA for office spaces should be greater than 75% and for other regularly

Table 5-9 (DL11) Recommended Annual Daylighting Design Criteria

Location	Minimum $sDA_{300,50\%}$	Maximum $ASE_{1000,250}$
Open offices	75%	10%
Private offices	75%	10%
Conference rooms	55%	10%
Corridors	55%	25%
Break rooms and restrooms	55%	25%

occupied spaces such as break rooms, conference rooms, and corridors should be greater than 55% (see Table 5-9). Direct sunlight should not exceed 1000 lux (over ambient) for more than 250 hours per year. The ASE should not exceed the values shown in Table 5-9.

SPACE-SPECIFIC STRATEGIES

DL12 Open Offices

In climates with predominantly clear skies, the following set of design decisions provides one possible solution for a sufficiently daylighted work environment with low glare potential:

- A WWR of 30% on the south and north façades with separate windows for daylight and view
- Daylight windows on the south façades starting at 7 ft AFF extending up 3 ft with interior louvers optically designed to redirect sunlight onto the ceiling at a 60 ft depth for all annual solar angles from 10:00 a.m. to 2:00 p.m.
- Untreated daylight or clerestory windows on the north façade
- View windows shaded with exterior hoods that block all direct sun from striking the window from 10:00 a.m. to 2:00 p.m., April through September
- Workstations set back from the south perimeter wall to create a walkway that absorbs the direct winter sun, preventing the need for shades or blinds for glare control, as shown in Figure 5-37
- Low workstation partitions with light, diffuse interior finishes
- Indirect/direct electric fixtures with a manual-ON control scheme and automatic daylight dimming to OFF on all rows of fixtures parallel to the south façade

For climates with predominantly overcast skies, design parameters can shift for a higher WWR allocated toward daylight windows or clerestory windows, which, depending on the site context, can remain untreated if direct sun instances will be limited and welcomed. However, for many climates, instances of direct sun in a working zone will be sufficiently high to warrant automatic shading devices. When well designed and integrated into an ongoing maintenance and fault detection system, automatic shades or blinds can optimize visual comfort, access to views, direct heat gain to work areas, and the ability to reduce electric lighting load.

The Daylighting Pattern Guide (NBI 2019) is a simple tool that enables design teams to gain a sense of the relationship between WWR, window placement, and resulting daylight performance. This tool is freely available from https://patternguide.advancedbuildings.net.

DL13 Private Offices

Typical private offices need only a small WWR of 30% or less to provide functional daylight. However, access to a wider view or a different architectural goal might suggest that the WWR be higher for private offices. Evaluate the allowance for private offices in context with the whole-building WWR goal. Place private offices on the north façade to prevent the need for shades or blinds. (Do provide small vertical fins or some way to rotate monitors or working ori-

Annual Metric Descriptions

Point-in-time daylighting calculations (for example, work-plane illuminance on December 21 at 9:00 a.m.) can be useful for understanding best- or worst-case scenarios, but they do not provide a good picture of whether a space or building is performing well on an annual basis. Dynamic daylight metrics take local climate and sunlight conditions into account, as well as detailed information about the size, shape, and reflectances of the space and the daylighting aperture shading and redirection devices. Two metrics adopted by Illuminating Engineering Society (IES) are helpful for evaluating daylighting distribution and heat gain potential: spatial daylight autonomy (sDA) and annual sun exposure (ASE). Additional explanation on these metrics is available in IES LM-83-12 (IES 2013), but in summary they can be described as follows.

Spatial daylight autonomy (sDA) is the percentage of an analysis area that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year. sDA can be calculated for any illuminance criterion and for any percentage of time, but the most common threshold is 300 lux for 50% of the time. Subscripts are commonly attached to indicate the illuminance criterion and percentage of operating hours. For example, $sDA_{300,50\%}$ indicates that the sDA is calculated for an illuminance of 300 lux and for 50% of the operating hours. If a daylighting design for an open office has $sDA_{300,50\%} = 65$, this means that 65% of the floor area meets this condition. Calculation of sDA requires software that can estimate the daylighting contribution at different points within a space for a range of sun and sky conditions representing the occupied window of the year; such software is offered by a number of vendors. Typically, lighting levels are calculated on an hourly basis for a 2 × 2 ft grid within the space.

Annual sunlight exposure (ASE) is a metric that describes the potential for visual discomfort in interior work environments. It is defined as the percentage of an analysis area that exceeds a specified direct sunlight illuminance more than a specified number of hours per year. Like sDA, subscripts are commonly used to indicate the thresholds: $ASE_{1000,250}$ indicates that the thresholds are 1000 lux of direct sunlight for 250 hours per year.

A well-daylighted office space has a high sDA and a low ASE. Both dynamic metrics are needed to evaluate daylighting designs. sDA gauges if there is enough daylight and ASE gauges if there is too much. sDA and ASE are now incorporated in common lighting analysis and design software tools. New tools are being offered each year, so not all the available tools are included in this list, and each tool offers a specific method of analysis appropriate for various design questions.

Annual whole-building energy simulation should account for the results of the detailed daylighting design analysis. At least one tool available produces an annual lighting power density (LPD) schedule grounded in the behavior of a specified lighting control system in response to a given daylighting design. The LPD schedule can be fed into the whole-building energy simulation for an accurate picture of the electric lighting impact of daylighting (Guglielmetti et al. 2011).

entation for early morning and late afternoon summer sun that will strike the north façade.) Create low office walls as shown in Figure 5-38 and add clerestory glazing above private offices to provide daylight to open office or core areas to the south.

DL14 Conference Rooms

Place large conference rooms on the east façade and smaller conference rooms and huddle rooms, as shown in Figure 5-39, on the west façade. Use daylight redirection devices for larger conference rooms with automatic shades on view glass. Automatic shades, tied to the audio/visual system, are appropriate in high-use spaces because manual control can lead to quick degradation of components.

DL15 Corridors

Use borrowed or heavily filtered daylight to light corridors as shown in Figure 5-40. Corridors (and atriums) are a good match for tubular daylight devices or strategically placed and well-shaded toplighting. Place electric lighting on a photocell and commission the system to

Figure 5-37 (DL12) Example of Walkway that Buffers Direct Sun from Striking Work Areas
Photograph by Rob Guglielmetti, NREL 55608

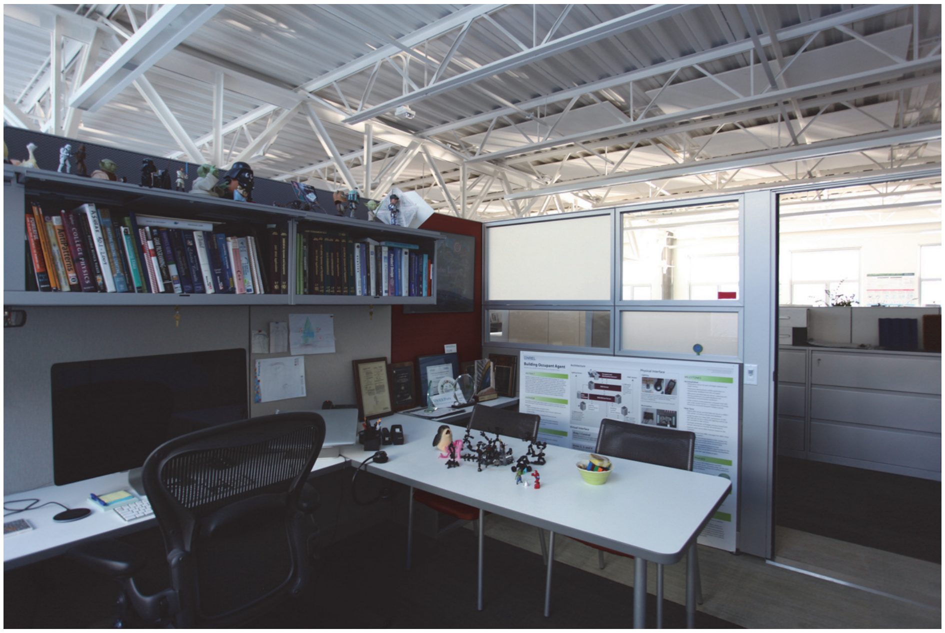

Figure 5-38 (DL13) Example of Low Office Walls and Clerestory Glazing
Photograph by Rob Guglielmetti, NREL 55607

Figure 5-39 (DL14) Huddle Room Example
Photograph by Rob Guglielmetti, NREL 55606

Figure 5-40 (DL15) Filtered Daylight
Photograph by Dennis Schroeder, NREL 17614

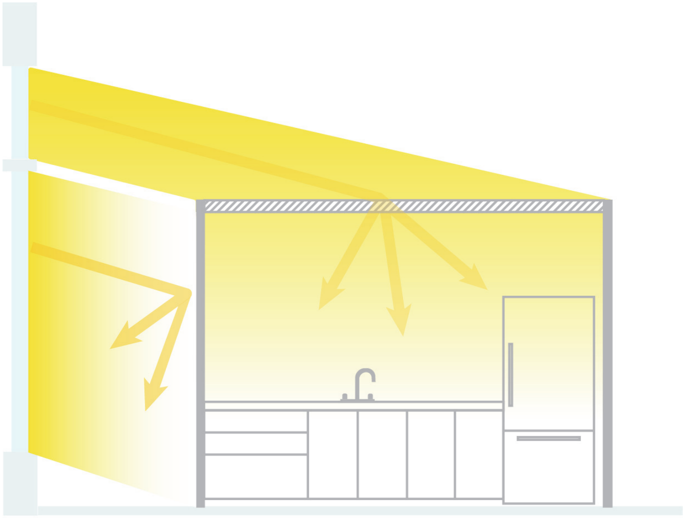

Figure 5-41 (DL16) Example of Translucent Ceiling

turn off for most daylight hours, maintaining the minimum required illuminance for safe navigation. Use accent lighting in main corridors to improve wayfinding and use other corridors as adaptation spaces for occupants in transition from exterior to interior.

DL16 Break Rooms and Restrooms

For break rooms, use translucent ceiling or wall panels to borrow daylight from open offices or corridors, as shown in Figure 5-41. For restrooms use translucent daylight windows or tubular daylighting devices to provide high and even daylight to the space, overcoming partitions. In both spaces, only a base level of ambient daylight is needed for wayfinding, and manual-ON accent lighting can be provided at wash areas in restrooms or food preparation counters in break rooms. Often, occupants quickly enter break rooms to perform a simple task such as taking a lunch out of a refrigerator. A 5–10 fc ambient daylight condition is often sufficient to prevent a 10–15 minute ON time for electric lighting for a minute or less of occupant use.

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LIGHTING CONTROLS

LC1 Goals for Office Lighting Controls

Zero energy office buildings are typically high-performance buildings in that they aim to meet a variety of human well-being, environmental, and cost-effectiveness goals. In a high-performance building, the primary objectives for lighting control and sensor systems are 1) to contribute to a comfortable and productive environment by providing dynamic lighting that responds to variation in occupants' needs for quantity, distribution, and spectrum of light depending on their task, individual preferences, and time of day, and 2) to support energy- and capital-cost-saving services by providing data about occupant and space patterns and equipment performance to building information and control systems.

In the pursuit of zero energy, an additional focus must be placed on providing electric light only at the time and quantity needed to meet occupant needs. Additionally, the services made possible with a building-integrated or internet-connected lighting control system should be selected based on the ability of the service to support zero energy operation over time.

The following tips highlight the most impactful steps toward realizing a high-performance lighting control system for a zero energy target.

DESIGN STRATEGIES

LC2 Lighting Control Basics

Lighting controls range from manual wall switches to advanced controls (networked occupancy and daylight sensors) integrated into luminaires. Table 5-10 provides a basic description of typical controls and their energy-saving potential. Advanced controls are described in greater detail throughout this section.

LC3 Separately Control Electric Light Distribution, Intensity, and Spectrum

Leverage the lighting design's lighting layers and solid-state lighting color tunability to create a variety of scenes that are most appropriate for various tasks and enable occupants to select the appropriate scene if the automatically selected scene is not sufficient. To control light distribution and intensity, separately switch or dim ambient, task, and accent lighting in each space. For the recommendations in this Guide, luminaire-level lighting control (LLLC) luminaires are used in all open and private office spaces. LLLC allows individual or small groups of luminaires to have their own sequence of operations or response based on specific occupant behaviors or preferences. More information is available in the "Luminaire-Level Lighting Control (LLLC)" sidebar.

To control the light spectrum (change the color temperature—see EL6), consider tunable white or full-color tunable light-emitting diode (LED) sources for office areas where occupants work in one location for contiguous hours and have indirect connection to daylight. Spectral tuning can allow the lighting system to enhance the connection to the daylight spectrum for partially daylighted spaces and enable circadian lighting for compliance with the WELL Building Standard certification (IWBI™ 2019). Guidance on understanding LED color-tunable products is available from the DOE Office of Energy Efficiency and Renewable Energy (EERE) webpage https://www.energy.gov/eere/ssl/understanding-led-color-tunable-products (EERE n.d.).

> ***Caution:*** Consider spectral tuning carefully. Open office spaces should only have preprogramed color-changing sequences based on time of day. Private offices under the control of a single occupant may have manual control, but the color temperature range (EL6) should be limited so as to not create a rainbow effect of colors emanating from the private offices.

Table 5-10 (LC2) Typical Lighting Control Characteristics

Control	Basics	Energy-Saving Potential
Manual switching	A basic wall-mounted control that allows the user to turn lights on and off.	Occupants are empowered to turn the lights off when they leave the room.
Manual dimming	A control to reduce the intensity of the lights due to user preference. Useful in private offices and conference rooms.	Occupants are empowered to dim the lights to improve their comfort in the space. Combined with a manual switch, a dimmer creates a single preset that provides persistence in savings.
Scene/preset control	A grouping of manual switching and dimming into a single control station to allow the user to select different lighting scenes for different tasks from a single button. Typically found in conference or training rooms and classrooms.	User acceptance and energy savings are based on the setup of the scenes and the initial grouping of the lights in the space.
Occupancy sensor	An automatic control that turns the lights on when users enter the space and off after all users have left the space.	Provides persistence in energy savings due to automatic OFF. Placement of sensor is critical; it must “see” the entire space and the user must not be blocked by furniture. Option—set sensor to turn lights to 50% ON initial trigger, because occupants may find lower light levels acceptable.
Vacancy sensor	A control that requires the user to manually turn the lights on but will automatically turn the lights off after all users have left the space.	Provides persistence in energy savings due to automatic OFF. Additional savings are gained over occupancy sensors in transient spaces by requiring the user to turn the lights on. Placement of sensor is critical; it must “see” the entire space and the user must not be blocked by furniture.
Daylight-responsive dimming	Automatic control that adjusts the lighting in response to available daylighting in the space.	Provides persistence in energy savings in areas with daylighting. Manually operated blinds reduce savings.
Task tuning	Fixing the light level to a lower level than factory maximum.	Often the initial light level can be reduced because the designed/desired light level is higher than required due to luminaire spacing and lumen maintenance factors. Savings are dependent on the tuning level but can be as high as 25%.
Time scheduling	Using a time switch to automatically turn the lights on or off at predetermined times.	Saving is generally zero because time scheduling is often the minimum code-required control.
NLC (networked lighting control)	Dimmable luminaires, occupancy sensors, daylight-responsive controls, wall control stations, and network interface devices combined together to act as a complete system.	Savings can be high because all luminaires and controls are integrated together. These systems include the ability to task-tune on a luminaire/group or space depending on the granularity of the sensors. These systems generally provide system monitoring.

Table 5-10 (LC2) Typical Lighting Control Characteristics *(Continued)*

Control	Basics	Energy-Saving Potential
LLLC (luminaire-level lighting control)	Daylight and occupancy controls are integrated into each luminaire. Luminaires have built-in wireless network interfaces.	Due to the granularity of the controls these systems have the highest potential energy savings.
PoE (power over ethernet)	Similar to NLC and LLLC but uses ethernet cabling for power and control signal.	Savings can be high because all luminaires and controls are integrated together. These systems include the ability to task-tune on a luminaire/group or space depending on the granularity of the sensors. These systems generally provide system monitoring.
Spectral tuning	Changing the color temperature (EL6) of the light to match the mood of the space or user.	By itself does not save energy but may provide higher user satisfaction.
Astronomic scheduling	Time switch includes settings for geographical location and local time to automatically turn the lights on/off at sunrise/sunset and other predetermined times.	Savings are similar to those of exterior photo control. Employ time-switch capabilities to turn lights off or on during astronomic-ON periods to save additional energy. Time scheduling is often the minimum code-required control.
Exterior photo control	Daylight sensor that turns the light on around dawn and off around dusk.	Photo control is often the minimum code-required control.

The resolution of control (per fixture or zone and per spectral tuning type) for the selected luminaire and control equipment inform lighting control protocol. Lighting control protocol descriptions are available from IES (2017). It is important to understand the pros and cons of the selected lighting control protocol and control system architecture for integration with building-level information on control systems (see LC7).

Luminaire grouping control zones need to respond to daylight zones and to occupancy. The two daylight zones are the primary daylight zone (one window head height from the window wall) and the secondary daylight zone (from the edge of the primary daylight zone to two window head heights from the window wall). These two daylight zones must dim in response to daylight separately from each other and separately from the nondaylight zone. Occupancy zones, especially in open office areas, are harder to define but are a source of significant savings. Luminaires in a “virtual hallway” should be zoned separately from other luminaires. For cubicle areas, zone the luminaires in rows parallel to cubicle corridors. Using LLLC luminaires provides the ability to create and modify the daylight zones and occupancy zones because each luminaire has its own daylight and occupancy sensors.

Dimming is a common and affordable option for solid-state lighting, typically implemented using the 0–10 V protocol (IES 2017). Dimming is an important function for effective daylighting and task tuning, so take time to consider the control signal versus power curve of the specified driver. For example, if it is expected that a task will require a small amount of ambient light to balance luminance in a daylighted area, ensure that the driver operates in the signal input range of 0%to 10% versus cutting off at 10% input signal.

In addition to dimming curves, consider potential dimming quality issues such as flicker, power quality, and color consistency. Set performance criteria for each parameter in the control specification.

Luminaire-Level Lighting Control (LLLC)

LLLC luminaires at a minimum have an integral occupancy sensor, an integral daylight sensor, a dimming driver, and individual control logic (with the ability to communicate with other luminaires—typically wirelessly) built into each luminaire. LLLC luminaires can be grouped to respond to occupancy patterns (e.g., lights over a row of open office cubicles), can be set to dim in response to increased daylight light levels in the space, and can be tuned to match a user-preferred light level in the space.

LLLC luminaires are initialized/commissioned using a handheld remote or smartphone, which allows the grouping of luminaires, the setting of the daylight low set point, the occupancy sensitivity and timeout setting, and tuning the light level to match user preference.

The control logic allows luminaires to detect and share information with one another to adjust to occupancy and/or daylight in the space. The control system allows zoning of the luminaires and has the capability to adjust light levels either individually or in a zone.

While LLLC luminaires cost more than non-LLLC luminaires due to the costs of the integrated controls, these costs may be offset by the costs of the stand-alone controls, control installation, and associated wiring necessary to comply with standard code control requirements.

Many offices are being used outside the traditional 8 to 5, Monday through Friday times as occupants are flexing their schedules earlier or later. LLLC luminaires respond automatically to these shifting schedules and turn on only the lights needed for the occupant instead of large areas of lighting.

LC4 Use an Occupant-Engaged Control Strategy

As a default strategy for all zero energy offices, employ an “opt-in” or “occupant-engaged” lighting control strategy, which is characterized by manual-ON settings on digital switches. The default and obvious control interface for the occupant should, when pressed, cause lights to turn on to the power level needed to perform the simplest visual task in the space (no more than 50% light output of ambient luminaires for a space type). Allow occupants to turn on additional zones or layers of light or increase the intensity of the ambient luminaires as needed for their task. This strategy allows occupants to consider the amount of light they need at a particular time and prevents the automatic-ON of luminaires in spaces with borrowed daylight when an occupant is passing through, for example.

An occupant-engaged control strategy is also characterized by an automatic-OFF function using occupancy sensors for small areas and time-clock sweeps (automatic OFF at a preprogrammed time) as an option for large areas with relatively consistent occupancy and schedules.

While an occupancy-engaged control strategy is a good starting point for many zero energy offices, do consider an LLLC automatic-ON strategy in open office areas with limited daylight. An automatic-ON scenario can prevent overlighting in some manual-ON scenarios with large switching zones, such as when occupancy is intermittent and small zones can be lighted individually with maintained visual comfort.

LC5 Photosensors

LLLC luminaires include integrated photosensors, or daylight sensors, which will meet all ANSI/ASHRAE/IES Standard 90.1 daylight control requirements (ASHRAE 2016). If not using LLLC luminaires, locate a separate daylight sensor in the center of each of the primary and secondary zones. Consider the primary daylighting zones when selecting and laying out fixtures to make sure that perimeter rows of fixtures can be turned off for most of the day.

In all daylighted spaces specify dimming drivers that dim to at least 20% of full output and that have the ability to turn off when daylighting provides sufficient illuminance. Provide a

An Occupant-Engaged Controls Approach

Occupant-engaged controls allow occupants to opt-in for a minimum level of service from a building system and require them to engage with the system to request more light, heating, cooling, or views to meet their current tasks and needs. For example, an occupant might press a main light switch upon entering a space and receive 25% light output to provide sufficient illuminance for wayfinding to their office. This default operational mode might correspond to safety requirements, thresholds of comfort, or energy-efficient operation (e.g., blinds down in cold climates). The occupant can opt in for a different level of service, such as higher illuminance or blinds opening to views, with a simple and obvious occupant control interface. Automatic control is then initiated to turn down the level of service when it is not needed (e.g., when the occupant leaves the area) or turn it off after a given amount of time (e.g., light used during nighttime hours is turned off after one hour with a flash warning).

This manual-ON, automatic-OFF controls approach requires designing beyond energy codes to consider the base occupant needs as the default setting. It also requires attention to the manual control interface so that a simple system is presented to the user. The way to opt in for more light, heating, cooling, and views should be obvious to the user. In contrast, complex systems that take control away from the occupant or present a complicated interface can lead to overrides due to frustration, to the detriment of the zero energy goal. An occupant-engaged controls approach does not preclude advanced control algorithms behind the scenes. However, the default or failure state of a complex control system should be a basic manual-ON and automatic-OFF sequence.

No matter how simple or complex the control system, a monitoring system that includes equipment and environmental sensors, data analysis, and information display can be critical for maintaining zero energy operation over time. An automatic fault detection and diagnostics (AFDD) system as part of a larger energy management and information system (EMIS), for example, can provide occupants, operators, and owners with actionable information about issues such as failed automatic-OFF equipment (SEAC 2019). At a minimum, for nonnetworked HVAC, lighting, and plug load systems, panel-level submetering can provide course insight into which building systems are performing as expected. To acquire a monitoring system most cost-effectively, request the system in the project contract and discuss the depth of monitoring (panel level or equipment level) and automatic correction (manual intervention or automatic optimization) with the team early to make sure electrical distribution and control system networking decisions are made with this end goal in mind.

means and a convenient location to override daylighting controls in spaces that require darkening for visual presentations.

Even a few days of occupancy with poorly calibrated controls can lead to permanent overriding of the system and loss of savings. Photosensor Cx should be performed after furniture installation but prior to occupancy to ensure user acceptance. Scan the space and adjacent exterior environment for any highly reflective materials that could produce high illuminance on the photosensor. Shield the photosensor from view of these materials if possible. Evaluate the set point under sunny daytime, overcast daytime, and nighttime conditions to ensure the illuminance is maintained in each scenario.

The photosensor manufacturer and the quality assurance (QA) provider should be involved in the calibration. Document the calibration and Cx settings and plan for future recalibration as part of the maintenance program.

LC6 Vacancy/Occupancy Sensors

Vacancy sensors (manual ON) are similar to occupancy sensors but require the user to manually turn the lights on when entering the space. Vacancy sensors are typically switch mounted because user input is required.

Occupancy sensors (automatic ON) can be switch mounted (replacing the traditional wall switch), ceiling-mounted, or attached directly to each light luminaire:

- *Switch-mounted sensors* typically use infrared technology to sense occupants. When using switch-mounted sensors, confirm that they are set to manual-ON operation during installation, as many manufacturers ship sensors with a default setting of automatic ON.
  Caution: Confirm during space planning that switch-mounted sensors' line of sight to the occupant will not be blocked by furniture. If the line of sight is blocked, use ceiling-mounted occupancy sensors.
- *Ceiling-mounted sensors* can use infrared technology, ultrasonic technology, or both (dual technology) to sense occupants. Dual-technology sensors provide the best overall coverage.
  Caution: Ceiling-mounted sensors can see outside of spaces if a door is left open, thereby turning lights on when someone walks by the open door. Dual-technology sensors typically resolve this issue because both systems must sense the occupant entering the space before lights are turned on.

Unless otherwise recommended, factory-set sensors should be set for medium to high sensitivity with a maximum 10-minute time delay (the optimum time to achieve energy savings without creating false OFF events). Work with the manufacturer for proper sensor placement, especially when partial-height partitions are present.

Periodically confirm that sensors are turning the lights off after occupants leave the space.

LC7 Use Information Available from the Lighting Control System

Identify the energy- and capital-cost-saving applications that make use of lighting control system sensor data. Example data flow and applications include the following:

- Sending occupancy information to the building automation system to trigger HVAC setbacks
- Sending luminaire power and occupancy information as input to a fault detection and diagnostics (FDD) tool to assess sequence of operations or equipment failures
- Sending occupancy and assumed task information to a building control system during a demand-response event to enable demand response without necessarily reducing the needed level of service by the electric lighting system
- Sending occupancy and assumed task information to a building control system to optimize the lighting control scene for enhanced occupant well-being (e.g., circadian lighting) and grid-friendliness while maintaining a base level of electric lighting service for occupants
- Sending occupancy information to facilities management tools as input for space utilization metrics to inform the programming for renovation and new occupancy

Many of these applications are not off-the-shelf specifications but should be considered in the design process since product offerings are rapidly changing. Zero energy is a goal that is often used in concert with other high-performance goals such as WELL certification (IWBI™ 2019), being grid-friendly, and being resilient, all of which require a higher degree of information exchange than offered by traditional, stand-alone lighting control systems.

When considering sensor, driver, and system controller selection, ensure compatibility between the lighting system and building controls (to the extent that control system integration is part of the zero energy maintenance strategy). Ensure that dimmable drivers are specified according to the protocol consistent with the lighting control system and using a dimming method appropriate for the common operating power of the source.

Coordination between the HVAC design, interior design, controls integrator, information technology (IT), and facilities maintenance staff is critical to the success and ongoing use of the applications. If workstation task lights are installed (see EL5) they need to be automatically controlled to turn off when the workstation is unoccupied for plug load control options (see PL4).

Direct Current Lighting and Control

Every watt matters: the cost-effectiveness of zero energy buildings is possible with considered trade-offs and priorities as well as attention to every operational watt. While equipment efficiencies become hard to realize over base product offerings, a new look at transporting energy resource to load can offer energy cost and efficiency benefits. Specifically, direct current (DC) microgrids that leverage the inherent operating state of much lighting and plug and process load (PPL) equipment can realize 6% to 8% more efficient use of PV recourse than an alternating current (AC) distribution system (Fregosi 2015). The increased PV system utilization, and ultimately energy purchased from the grid, is primarily due to reduced conversions from PVs (DC to AC in the base case) and to solid-state devices (AC to DC in the base case). Such a system efficiency increase is dependent on the load (high-bay LED lighting load in the referenced study) being operational when the PVs are producing power.

An emerging implementation of DC lighting is Power over Ethernet (PoE). It combines DC-powered solid-state lighting with control in one ethernet cable, demonstrating the fusing of function into an apparently simpler system. If realized, such as system could offer cost benefits due to installation, Cx, and integration with other building systems, as well as energy efficiency improvement due to the ability to implement advanced control algorithms adaptable to varying occupant types and needs. However, this technology is at an early stage and the understandings of the true ease of Cx, the ability to realize operational energy savings, and different system approaches to monitoring and reporting lighting power are not yet clear.

LC8 Measure and Verify Expected Lighting Power Profiles

The lighting power profile for a zero energy office building typically looks like that shown in Figure 5-42. The base load should be very low at night (see EL16), then lights gradually turn on in the morning, daylight dimming occurs during the day, and lights gradually turn on in the later afternoon as occupants and tasks require it. For nonvacancy/occupancy-controlled lights, an automatic sweep should turn all lights off typically at the end of the day. Provide for one- or two-hour override as needed. As occupants leave for the night, the only lighting load ON peri-ods should be brief as custodial or security staff enter spaces.

Additional features of a zero energy lighting profile include the following:

- ***Low baseload.*** Perform a detailed inspection of potential always-ON lighting that can be controlled to OFF, such as elevator lights and vending machine lights.
- ***Switched egress lighting.*** Use UL-924 devices to allow egress lighting to be dimmed and switched in response to occupancy and daylighting.
- ***Lights off at night.*** The only sources that should be on at night are lights in vestibules or other points and pathways of entry. The lighted entry paths should lead to manual-ON switches, which allow for all other lights to be off when the building is not in use.
- ***Atypical occupant types show as such.*** Security walk-throughs and other intermittent uses of space should show up as approximately 10-minute spikes versus hour or longer ON-times after hours.
- ***Daylighting dip and plateau midday to evening.*** Identify any sensor interactions with shadows or reflections that might be causing overdimming or underdimming. If lights are all automatically turning on due to reduced daylight contribution in the afternoon, consider implementing a noontime sweep to turn all the lights off. Enable occupants to manually turn on lights at any time after the sweep.
- ***Lights off next to windows.*** Lights at the perimeter of the building that are within the primary daylight zone of glazing (one window head height deep) are off during daytime hours.
- ***Lighting-only circuits.*** Luminaires are circuited on dedicated lighting circuits so metering/monitoring equipment can be easily installed.

These strategies can be included in the Cx scope and included in ongoing Cx procedures.

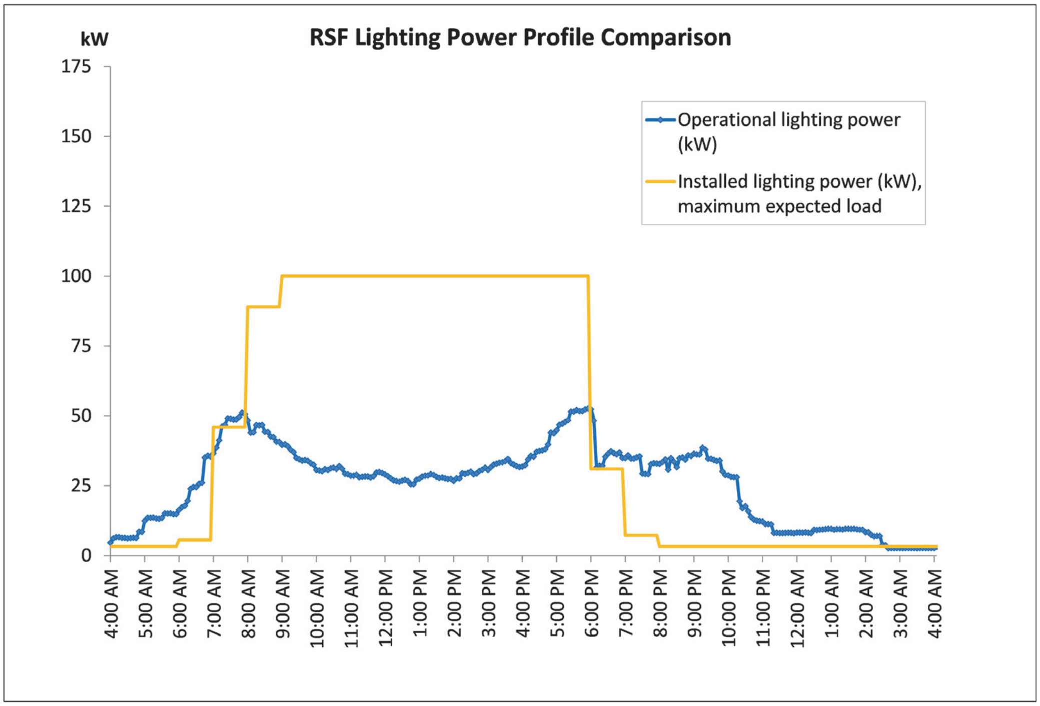

Figure 5-42 (LC8) Example Zero Energy Daily Lighting Load Profile

LC9 Exterior Lighting Controls

Use photocells or astronomical time switches on all exterior lighting. If a building energy management system is being used to control and monitor mechanical and electrical energy use, it can also be used to schedule and manage outdoor lighting energy use.

Reduce the power of all parking lot lighting by at least 75% when no activity is detected for not longer than 10 minutes by using individual occupancy sensors.

Reduce the power of all remaining exterior lighting by at least 75% of the design level when no occupants are present between 9:00 p.m. and 6:00 a.m. This can be done with either time-based or occupancy sensors. Lighting at building entries and exits may be left at full power; however, by using occupancy sensors at entries users will automatically trigger the higher light level. The higher light level will identify to the occupant and security that the area is or has recently been occupied.

LC10 Parking Garage Controls

Reduce the power on all luminaires in the parking and drive areas by at least 75% when no activity is detected for not longer than 10 minutes by using occupancy sensors on each luminaire. Lighting at elevator landings and in stairwells should be grouped together and controlled to reduce the power by at least 50% when no activity is detected for not longer than 10 minutes by using occupancy sensors on each group of luminaires.

LLLC luminaires in parking garages provide greater flexibility in grouping luminaires, provide the ability to dim in response to daylight in aboveground parking, and provide easier setup of the occupancy sensor and high-end trim settings.

> ***Caution:*** Occupancy sensors can be set to turn the lights completely off, which saves additional energy, but care should be taken to maintain a feeling of safety in garages, especially at night in aboveground garages and at all times in underground garages.

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ELECTRIC LIGHTING

INTERIOR LIGHTING

EL1 New and Existing Buildings

The electric lighting recommendations in this chapter can be used in new construction, tenant improvement, and retrofit projects with similar achievable savings. In tenant improvement and retrofit projects the daylighting potential is determined by the existing building apertures and orientation, but the daylight-responsive control recommendations are still valid. Lighting layouts may need to be adjusted to work around existing structural, mechanical, plumbing, and sprinkler elements, but moving a luminaire 2 ft to one side will not adversely affect the lighting in the space.

EL2 Goals for Office Lighting

The primary lighting goals for office lighting are to optimize the open office spaces for daylight integration, to control the lighting to respond to daylight and the occupant, and to provide appropriate lighting levels for office functions while producing a vibrant environment.

DESIGN STRATEGIES

EL3 Savings and Occupant Acceptance

To meet the goals for office lighting, first the electric lighting system needs to respond to daylighting as it enters the spaces. Through automatic controls the electric lighting will decrease in intensity and power as the daylight increases in the morning. The system will automatically increase electric lighting in the late afternoon as the available daylight decreases. This decrease in the morning and increase in the afternoon of electric lighting intensity is imperceptible with modern LED continuous dimming systems. Energy savings are dependent on many factors, but typical savings for the first row of luminaires can be as high as 30%.

Second, the electric lighting needs to respond to office workers by automatically turning off the lighting after they have left a space. One of the biggest wastes of lighting energy is leaving lights on in unoccupied spaces. Turning the lights on can be achieved by either manually using a switch or having the lights automatically turn on when the user enters the space (see LC4).

Lastly, the combination of daylight and electric light needs to provide an appropriate lighting intensity for office workers to accomplish their tasks. In computer-dominated offices lighting levels can be reduced, but lower light levels can produce a dull-feeling environment. Selectively adding wall lighting by using wall sconces, art lighting, or wall washing in larger open office spaces can create a more vibrant environment.

A good lighting control system is invisible to occupants, but users should be educated on the energy-saving benefits of the system and on how to spot and report systems that appear to be malfunctioning.

LLLC luminaires described in the “Luminaire-Level Lighting Control (LLLC)” sidebar combine daylighting and occupancy controls into the individual luminaires

For the recommendations in this Guide, LLLC luminaires are used in all open and private office spaces. LLLCs allow individual or small groups of luminaires to have their own sequence of operations or response based on specific occupant behaviors or preferences, maximizing energy savings.

EL4 Light-Colored Interior Finishes

For the electric lighting to provide the recommended light levels at the low LPD recommendations, surfaces must have light-colored finishes. Ceiling reflectance should be at least 80% (preferably 90%), which in general means using smooth white acoustical tile or ceiling paint. The average reflectance of the walls should be at least 50%, which in general means using light tints or off-white colors for the wall surfaces, as the lower reflectances of doors, tack surfaces, windows, and objects on the walls will reduce the average. Floor surfaces should be at least 20%; for this there are many suitable surfaces.

In open-plan offices, cubicle partitions should also have a reflectance of at least 50%. Partitions between cubicles that are parallel to the window wall should be at least 50% translucent or be limited to 42 in. to maximize daylight potential past the first cubicle.

EL5 Task Lighting

If the space-planning recommendations in EL8 through EL9 are followed by locating office spaces in the daylight zones, task lighting should not be needed during daylight hours. In daylight zones, task lights should be evaluated on a needs basis and should not be automatically installed at each workstation. Connect all task lights to vacancy sensors (see LC6) to turn the lights off when the space is unoccupied.

Periodically confirm that task lights are controlled and are turned off during daylight hours and when occupants leave the spaces during non-daylight hours.

EL6 LED Color characteristics

There are a number of color characteristics of light sources that should be considered when specifying LED sources:

- Color Rendering Index (CRI), Fidelity Index, and Gamut Index are measurements identifying a lamp’s ability to adequately reveal color characteristics of objects and people.
- Correlated color temperature (CCT) is a scale identifying a lamp’s relative warmth or coolness.
- Spectral power distribution (SPD) is the distribution of the wavelengths across the visible light spectrum.

For a more detailed discussion of these metrics, see *Advanced Energy Design Guide for K-12 School Buildings: Achieving Zero Energy* (ASHRAE 2018).

EL7 Light-Emitting Diodes (LEDs)

LEDs are solid-state semiconductor devices that can produce a wide range of saturated colored light and can be manipulated with color mixing or phosphors to produce white light. To achieve the LPD recommendations discussed in the sample design layouts for office buildings (EL8 through EL15), LED luminaires were used for all general, decorative, task, and accent lighting. LED specifications are shown in Table 5-11.

Unlike fluorescent ballasts, LED dimming drivers generally do not cost more than non-dimming drivers, so always specify dimming drivers. Furthermore, LED luminaire and control manufacturers offer high-end trim and tuning. Under this condition, light output is reduced by a certain percentage, most often 20% reduction to 80% lumen output. The human eye sees a very small difference at 80% of typical office light levels, and in many circumstances the luminaire's light output can be further reduced. As an LED dims over time, additional energy will be applied to the luminaire to maintain the same light levels over the course of the luminaire's life. High-end trim/tuning may reduce the energy over the lifetime of the luminaire by 10% or greater depending on the settings.

SPACE-SPECIFIC STRATEGIES

EL8 General Guidance

The 0.40 W/ft^2 goal for LPD represents an average LPD for the entire building. Individual spaces may have higher power densities if they are offset by lower power densities in other areas, as shown in Table 5-12. The example designs described in the following how-to strate-

Table 5-11 (EL7) LED Specifications

Metric	Recommendation (Minimum)
Efficacy	125 LPW
End of life	L70 50,000+ hours
CRI	80+
Fidelity Index and Gamut Area Index	Rf above 85, Rg 90–110
Warranty	5+ years
Dimmable	Specify dimming driver

Table 5-12 (EL8) Interior Lighting Power Densities

Interior Space	LPD, W/ft^2	90.1-2016	90.1-2019 (proposed)
Open-plan office	0.31	0.81	0.67
Private office	0.42	0.93	0.88
Conference room/meeting room	0.77	1.07	0.97
Corridor	0.34	0.66	0.41
Storage area	0.34	0.46	0.38
Restroom	0.51	0.85	0.63
Break room	0.47	0.62	0.59
Electrical/mechanical room	0.42	0.43	0.42
Stairway	0.49	0.58	0.49
Lobby	0.77	1.0	0.84
Other spaces	0.49		
Average building LPD	0.40		

Chapter 5

EL

Table 5-13 (EL8) National Average Space Distribution

Interior Space	% of Floor Area
Open-plan office	50%
Private office	12%
Conference room/meeting room	4%
Corridor	8%
Storage area	6%
Restroom	3%
Break room	1%
Electrical/mechanical room	4%
Stairway	2%
Lobby	4%
Other spaces	6%

gies offer *a way*, but *not the only way*, that this watts-per-square-foot limit can be met. Daylighting (see DL12) is assumed in all open office areas.

The examples in EL9 through EL15 are based on national average building space distributions. These averages are shown in Table 5-13. No building is average and each building will have a different space allocation. When following the recommendations in the following how-to strategies, adjust the standard space allocation to match the specific building's space allocation.

EL9 Open-Plan Offices $ 🔧

Space planning. To maximize the energy savings from dimming electric lighting in response to daylight, the open office workstations should be located on the north and south sides of the building. By maximizing daylight penetration, workstations can be within the daylight zone. This generally limits the workstations to three deep from the window wall. Additionally, the partitions separating the workstations that are parallel to the window wall should be no taller than 42 in. or be at least 50% translucent above desk height to allow daylight to reach the second and third workstations.

Illumination level. The target lighting in open offices is 25–30 average maintained footcandles for ambient lighting, with approximately 50 fc provided on the desktop by a combination of LLLC luminaires and daylight.

Existing building opportunity. Typically, open office spaces are controlled by local switches or a central time controller. Wireless-controlled LLLC luminaires are a perfect opportunity for existing buildings because they mount and wire like typical luminaires with hot, neutral, and ground wires. The control of the luminaire is wireless, so no additional control wires need to be installed in the ceiling or in the walls.

Sample design. Open-plan office areas account for approximately 50% of the floor area and are designed to 0.31 W/ft^2 excluding task lighting wattage (see EL5 for recommendations on task lighting). The desired lighting and energy target can be achieved by using one 25 W, 125 LPW LLLC luminaire for every 80 ft^2 of office area. Supplemental task lighting should not be included in the initial cubicle layout and should be evaluated on a needs basis.

Use LLLC luminaires in all open office areas even if the luminaires fall outside the secondary daylight zone, as the LLLC luminaires can be occupancy zoned and task tuned with luminaires in the daylight zones.

Depending on the height of the partitions that separate the corridor from the workstations, it is possible that the corridor will be lighted by the workstation luminaires. At the low lighting power recommended for open office areas it is important to provide some vertical layer of

Puget Sound Energy—Bothell Office LLLC Retrofit

The Bothell Office of Puget Sound Energy (PSE) is home to 80+ employees and is composed of open office space, private offices, and conference rooms. The team recognized the clear business case for LED fixtures with LLLCs. The LLLC luminaires allowed the team to significantly enhance employee satisfaction, modernize the building, and enable seamless control over different areas. The retrofit involved replacing 84 T8 fluorescent luminaires with 122 LED luminaires.

The benefits include the following:

- ***Maximum energy savings.*** PSE achieved More than 70% energy savings due to the integrated controls compared to the previous lighting system. Approximately half of the energy savings is from the integrated controls.
- ***Easy installation and control.*** PSE worked with a local contractor to install the luminaires and wireless integrated controls systems, which took two weeks during summer 2015. The luminaire installation was as simple as if luminaires were installed without controls, given that the wireless controls do not require changing the existing circuits or installing separate occupancy or daylight sensors. Adjustments to customize light levels were simple thanks to the system's wireless remote control.
- ***Increased occupant comfort.*** Employees are more comfortable in the building now than they were before the retrofit and have expressed positive feedback in response to the improved light levels, better distribution of light, and the new system's dimming capabilities.

Cleaning crews also benefit from the system's occupancy sensing and no longer need to wonder if staff are still in the office when they are finished cleaning because the lights are set to automatically shut off.

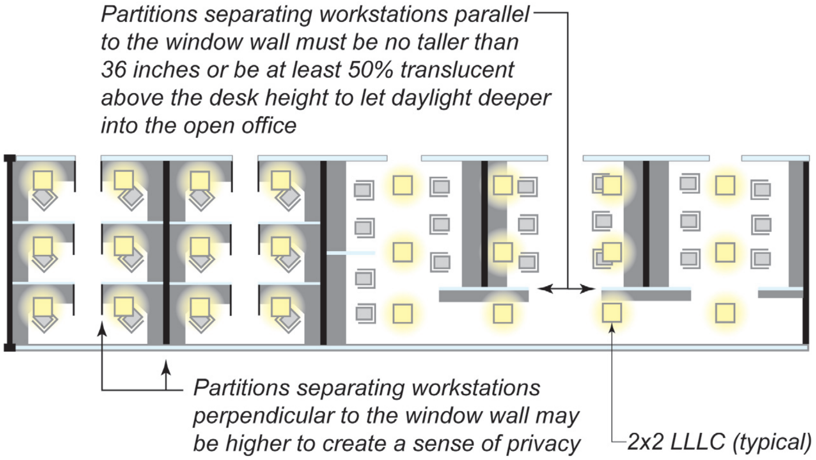

Figure 5-43 (EL9) Sample Open-Plan Office Layout

lighting to the space. Highlight feature walls and corridor file areas with wall-wash luminaires. See Figure 5-43 for an example open-plan office layout.

Control. LLLC luminaires exceed code requirements for daylight and occupancy control in the primary and secondary daylight zones. Where supplemental task lighting is installed, use a vacancy sensor on each task light.

EL10 Private Offices

Space planning. Locate private offices on the east and west sides of the building, as these spaces are the most difficult to control the daylight in due to low sun angles and the tendency of tenants to close blinds.

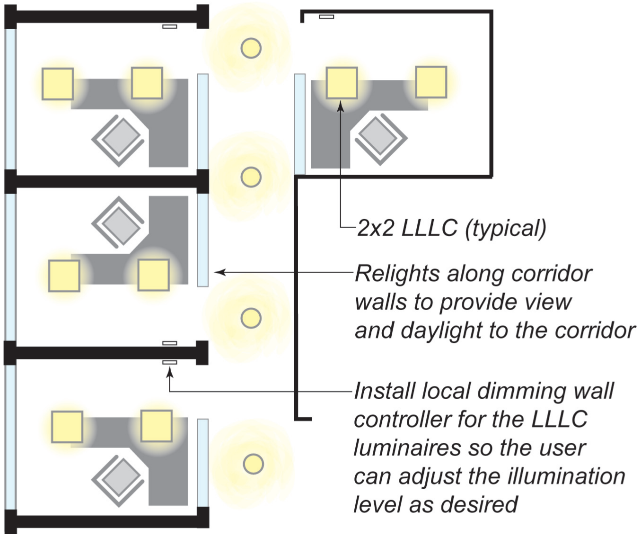

Figure 5-44 (EL10) Sample Private Office Layout

Illumination level. The target lighting in private offices is 25–30 average maintained footcandles for ambient lighting, with approximately 50 fc provided on the desktop by a combination of LLLC luminaires and daylight. Supplemental task lighting is only required during nondaylight hours and must be vacancy-sensor controlled.

Existing building opportunity. Typically private office spaces are controlled by an occupancy sensor or, for vintage buildings, local switches. Wireless-controlled LLLC luminaires are a perfect opportunity for existing buildings because they mount and wire like typical luminaires with hot, neutral, and ground wires. The control of the luminaire is wireless, so no additional control wires need to be installed in the ceiling or in the walls. Replace the occupancy sensor or wall switch with a compatible switch or dimmer.

Sample design. Private offices account for approximately 12% of the floor area and are designed to 0.42 W/ft^2 including task lighting wattage (see EL5 for recommendations on task lighting).

The desired lighting and energy target can be achieved by using one 25 W, 125 LPW LLLC luminaire for every 60 ft^2. However, always use a minimum of two luminaires per office, because one luminaire will not provide adequate lighting distribution in a typical private office. See Figure 5-44 for an example private office layout.

Control. LLLC luminaires exceed code requirements for daylight and occupancy control in the primary and secondary daylight zones. Include a local dimming wall controller near the desk location so the user can adjust the illumination level as desired.

EL11 Conference Rooms/Meeting Rooms

Space planning. Locate conference/meeting rooms on the east and west sides of the building because these spaces are the most difficult to control the daylight in due to low sun angles and the tendency of tenants to close blinds. Larger conference rooms may also be located along the core of the building, but if this is done be sure to provide translucent glass along the corridor wall to provide some connection to daylight.

Illumination level. The target lighting in conference rooms and meeting rooms is 25–30 average maintained footcandles.

Existing building opportunity. Existing conference/meeting rooms may be controlled by switches, occupancy sensors, or multiscene dimming controllers. LED luminaires come standard with dimming drivers, so if dimming is not currently available in a conference room it can

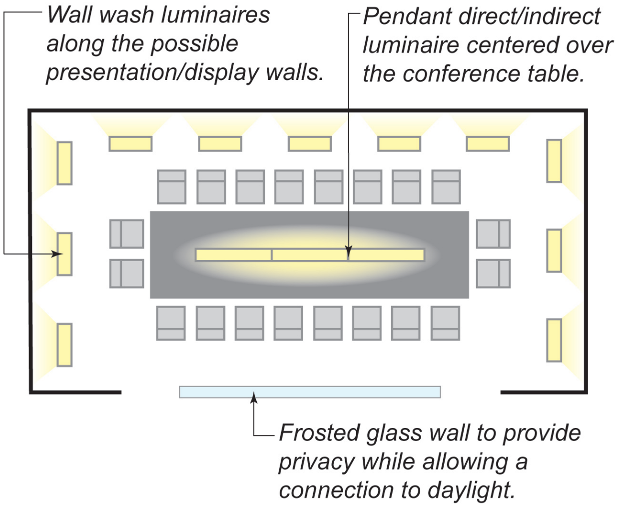

Figure 5-45 (EL11) Sample Conference Room/Meeting Room Layout

be added through a 0–10 V or wireless dimming controller. Some LED dimming drivers may be compatible with existing multiscene controllers; consult with the controller manufacturer.

Sample design. Conference rooms account for approximately 4% of the floor area and are designed to 0.77 W/ft^2. A typical lighting layout for a conference room is to provide task lighting on the table from lights located over the table. Using pendant-mounted direct/indirect luminaires over the table, where the indirect lighting is separate from the downlight, along with lighting on the presentation wall provides a flexible lighting solution. See Figure 5-45 for an example conference/meeting room layout.

Control. Use vacancy sensor or automatic ON to 50% occupancy sensor local control. Use scene/preset control to provide user flexibility (group wall lighting together, separate from general lighting, separate from table lighting, separate from video wall lighting).

EL12 Corridors

Illumination level. The target lighting in corridors is 5–10 average maintained footcandles. Choose luminaires that light the walls and provide relatively uniform illumination.

Existing building opportunity. Existing buildings should follow the recommendations in the “Sample Design” subsection that follows.

Sample design. In the virtual hall of the open office area, LLLC luminaires can be continued at the same spacing as used in the open office area. Alternatively, use a 15 W LED downlight or a combination of LED downlights, wall washers, or wall sconces, one for every 45 ft^2 of the hallway. The downlight/wall washer/wall sconce option provides a different layer of lighting, making the space more visually interesting.

In other corridors, options include using one LLLC 25 W, 125 LPW luminaires per 75 ft^2 or a 15 W LED downlight or combination of LED downlights/wall washers/wall sconces, one for every 45 ft^2 of the hallway. See Figure 5-46 for an example corridor layout.

Control. In typical corridors use wireless ceiling-mounted occupancy sensors at each end of the corridor that communicate together. *Note:* LLLC luminaires can be used in these spaces; they allow occupancy communication and task tuning of the lighting in the space. Lights should be set to reduce lighting to 25% or lower when no occupants are present during normal office hours and to OFF after hours.

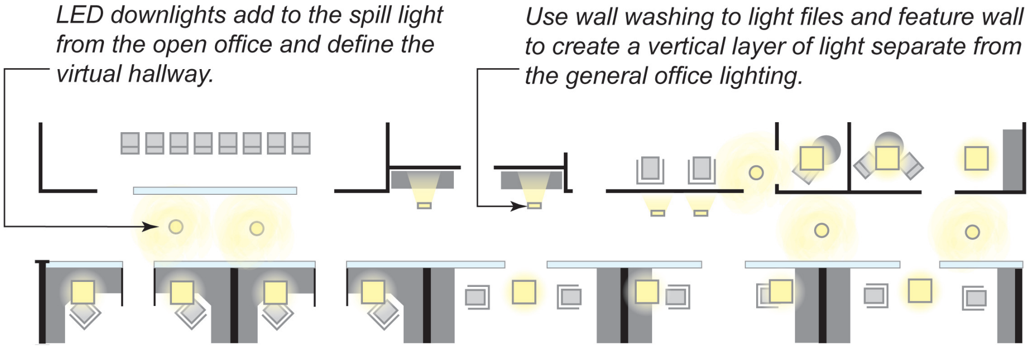

Figure 5-46 (EL12) Sample Corridor Layout

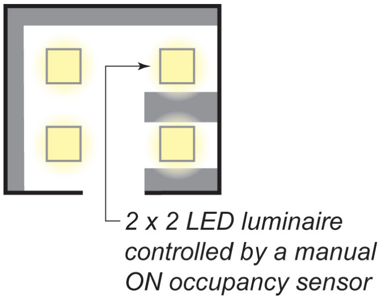

Figure 5-47 (EL13) Sample Storage Area Layout

EL13 Storage Areas

Illumination level. The target lighting in storage areas is 5–15 average maintained footcandles.

Existing building opportunity. Existing buildings should follow the recommendations in the "Sample Design" subsection that follows.

Sample design. Storage areas account for approximately 6% of the floor area and are designed to 0.34 W/ft^2. Use one 25 W,125 LPW LED luminaire per 75 ft^2.

Control. Use a manual-ON occupancy sensor. In more complex spaces where users may not be visible from a single-location occupancy sensor, use a wireless ceiling-mounted sensor with multiple sensors that communicate together. *Note:* LLLC luminaires can be used in these spaces; they allow occupancy communication and task tuning of the lighting in the space. See Figure 5-47 for an example storage area layout.

EL14 Lobbies

Illumination level. The target lighting in lobby areas is 10–15 average maintained footcandles. Highlight wall surfaces and building directories.

Existing building opportunity. Existing buildings should follow the recommendations in the "Sample Design" subsection that follows.

Sample design. Lobbies account for approximately 4% of the floor area and are designed to 0.34 W/ft^2. Lobbies provide the first impression to visitors, so provide pendant or decorative ceiling lights over the reception desk. *Note:* if there is one receptionist use two luminaires, one on each side, to frame the receptionist; repeat spacing of luminaires if there are multiple receptionist locations. Highlight the feature wall behind the reception desk with LED wall washers or accent lights.

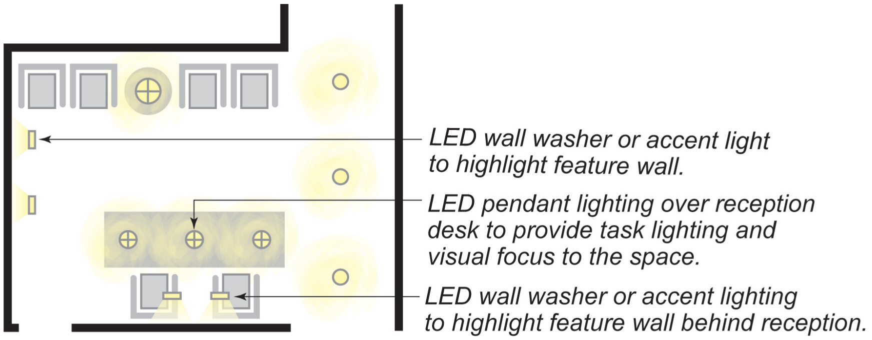

Figure 5-48 (EL14) Sample Lobby Layout

Lobbies may also have small phone spaces. Install downlights, pendants, or 2×2 LED fixtures coupled with manual dimming and occupancy sensors. Average the connected load in these spaces to 0.47 W/ft^2, which is equivalent to about one 25 W LED luminaire for every 60 ft^2. See Figure 5-48 for an example lobby layout.

Control. In typical lobbies use ceiling-mounted occupancy sensors. Lights should be set to reduce lighting to 50% or lower when no occupants are present during normal office hours and to OFF after hours.

EL15 Other Spaces

Other space types include restrooms, break rooms, electrical/mechanical rooms, stairways, and any other spaces not addressed in the preceding tips. To address the lighting in these spaces, average the connected load in these spaces to 0.47 W/ft^2, which is equivalent to about one 25 W LED luminaire for every 60 ft^2.

EL16 Twenty-Four-Hour Lighting

Wherever possible use occupancy sensors on luminaires that provide egress lighting at night to further reduce electricity associated with lighting an unoccupied building. It should be noted that most jurisdictions allow the application of occupancy sensor controls on egress lighting. If needed, night lighting or lighting left on 24 hours to provide emergency egress needs when the building is unoccupied should be designed to limit the total lighting power to 10% of the LPD for that space.

EXTERIOR LIGHTING

EL17 Lighting Zones

Exterior lighting is an important factor in meeting the goal of a zero energy office building. The total exterior LPD is created from the individual area allowances shown in Table 5-14. Individual areas may have higher power allowances if they are offset by lower power allowances in other areas and the total designed lighting power is equal to or lower than the total LPD.

The exterior LPDs are classified into lighting zones (LZs). For this Guide it is assumed that most office buildings will fall into LZ3. See *Advanced Energy Design Guide for Small to Medium Office Buildings: Achieving 50% Energy Savings Toward a Net Zero Energy Building* (ASHRAE 2011) for a detailed discussion on lighting zones.

> ***Caution:*** Calculate LPD only for areas intended to be lighted. For this Guide, areas that are lighted to less than 1 lux (0.1 fc) are assumed to not be lighted and are not counted in the LPD allowances shown in Table 5-14. For areas that are intended to be lighted, design with a maximum-to-minimum ratio of illuminance no greater than 30 to 1.

Table 5-14 (EL17) Exterior Lighting Power Densities

Exterior Area	LZ3 and LZ4 LPD, W/ft^2	LZ2 LPD, W/ft^2
Parking lots and drives	0.05	0.04
Walkways, pathways, stairways, and special features	0.10	0.05
Decorative façade lighting	0.075	0.05
All other spaces	0.05	0.04

> Therefore, if the minimum light level is 0.1 fc, then the maximum level in that area should be no greater than 3 fc.

For parking lot and grounds lighting, do not increase luminaire wattage in order to use fewer lights and poles. Increased contrast makes it harder to see at night beyond the immediate luminaire location. Flood lights and wall-packs should not be used, as they cause glare and unwanted light encroachment on neighboring properties.

Limit poles to 20 ft mounting height and use luminaires that provide all light below the horizontal plane to help eliminate light trespass and light pollution. All pole lights must integrate an occupancy sensor that reduces the power by at least 50% when no activity is detected for not longer than 15 minutes.

EL18 BUG Ratings

BUG stands for *back, uplight, and glare* and is used to indicate how much spill light a luminaire may create, how much uplight it will produce, and its potential to create glare. This rating system is used by various municipalities as part of their night lighting ordinances to limit light trespass and reduce uplighting. The rating system is typically based on exterior lighting zones.

BUG ratings can also be used by designers to provide appropriate exterior lighting solutions. Balance is required when utilizing the glare aspect of this system. Too much glare can be unpleasant or even debilitating; however, efficacy may be significantly reduced when heavily frosted lenses are applied to reduce the glare rating.

Use forward throw optics or move exterior pole locations away from the perimeter. This will reduce spill light and may provide greater flexibility in luminaire choice and spacing

EL19 Exterior Lighting Power—Parking Lots and Drives

Limit exterior lighting power for parking lots to 0.04 W/ft^2 in neighborhood business districts or to 0.05 W/ft^2 in commercial business districts. Calculate only for paved areas, excluding grounds that are lighted to less than 0.1 fc.

Use LED parking lot luminaires with a dimming driver and exterior occupancy sensor that will reduce power by at least 75% when no activity is detected for 10 minutes.

> ***Caution:*** Parking lot lighting locations should be coordinated with landscape plantings so that tree growth does not block effective lighting from pole-mounted luminaires.

Parking lot lighting should not be significantly brighter than the lighting of the adjacent street.

If aboveground or underground parking garages are used, limit the lighting power to 0.6 W/ft^2 for stairwells and elevator lobbies. Limit the lighting power to 0.13 W/ft^2 for parking areas, drives, and ramps. See LC10 for control recommendations. Consider using LLLC luminaires for greater control setup flexibility and adjustment.

EL20 Exterior Lighting Power—Walkways, Pathways, Stairways, and Special Features

Limit exterior lighting power for walkways, pathways, stairways, plaza areas, and special feature areas to 0.10 W/ft^2 in commercial business districts or to 0.05 W/ft^2 in neighborhood business districts. Exclude grounds that are lighted to less than 0.1 fc.

EL21 Exterior Lighting Power—Decorative Façade Lighting

Decorative façade lighting is lighting that highlights the building architecture and is used sparingly if at all on zero energy office buildings. When façade lighting is included it should be limited to building entries; limit the lighting power to 0.075 W/ft^2 in commercial business districts or to 0.05 W/ft^2 in residential business districts for the area intended to be illuminated to a light level no less than 0.1 fc.

REFERENCES AND RESOURCES

ASHRAE. 2011. *Advanced energy design guide for small to medium office buildings: Achieving 50% energy savings toward a net zero energy building*. Atlanta: ASHRAE.

ASHRAE. 2016. ANSI/ASHRAE/IES Standard 90.1-2016, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASHRAE. 2018. *Advanced energy design guide for K-12 school buildings: Achieving zero energy*. Atlanta: ASHRAE.

IES. 2011. *The lighting handbook*, 10th ed. NY: Illuminating Engineering Society.

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PLUG LOADS AND POWER DISTRIBUTION SYSTEMS

OVERVIEW

Controlling plug and process load (PPL) energy usage is critical to achieving a zero energy building. PPLs, which are loads from sources excluding HVAC or lighting, provide a significant opportunity to contribute to the overall building energy savings. Office buildings likely need PPL management because they consume over 30% of the total commercial building energy use, and this consumption is expected to grow to 35% by 2025 as the number and energy intensities of plug-in devices continue to increase and as HVAC and lighting loads decrease (DOE 2015). In addition, heat generated from plug loads is removed by the HVAC system, adding to the energy impact.

PL1 Design Considerations $ 🔧

Often plug loads are overestimated for design purposes. This is typically seen when tenants are negotiating leases for office buildings. Studies show that tenants often request plug loads in the range of 5 to 10 W/ft^2 but, after occupying the building, their actual loads measure at less than 0.6 W/ft^2 (Sheppy et al. 2014). A plug load inventory should be performed to validate the maximum plug load required.

To reduce plug loads, two principal approaches are used:

- Select equipment with lower power demands.
- Control equipment so that it is off when equipment is not being used.

The first step to taking full advantage of the energy reduction potential is to consider a plug load management policy for the building. See PL3 for specific guidance on this.

Plug equipment typically runs at normal operating power during occupied hours and may have the capability to partially power down when not in use. There is potential to further reduce power during occupied hours when offices, cubicles, or other areas are not in use. Stud-

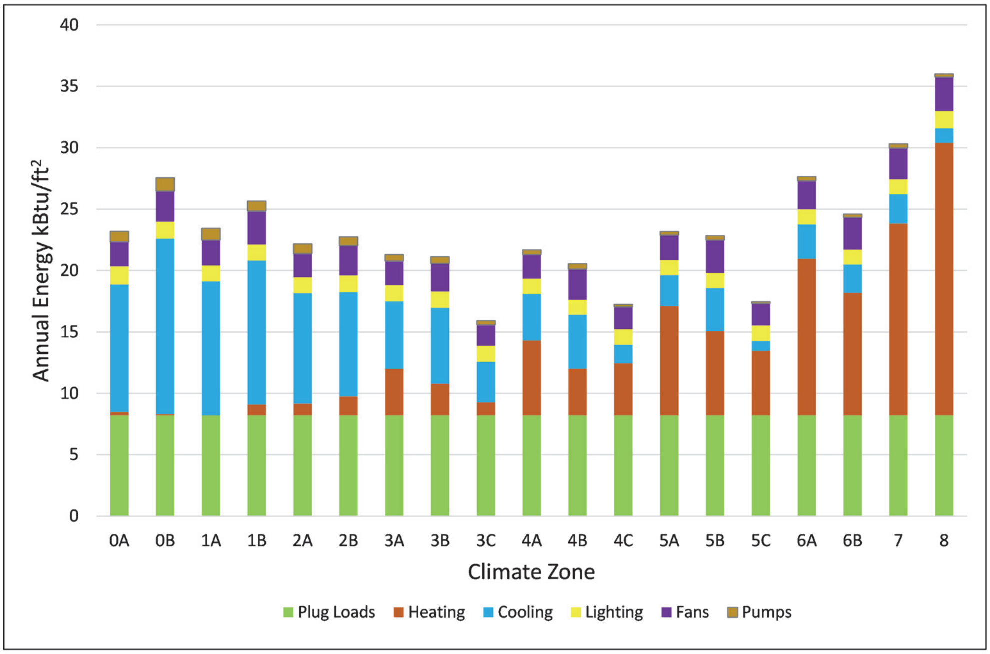

Figure 5-49 (PL1) Climate Zone EUI Breakdown by End Use

ies show that many types of plug load equipment remain on at full or reduced power even during unoccupied periods (Hart et al. 2004; Sanchez et al. 2007).

Modeled analysis across all climate zones shows that plug load equipment is always one of the top three energy uses in a building and therefore should always be one of the primary concerns in design and operations. Figure 5-49 shows that plug load EUIs tend to be constant across all climate zones.

PLUG LOAD MANAGEMENT

PL2 Plug Load Inventory and Reduction Strategies

High-level validation of required plug loads should occur at the outset of a project and include completing a plug load inventory. Performing a thorough plug load inventory and implementing a load reduction strategy could reduce plug loads by 20% to 50% (NEMA 2015).

PPLs can be divided into the following categories and energy reduction strategies focused individually throughout design and occupancy:

- *Work areas* include all electronic loads at individual open and private offices throughout the building as well as in meeting rooms and other collaboration areas. Energy users include laptops, desktop computers and monitors, phones, personal devices, task lighting, device chargers, and TV screens, as well as building-level services such as copiers, printers, copy/print stations, and Wi-Fi routers.
- *Break rooms* include appliances such as microwave ovens, refrigerators, coffee makers, dishwashers, water coolers, ice makers, and sometimes vending machines.
- *Building process loads* consist of centralized building system equipment such as telecommunications servers, routers, and uninterruptible power supplies as well as equipment for fire alarms, security, and digital surveillance. Other loads include building elevators, escalators, and sump pumps. Electrical vehicles and related equipment used within the building, such as forklifts and electric pallet jacks, are also included. Electric vehicle chargers used for cars that leave the site are considered an export of energy.

Successful implementation of energy reduction across PPLs is the responsibility of both the owner and the design team. During design, the design team should identify all equipment that is specified as part of the project that will be plugged in. This varies from project to project but often includes the equipment listed above. The design team should work with the building owner to identify equipment that will meet programmatic requirements and reduce plug loads. This often includes break room equipment, workstation equipment, and process loads.

Plug loads can be controlled either with a management plan requiring human actions or with an automation system that controls the plug load devices. A management plan can be as simple as banning all extraneous devices and achieving buy-in through an education process that explains the rationale for plug load management. Monitoring and reporting of PPL usage can incentivize occupants to reduce plug load usage, as it is part of the zero energy equation that they can directly impact. To ensure that plug loads are shut off, electrical circuits can be designed to turn off at certain times to match periods when the building is not occupied. See PL4 for more information on such controls.

PL3 *Plug and Process Load Management Policy*

Develop a PPL management policy for design and construction of the building. Implement this policy during design so that energy reduction is a key aspect of the selection process of all equipment. Designating an energy champion who evaluates equipment purchases looking for equipment that shuts off or meets requirements, such as ENERGY STAR® rated equipment (EPA 2019b), is valuable in the design process and during the occupancy of the building. During design this person may be a member of the design team; the role may shift to staff during occupancy.

The policy should outline the priority of a zero energy goal and indicate that all equipment selection must go through the energy champion or other review process and must be selected in a way that optimizes the opportunity for reaching zero energy. Selection of all equipment should indicate energy savings with different purchasing choices and options for energy use reductions through optional modes of operation.

When designing the power distribution systems, keep in mind the options and desires of the facility maintenance staff for monitoring and measuring electricity use by floor, department, or group. Seeing the power consumed in a building and being able to translate it into energy costs helps impact user behavior and increase opportunities for savings.

PL4 *Plug Load Controls*

Plug load controls minimize waste energy from devices left on when the user is not present but provide power availability when the equipment is needed. Automated controls are explicitly required by ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2010, 2013, 2016) and by California's Title 24 (CBSC 2016). Specifically, Standard 90.1 requires plug load control of 15 and 20 amp, 120 volt receptacles.

Generally, 50% of the receptacles should be controlled by an automatic shutoff device. Receptacles typically have one outlet that is uncontrolled and one that is controlled. Plug monitors, task lighting, portable appliances, personal fans, and even workstations into the controlled section of the receptacle. Connect computers with automatic sleep mode to the noncontrolled circuit. Devices requiring continuous power such as servers or security equipment are not required to be part of the plug load control system and may be plugged into the uncontrolled section of the receptacle. For most applications, IT equipment should only be powered on when it is needed and turned off when the building is not occupied. Settings available on most ENERGY STAR certified IT equipment can help deploy this option, turning down power when equipment is not being used.

Plug load control devices may consist of time-of-day control, where receptacle circuits are controlled via a contactor relay or other power management device that is in turn controlled through a time-of-day schedule via the building automation system (BAS) or a time clock.

Chapter 5

PL

Controlled receptacles are required to be identified with a permanent, distinct marking to prevent a 24-hour load from being plugged into an interruptible outlet. A popular option is to integrate the plug load controls with the lighting control systems, as many lighting control manufacturers incorporate an option to control local receptacle outlets. Lighting control systems also incorporate occupancy sensors that may be used as a further measure of plug load control in individual spaces. While these solutions can control plug loads, occupant behavior must still be engaged to ensure occupants plug items into the correct type of outlet. The energy champion can help occupants with minimizing plug loads.

> ***Caution:*** The use of smart power strips, even with occupancy sensors built in, does not meet the intent of ASHRAE/IES Standard 90.1 and should not be considered the primary source of plug load control. These devices can be used successfully as a secondary means of plug load control and work well in retrofit applications.

Plug load controllers should turn off devices at specific, programmed times when the building is unoccupied. The program should

- incorporate areas of 5000 ft^2 or less;
- provide manual override for late nights, weekends, and holidays with the provision that the programmed state resumes after a set time of two hours;
- program occupant sensors to turn off power within 10 minutes of occupants leaving a room; and
- turn off devices 10 minutes after an occupant has left a room, as sensed by the lighting control system when the devices are controlled via the lighting control system.

In spaces with local lighting controls and no requirements for 24-hour power, use the lighting controls to provide on/off control of all the receptacles in a room, such as conference rooms and offices. In other spaces, the need for 24-hour power may require lighting controls for the controlled ports of the receptacles and uncontrolled wiring for the 24-hour loads. Consider whether different workplace space types should have any uncontrolled receptacles to allow for flexibility of use. Another wiring option is to use centrally controlled receptacle circuits from the circuit breaker panels; for example, when time-switch controls are used. Uncontrolled receptacle circuits are then run from the panel directly, bypassing the central control system. Dual wiring scenarios are more popular due to the flexibility they offer.

> ***Caution:*** If end-use metering is desired for measuring plug loads and lighting loads separately, care must be taken to not mix lighting and plug load circuits, especially if a lighting controller is used for plug load management.

Plug load control opportunities include the following:

- Smart power strips that sense occupants with radio frequency or a BAS or lighting control interface (no stand-alone power strips—must be plugged into a controlled receptacle port that is controlled by an automatic control system)
- Time switch controls
- Half of switched outlets controlled via an automatic system
- Radio frequency receptacle controls via occupancy sensor or power pack
- Contactor control through BAS
- Compatibility with stand-alone or networked control systems in the building
- Written policies distributed to staff
- Enforcement of plug load management policy
- Signage reminding occupants of the importance of plug load management
- Competitions among employees
- Engagement of building occupants
- Removal of equipment not approved for use
- Removal of obsolete equipment that is energized but not being used

Control equipment so that it is off when not in use. Options include occupancy-sensor-controlled power strips, outlets, or circuits; occupancy-sensor-controlled vending machines; timer switches for equipment that is shared during occupied hours but can be off during unoccupied hours; and power management of computers and other devices, ensuring that sleep modes are fully active. Use of efficient low-voltage transformers and newer power management surge protectors can reduce phantom loads associated with low-voltage equipment (Lobato et al. 2011).

PL5 Occupancy Controls

Occupancy controls should be considered in addition to plug load controls as discussed in PL4. Specifically, occupancy-based control of devices can be used to reduce energy consumption when equipment is not in use. Occupancy-sensor-controlled power strips and timer-enabled power strips can be used to power down monitors and other workstation items, such as fans, chargers, and task lighting (task lighting control is described in detail in EL5). Another approach for enclosed offices is to control selected outlets with a room-based occupancy sensor. This approach can also reduce parasitic losses—small amounts of electricity used by appliances even when the appliances are switched off. Specific education that is ongoing can encourage occupants to plug most of their appliances into the occupancy-controlled plugs and ensure behavior does not change over time, leading to increased loads.

Use timer switches for central equipment that is unused during unoccupied periods but that should be available throughout occupied periods. Example equipment includes water coolers and central coffee makers.

PL6 Monitor Plug Load Usage

All plug loads, typically the 120 V circuits, should be separately metered to display power consumed by each tenant or building section. These can be totaled on a daily or monthly basis to ensure that no power creep is occurring. Power creep occurs when staff adds equipment or when predicted energy use exceeds modeled use. As time goes on, additional equipment may be added, but old equipment must also be retired to keep the plug load within the energy budget.

Plug load consumption monitoring should be part of the energy dashboard monitoring system along with the other major power systems (lighting and HVAC). The monitoring system should display the actual energy consumed, which can be compared with the predicted energy use for each of these systems. Actual energy use should be shared with occupants to educate and enable behavior change. Corrective actions are necessary if the variance between predicted and actual cannot be reconciled by occupancy, hours of use, or other factors affecting energy consumption.

PL7 Parasitic Loads

Reduce and eliminate parasitic loads, which are small amounts of energy usage from equipment that is nominally turned off but still using a trickle of energy. Transformers that provide some electronic devices with low-voltage DC from AC plugs also draw power even when the equipment is off. Transformers are available that are more efficient and have reduced standby losses. Wall-switch control of power strips, noted in PL4 and PL5, cuts off all power to the power strip, eliminating parasitic loads at that power strip when the switch is controlled OFF. Newer power management surge protector outlet devices have low or no parasitic losses (Lobato et al. 2011).

EQUIPMENT SELECTION

PL8 Choose Energy-Efficient Equipment

Purchase plug load devices that have a sleep-mode option. In addition, select IT servers to be scalable to minimize wasted or unused computational capacity. DC-powered servers are commercially available and may be complimentary with a PV power system that also contains battery storage.

Select office equipment and appliances that require low energy usage. ENERGY STAR rated equipment typically has significantly lower operational wattage and may include improved sleep-mode algorithms (EPA 2018). Desktop computers, laptops, printers, fax machines, copy machines, refrigerators, microwave ovens, coffee makers, and dishwashers are typical equipment types used in offices that have ENERGY STAR ratings. Refer to EnergyGuide labels to compare efficiencies of equipment. Note that ENERGY STAR also awards a Most Efficient designation for products that deliver cutting-edge energy efficiency along with the latest technological innovation (EPA 2019a).

Look for efficient equipment even if not rated by ENERGY STAR, such as high-output photocopying machines. Remember that once any energy-efficient equipment is installed, the energy reduction settings must be enabled. Some equipment such as hard drives and printers can also be scheduled through internal software, making it much easier to control and power down when not in use.

> ***Caution:*** Many organizations are minimizing on-site servers for cloud-based computing. While this reduces the energy footprint of the building, it causes servers to be located “in the cloud.” Computing and on-line storage do not come without an energy footprint; however, it is beyond the scope of this Guide to address the energy impact of non-site-located computing.

PL9 Unnecessary Equipment 🔧

The project team should engage end users in a discussion to determine whether there are pieces of equipment that are nice to have but are not fundamental to the core function of the office building and business. For example, large flat-screen TV arrays in lobby areas can be eliminated or at minimum placed on schedulers, and mechanically cooled drinking water can be replaced with filtered tap water.

PL10 Computers and Monitors 🔒 $

Select laptops, docking stations, and monitors with ENERGY STAR ratings. Laptop computers are designed to operate efficiently to extend battery life. Efficient operation includes lower connected power and effective power management. Where possible, avoid desktop computers because they draw more energy than laptops. In addition, computer monitors should be programmed to shut off when not in use. Involve the IT department, or whichever department specifies equipment, with the zero energy goals for the project, as they can support the use of laptops eliminating desktops. In some rare cases, occupants do need the computational power that exists in desktops and exceptions can be made. Typically, computer equipment is refreshed every three to five years, so to minimize costs start a transition during the early design phases of the building, and when the building is ready to be occupied much of the equipment can be replaced through attrition.

Computer power management allows computers to go into minimum energy usage when not active or to turn off during scheduled hours. Purchase individual devices with low power sleep modes, such as ENERGY STAR rated laptops. Activate the power management in devices that do not use these modes in their default setup. Network power management software allows central control for scheduled OFF hours and full activation of available power-saving modes while allowing the network management to turn units on for computer updates and maintenance. An added benefit of laptops is that uninterruptible power supplies, which are very inefficient, are not needed and can be eliminated from workstations.

PL11 Printing Equipment

Consolidate printing services to minimize the number of required devices. One study provides information on a strategy being applied in a new office building to eliminate personal printing devices and consolidate printing services to a smaller number of multifunction devices that reduces connected power and provides anticipated reduction in energy usage (Lobato et al. 2011). Use of multifunction devices that provide printing, copying, and faxing capabilities reduces power demand from multiple devices. The study indicates that printing services from these devices are provided with 1 device per 60 occupants rather than 1 device per 40 occupants, as in the building occupants' old space. As technology changes, this equipment is also changing. Some offices may have fax machines that are plugged in but not used; this equipment can be eliminated, saving energy.

PL12 Audio/Visual Equipment

Conference room use is varied and often sporadic. To ensure that equipment in conference rooms is not drawing power when the rooms are vacant, it is important to implement a control system that will turn off the equipment when the space is unoccupied or when the equipment is not needed for a meeting. Occupancy sensors are an option for controlling the rooms during operating hours and for tying the room equipment to an overall building controls system to allow it to be shut off outside of operating hours. In addition, choose energy-efficient equipment for conference rooms. There are energy-efficient options for screens, projectors, and conferencing phone and video systems (Sheppy et al. 2013).

PL13 Refrigerators

Specify larger, solid-door refrigerators in lieu of multiple mini fridges. All refrigerators should be ENERGY STAR certified and operated at their suggested temperature settings, not at the highest cooling settings, in order to reduce energy use. Ice trays, rather than automatic ice makers, will also save energy (Sheppy et al. 2013).

PL14 Vending Machines

If the break room will include vending machines, they should be equipped with occupancy sensor control for lighting and for cooling operation. ENERGY STAR rated vending machines include this type of control or can be retrofitted with add-on equipment.

PL15 Small Appliances

Select energy-efficient small appliances (such as coffee makers, microwaves, water coolers, dishwashers, and ice makers). These do not have to tie into a building-level controls system, as they are easily controlled with less expensive outlet timers to ensure they are off each night and on the weekends.

BUILDING PROCESS LOADS

PL16 Building-Level Services

Selection of building elevators should include a review of required travel speeds. There might only be a few seconds of travel time difference between the available options, which would be negligible to occupants but could result in large annual energy savings. Consider regenerative traction elevators that often do not need machine rooms or special heating and cooling systems. In addition, ensure elevator cabs are lit with LED lighting and are programmed to shut off the cab lights when the elevators are not in use. HVAC can also be programmed to shut off in cabs when not in use.

Incorporate active design principals, which suggest stairwells be centrally located and easily accessible, which will encourage their use.

Selection of electric car chargers should note load impacts on the building electrical system; these chargers should be selected with the user's charge time in mind to optimize the equipment's use.

PL17 Telecommunications Systems and Computer Infrastructure 🔒 $ 🔧

Energy-reduction strategies in telecommunications design can achieve drastic energy reduction without compromising the goal of telecommunications systems. Mitigate or eliminate equipment runtime during unoccupied hours, as this increases the longevity of the equipment, reduces costs, and helps achieve the zero energy goal. Request power ratings on telephone equipment and shop for equipment that has lower power ratings. If telephones have displays, turn off the displays except during occupied hours or, for more savings, turn off displays except when occupants are using the equipment.

Engage with the telecommunications team during design and reiterate the zero energy goal of the project. Employ strategies such as virtualization of servers, energy-saving settings on PC equipment, and Wi-Fi router shutdown during unoccupied hours—all of which can result in significant energy reduction.

For server closets and small data centers, temper to the specifications on the equipment, which are typically broader than historical temperature set points. In many cases, a closet can be ventilated to the zone without an active cooling system.

POWER DISTRIBUTION SYSTEMS

PL18 Rightsizing Power Distribution Systems 🔒 🔧

In 2014, *National Electrical Code* (*NEC*) included a new provision that allows design engineers to design to a lower general lighting load volt-ampere per area number when a facility is designed to comply with an energy code adopted by the local authority having jurisdiction (NFPA 2014). When using this option, a power monitoring system is required that requires an alarm value be set to alert the building manager whenever the lighting loads exceed the values set by the energy code. When this provision is used, designers may not apply any further demand factors in sizing the lighting infrastructure. This provision does allow new buildings to receive the first-cost benefit of designing to a smaller infrastructure. Lighting loads have fallen rapidly with the advent of lighting controls and LED lighting. In the 2017 *NEC*, a new exception has been added to allow a further reduction in lighting load unit loads of 1 VA/ft^2 under certain conditions (NFPA 2017).

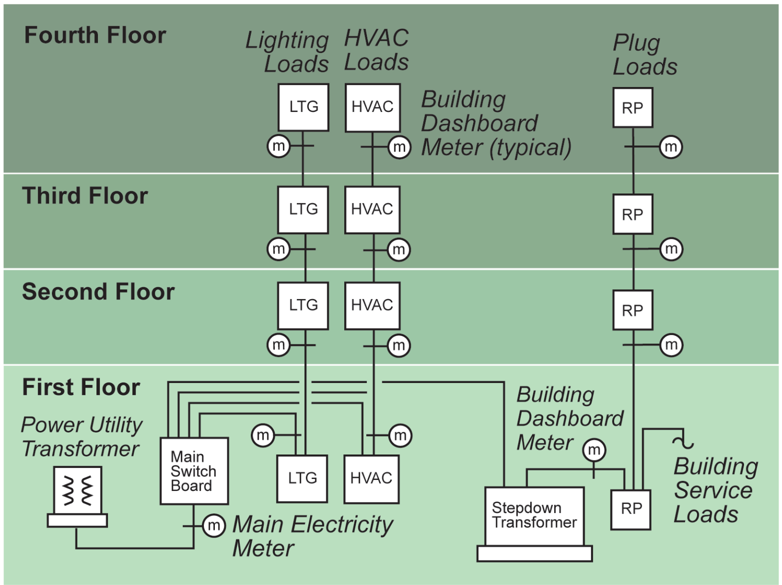

Figure 5-50 (PL18) Typical Power Distribution for a Medium Office

Most small and medium office buildings are anticipated to use 120/208 V power distribution systems. It should be noted that where 277/480 V systems are needed and a secondary transformer is used to step down the power from the higher voltage to the plug load voltage for receptacles, computers, and other devices that function at 120 V, transformers fall under DOE minimum efficiency rules (DOE n.d.). The DOE efficiency standards apply at a single 35% load point, a common demand load point for transformers. However, this may still result in oversized transformers and higher than desirable losses due to lower efficiencies at light loads. When designing power distribution systems for larger offices, the step-down transformers for plug loads should be sized as closely as possible within the *NEC* requirements (NFPA 2017). When they are more heavily loaded, transformers operate more efficiently. Transformers should be specified to have a load loss profile that is higher under light loads to reduce energy losses. DOE transformer efficiencies (GPO 2016) will result in transformers with losses of only 1.6% to 1.26% (45 to 112.5 kVA). Therefore, the use of a high-efficiency transformer, operated close to its capacity in accordance with local electrical codes, will minimize energy losses in a zero energy office. The use of 100% rated devices on main services and large feeders may also help to reduce line losses. Transformers should be located so that they serve multiple electrical panelboards. Electrical closets should be stacked in order to reduce voltage drop. Lower temperature rise ratings and specialty transformers offering 30% to 50% reduction in losses may further reduce energy consumption due to transformer losses. Additionally, many designers add in a 20% to 25% “spare capacity” allowance to their plug load transformer sizing calculations. This may be eliminated to reduce oversizing, since the *NEC* minimum demand sizing requirements will result in a transformer oversized for the actual demand load (NFPA 2017). Engineers should study the usage patterns proposed for the office building and design accordingly. Transformer losses are an important part of the energy consumption of a building and must be included in the energy modeling and be within the overall energy target of the building.

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SERVICE WATER HEATING

OVERVIEW

Water-heating requirements for office buildings typically fall into the general category of distributed low-consumption fixtures, including hand-washing and break-room sinks, and small undercounter dishwashers. Some buildings may include showers, either for bicycle commuters or for operating staff. The first step for determining service water heating (SWH) strategies is to develop an inventory of service water end-use applications in the facility. The second step is to establish the frequency of use and flow requirements for these end uses. With that programmatic information the appropriate strategy for each end use can be identified. Energy-efficiency strategies for these applications should emphasize both the efficiency of generation of hot water and the minimization of energy losses in delivering the hot water to its end use. In general, the distributed end uses should be served by simple local hot-water generators to avoid the need for pumped loops to ensure quick availability.

WH1 System Descriptions

Several different types of water-heating systems are used in office buildings. System selection depends on fuel availability, fuel cost differentials at the location, and the magnitude of the loads to be served. The ENERGY STAR rating system (EPA 2019) designates water heaters as either residential or commercial depending upon nominal energy input and water storage capacity. Depending on end use and size, the water heaters discussed in this Guide may fall into either of these two categories. Systems considered in this Guide are as follows.

Gas-fired storage water heater. This system consists of a water heater with a vertical or horizontal water storage tank. A thermostat controls the delivery of gas to the heater's burner. The heater requires a vent to exhaust the combustion products. An electronic ignition is recommended to avoid the energy losses from a standing pilot light.

Gas-fired instantaneous water heater. This system consists of a water heater with minimal water storage capacity. Such heaters require vents to exhaust the combustion products. An electronic ignition is recommended to avoid the energy losses from a standing pilot light. Instantaneous, point-of-use water heaters should provide water at a constant temperature regardless of input water temperature or flow rate.

Electric-resistance storage water heater. This system consists of a water heater that has a vertical or horizontal storage tank with one or more immersion heating elements. Thermostats controlling heating elements may be of the immersion or surface-mounted type. Electric-resistance water heaters are not included in the ENERGY STAR rating system.

Electric-resistance instantaneous water heater. This system consists of a compact under-cabinet or wall-mounted water heater with an insulated enclosure and minimal water storage capacity. A thermostat controls the heating element, which may be of the immersion or surface-mounted type. Instantaneous, point-of-use water heaters should provide water at a constant temperature regardless of input water temperature or flow rate.

> ***Caution:*** Electric-resistance instantaneous water heaters can save energy for small loads, such as restroom sinks, but larger systems should be avoided, as they may add to electrical demand charges if they operate coincidently with the peak load of the rest of the building.

Heat pump electric water heater. This system is a storage-type water heater using rejected heat from a heat pump as the heat source. Water storage is required because the heat pump is typically not sized for the instantaneous peak demand for service hot water. The heat source for the heat pump may be the interior air (within the kitchen or nearby data closet is ideal because of the internal heat gain in those spaces), which is beneficial in cooling-predominant climates; the circulating loop for a water-source heat pump (WSHP) system, also beneficial in cooling-dominated climates; or a ground-coupled hydronic loop. Analysis of this water heater type should include incorporation of energy consumption due to heat loss through hot (but insulated) piping and the recirculation pump. These types of water heaters should be considered as alternatives to electric-resistance tank-type water heaters. Heat pump water heaters should have an energy factor (EF) of at least 2.2. Currently, commercial (large heating-capacity and/or storage-capacity) heat pump water heaters are not included in the ENERGY STAR program.

Where electricity is the preferred energy source for SWH, consider specifying a heat pump water heater, meeting the ENERGY STAR criteria for residential heat pump water heaters, for additional energy savings. Products now available using carbon dioxide (CO_2) as a refrigerant have demonstrated much higher coefficients of performance (COPs) than systems using more common refrigerants, but even residential-size versions of these products do not yet have an ENERGY STAR rating, as the official test procedures for the products have not been finalized.

> ***Caution:*** Use of heat pump water heaters may not be ideal in climate zones 7 and 8. If the evaporator units are located outdoors, extremely cold conditions may prevent the units from developing the required temperature in the heated service hot water. Location of the evaporator units indoors would actually be removing heat from the occupied space that, in the wintertime, had been added to the space by the heating system to maintain comfort, resulting in greater energy consumption than using the same heating source for both space heating and SWH.

DESIGN STRATEGIES

WH2 *Reduce Overall Water Consumption*

The first step to reducing the energy consumption of the SWH system in an office is to reduce the demand for hot water. The simplest step to achieving this is to specify low-flow hand-washing and break-room sinks and showerheads, if used. These fixtures should comply with the criteria in EPA's WaterSense program (EPA n.d.). Break-room dishwashers should meet the ENERGY STAR criteria shown in Table 5-15. Once hot-water usage has been minimized, the efficiency of the systems and equipment that provide the hot water can be addressed.

WH3 *Properly Size Equipment*

The water-heating system should be sized to meet the anticipated peak hot-water load. In office buildings, hot-water loads are usually limited to low-flow distributed fixtures. Calculate the demand for each water heater based on the fixture units served by the heater according to local code.

Hot-water temperature requirements vary by local and state code within the range of 100°F to 120°F. If showers are included in the project, the temperature of the hot water provided should be 100°F to 110°F. Note that the American Society of Plumbing Engineers (ASPE) Research Foundation recommends that storage-tank water heaters maintain a water temperature of no less than 135°F to prevent bacterial growth in the storage tank (ASPE 1988), so end uses with lower temperature requirements should be served from a storage-type heater with a thermostatic mixing valve.

In designing and evaluating the most energy-efficient hot-water system and its associated life-cycle costs for an office building, consider installing small, local water heaters in most locations. Only in areas where large volumes of hot water are required (which is not within the scope of this Guide) should large water-heater systems be installed.

WH4 *Equipment Efficiency*

Water-heating equipment fuel source and efficiency should recognize the impacts of site/source energy multipliers, both regionally and nationally. While the site/source multipliers for electricity are greater than those of fossil fuels for almost all regions, in some applications, use of electric-resistance water heating in a manner that avoids recirculation pump energy consumption and heat loss through extensive piping will result in less source energy consumption than centralized water-heating systems that use a more efficient heating source.

Efficiency levels are provided in this Guide for gas-fired storage, gas-fired instantaneous, electric-resistance storage, and electric-resistance instantaneous water heaters and electric heat pump water heaters. ENERGY STAR divides water heaters into residential and commercial classifications and provides specifications for gas heaters and electric heat pump heaters; it no longer lists electric-resistance heaters. Unfortunately, heat-pump-type water heaters are available only in larger tank sizes and may not be appropriate for small, distributed end uses.

Table 5-15 (WH2) ENERGY STAR Criteria for Dishwashers

Equipment	Corresponding Base Specification	High-Temperature Efficiency Requirements per CEE (2008)		High-Temperature Efficiency Requirements*	
		Idle Energy Use**	Water Consumption	Idle Energy Use**	Water Consumption
Undercounter	ENERGY STAR	≤0.90 kW	≤1.00 gal/rack	≤0.50 kW	≤1.70 gal/rack

*Machines designed to be interchangeable in the field from high temperature to low temperature and vice versa must meet both the high-temperature and low-temperature requirements to qualify.
**Idle energy rate as measured with the door closed and rounded to two significant digits.

The small tank-type water heaters recommended for small distributed end uses have historically been classified as residential water heaters and are typically rated for the uniform energy factor (UEF) that reflects the ratio of the heat added to the delivered hot water to the total thermal input to the heater over a prescribed schedule of hot-water delivery.

Commercial tank-type water heaters, suggested for larger, central end uses, and which likely have far different schedules of hot-water delivery, are currently rated by thermal efficiency (E_t) and standby heat loss. Standby heat losses are dependent upon tank volume and configuration in addition to jacket insulation value and are typically established by a standardized testing procedure.

For commercial gas-fired storage water heaters, the standby loss criteria is given by the following equation:

$$\text{Standby loss (Btu/h)} \le 0.84 \cdot (\text{Input rate (Btu/h)}/800) + 110 \cdot \sqrt{}\text{Volume (gal)}$$

For gas-fired instantaneous water heaters, the EF and E_t levels are nearly the same because there are no standby losses. The incorporation of condensing technology is recommended for all gas-fired water heaters to achieve a minimum E_t of 94%. For multistory office buildings, incorporation of gas-fired instantaneous water heaters may be problematic because of flue and combustion air requirements.

Table 5-16 gives performance requirements for residential and commercial gas-fired water heaters of various capacities and sizes. These requirements are derived from a variety of sources, including ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2016), the ENERGY STAR program (EPA 2019), and IgCC/189.1 (ICC 2018). Performance values are given for a low draw pattern (38 gal/day).

The levels of performance specified in this Guide for gas water heaters require that the units be of the condensing type, not only recovering more sensible heat from the products of combustion but also recovering heat by condensing moisture from these gases. The construction of a condensing water heater as well as the water heater venting must be compatible with the acidic nature of the condensate for safety reasons. Disposal of the condensate should be done in a manner compatible with local building codes.

Efficiency metrics for residential and commercial high-efficiency electric storage water heaters are also provided in this Guide. These efficiency metrics represent premium products that have reduced standby losses but that are no longer rated by the ENERGY STAR program. Table 5-17 summarizes required EFs for residential electric-resistance water heaters and thermal

Table 5-16 (WH4) Gas Water Heater Performance

Storage Volume, gal	Capacity, kBtu/h	UEF (Residential)	E_t % (Commercial)	Standby Loss, Btu/h (Commercial)
0.0	Varies	0.87	0.94	N/A
55.0	70	0.68	N/A	N/A
55.1	75	0.80	N/A	N/A
140	75	N/A	0.94	1380

Table 5-17 (WH4) Electric Resistance Water Heater Performance

Storage Volume, gal	UEF (Residential)	E_t , % (Commercial)	Standby Loss, %/h (Commercial)
0.0	0.98	0.98	N/A
30	0.9164	0.98	1.2
40	0.9134	0.98	0.98

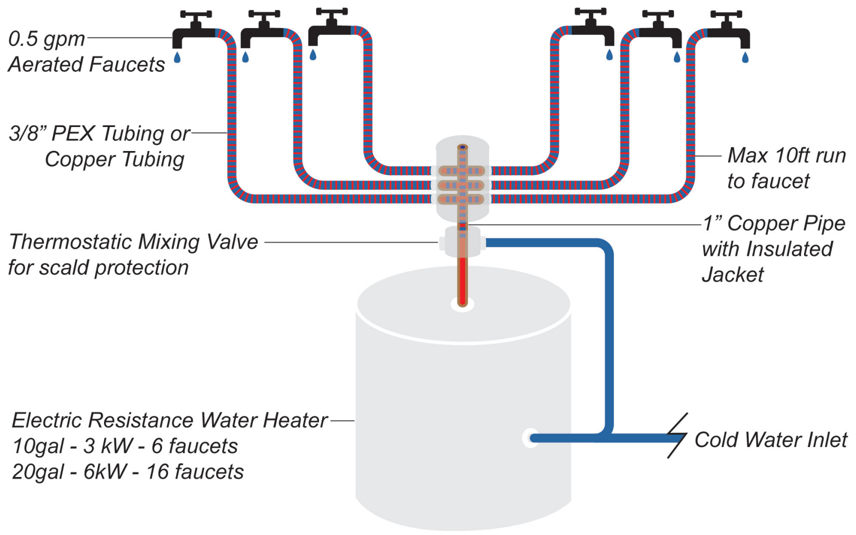

Figure 5-51 (WH4) Hot-Water Service for Bank of Hand-Washing Sinks with Local Point-of-Use Water Heater

efficiency and standby loss limits for commercial electric-resistance water heaters, according to IgCC/189.1 (ICC 2018). Because these heaters are recommended only for small, distributed loads, performance ratings are given only for smaller-sized units. Standby losses for electric storage water heaters are calculated in the same way as for gas-storage-type water heaters.

Electric instantaneous water heaters are a more efficient alternative to high-efficiency storage water heaters for very-low-volume distributed end uses because they have no tank losses. In addition, they can be located near the end use, minimizing pipe losses. However, their impact on the first cost of electrical distribution may be significant and should be taken into account during design. For a bank of hand-washing sinks in a large restroom, an electric-resistance heater with a small tank (20 gal) would require a much less extensive electrical distribution approach than would providing an instantaneous electric-resistance heater for each sink. A schematic of a proposed layout for serving a bank of hand-washing sinks in a public restroom is shown in Figure 5-51. Note that the home-run piping feeds to the individual faucets are smaller than typical practice. Because they are short, the pressure drop is inconsequential, but the higher fluid velocity entailed by the reduced piping diameter decreases the period of time for water to flow from the heater to the fixture.

Where unusually high hot-water loads (e.g., dishwashers) are present during periods of peak electrical use, electric heat pump storage water heaters are recommended over electric instantaneous water heaters. Current ENERGY STAR standards require heat pumps for all electric water heaters. Table 5-18 shows ENERGY STAR performance requirements for residential heat-pump-type water heaters. Requirements for commercial heat pump water heaters have not yet be determined, but products are available on the market that deliver EFs higher than 3.0. For electric water heaters serving substantial water-heating loads, this Guide recommends using a product with the highest EF available for a competitive price.

WH5 Minimizing System Losses

Office SWH requirements most often consist of low-volume distributed end uses, such as hand-washing and break-room sinks. As stated previously, the most important strategy for reducing hot-water consumption is to provide water-efficient fixtures. Aerated proximity faucets are available with rated flow rates as low as 0.35 gpm. These faucets not only have the benefit of very low flow rates but also initiate and curtail flow in response to the proximity of the object to be washed (hands, etc.).

Table 5-18 (WH4) Heat Pump Water Heater Performance Requirements

Storage Volume, gal	UEF (Residential) ENERGY STAR	UEF Recommended
≤55	2.0	3.0
>55	2.20	3.0

Table 5-19 (WH5) Parameters for Recirculation Pump Loss Calculation

Faucet Flow	0.5	gpm
Faucet Hot-Water Fraction	35%	
Faucet Hot-Water Flow	0.175	gpm
Faucets	6	#/pump
Usage Duration	30	seconds
Faucets per Pump	6	
Faucet Utilization	20	uses/hour
Pipe Distance	200	feet

The second most important strategy for reducing hot-water consumption in office buildings is to eliminate the heat loss from pumped circulating loops that are required to minimize hot-water latency (the period of time it takes to get hot water after a faucet is opened). Pumped loops are required when the source of the hot water is remote from the hot-water end use. Potential locations for gas-fired water heaters adjacent to office-building end uses such as hand-washing sinks may be limited by flue and combustion air and local code requirements. Based on the calculation parameters shown in Table 5-19, the energy consumed by the recirculation pump and required to offset heat losses through the circulation piping is as much as the energy required to heat the service hot water required by the faucets.

Low-volume end uses, including hand-washing sinks, janitorial closets, and implement-washing sinks in food preparation areas, likely do not justify service from a central source with required recirculation and should be served with point-of-use water heaters, either instantaneous heaters for single fixtures or small tank-type heaters for groupings of fixtures.

All hot-water piping should be insulated at least to the requirements of ASHRAE/IES Standard 90.1 (ASHRAE 2016), no matter the requirements of the local energy code.

WH6 Renewable and Heat-Recovery Service Hot Water Sources

While solar thermal water heating and various types of heat recovery water heating are appropriate for occupancies with large, centralized SWH loads, they are difficult to accommodate to the small, distributed end-uses that characterize office buildings. The recirculation pump energy required by the central location of the water heater might exceed the energy consumption required to generate the service hot water for these small end uses, such that even if the heat source is “free” the net energy savings may be small or negative and the capital cost could be excessive.

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HVAC SYSTEMS AND EQUIPMENT

OVERVIEW

The design challenge of a zero energy HVAC system is maximizing energy efficiency. The lower the operating EUI of the building is, the lower the amount of renewable energy required to achieve zero energy is, which reduces first cost. Therefore, strategies must be developed to address energy consumption with respect to cooling generation, heating generation, air distribution fan energy, water recirculation pump energy, and outdoor air ventilation energy.

HV1 System Descriptions

Several different types of HVAC systems are used in office buildings. System selection depends on building configuration, owner preference, zone configuration, and the magnitude of the loads to be served. Several system types small office buildings are discussed in this Guide. While many systems can be considered for all the different climate zones, the systems recommended in this Guide are common and readily available, in order to encourage zero energy adoption for a larger audience of building owners. It is important to recognize that zero energy is achievable with commonly available system types. Systems considered in this Guide are as follows:

- System A—Rooftop Multizone Variable Air Volume (VAV) with Hydronic Heating (Small Office Only)
- System B –Air-Source Variable Refrigerant Flow (VRF) Heat Pump with Dedicated Outdoor Air System (DOAS)
- System C—Ground-Source Heat Pump (GSHP) with DOAS
- System D—Sensible Cooling Chilled-Water Fan-Coils with DOAS

Details on each system are provided in this Guide, along with specific recommendations for each system type. Overall tips for all system types are also present. Table 5-20 shows minimum recommendations for efficiency and requirements for all system types. Tables 5-21 through 5-23 show primary and secondary cooling and heating sources.

SYSTEM A—ROOFTOP MULTIZONE VAV WITH HYDRONIC HEATING (SMALL OFFICE ONLY)

HV2 Description—System A

In this system, a packaged direct-expansion (DX) rooftop unit serves several individually controlled zones. Each thermal zone has a VAV terminal unit that is controlled to maintain temperature in that zone. See Figure 5-52 for a typical configuration of this system. The components of the rooftop unit are factory designed and assembled and include outdoor air and return air dampers, filters, fans, an air-to-air exhaust energy recovery exchanger, a cooling coil, an optional heating source, compressors, a condenser, and controls. The components of the VAV terminal units are also factory designed and assembled and include an airflow-modulation device, controls, and possibly a heating coil, fan, or filter. To achieve the best energy and cost

Table 5-20 (HV1) Minimum Efficiency Recommendations by System Type

System A—Rooftop Multizone VAV with Hydronic Heating	
Air-cooled rooftop efficiency[a]	≥18 IEER
Compressor capacity control	Variable-speed drive (VSD) compressor Minimum turndown ≤20% of compressor capacity
Supply fan	Minimum turndown ≤30% of design flow
Exhaust energy recovery[a]	Humid (A) zones and marine (C) zones: 72% enthalpy reduction Dry (B) zones: 72% dry-bulb temperature reduction
Gas heat	Gas heat AFUE > 80%, modulating
Boiler efficiency (where supplemental hydronic heating is used)	Condensing boiler, >92% efficiency
Water circulation pumps	VSD and NEMA premium efficiency <12 W/gpm at design
System B—Air-Source VRF Heat Pump System with DOAS	
Ducted air-cooled VRF multisplit with heat recovery (cooling mode)	<65,000 Btu/h; 15.0 SEER; 12.5 EER[b]
	>65,000 Btu/h and <135,000 Btu/h; 11.1 EER; 14.4 IEER[b]
	>135,000 Btu/h and <240,000 Btu/h; 10.7 EER; 13.7 IEER[b]
	<240,000 Btu/h; 10.1 EER; 12.5 IEER[b]
Ducted air-cooled VRF multisplit with heat recovery (heating mode)	<65,000 Btu/h; 8.5 HSPF[b]
	>65,000 Btu/h and <135,000 Btu/h; 3.4 COP[b]
	>135,000 Btu/h and < 240,000 Btu/h; 3.2 COP[b]
Terminal fan	ECM <0.38 W/cfm at design
Boiler efficiency (where supplemental hydronic heating is used)	Condensing boiler, >92% efficiency
Water circulation pumps (where supplemental hydronic heating is used)	VSD and NEMA premium efficiency <12 W/gpm at design
System C—GSHP System with DOAS	
GSHP cooling efficiency[c]	>18.0 EER at 59°F entering water temperature
GSHP heating efficiency[c]	>3.7 COP at 50°F entering water temperature
Terminal fan	ECM <0.38 W/cfm at design
Compressor capacity control	VSD compressor
Water circulation pumps	VSD and NEMA premium efficiency <20 W/gpm at design
Cooling tower/fluid cooler (for hybrid systems)	VSD on fans
Boiler efficiency (for hybrid systems)	Condensing boiler, >92% efficiency
System D—Sensible Cooling Chilled-Water Fan-Coils with DOAS	
Air-cooled chiller efficiency	Meet or exceed ASHRAE/IES Standard 90.1 (ASHRAE 2016b) requirements
	<150 tons; 10.1 EER; 13.7 IPLV @ AHRI conditions
	<150 tons; 12.2 EER; 15.5 NPLV @ 55°F chilled water temperature
Compressor capacity control	VSD compressor
Water circulation pumps—cooling	VSD and NEMA premium efficiency <16 W/gpm at design
Water circulation pumps—heating	VSD and NEMA premium efficiency <12 W/gpm at design
Terminal fan	ECM <0.38 W/cfm at design
Boiler efficiency	Condensing boiler, >92% efficiency

Table 5-20 (HV1) Minimum Efficiency Recommendations by System Type *(Continued)*

DOAS Used with Systems B, C, and D	
Air-cooled direct-expansion (DX) efficiency	>5.2 ISMRE @ AHRI conditions
Compressor capacity control	VSD compressor Minimum turndown ≤20% of compressor capacity
Supply fan	Minimum turndown ≤30% of design flow
Exhaust energy recovery[a]	Humid (A) zones and marine (C) zones: 72% enthalpy reduction Dry (B) zones: 72% dry-bulb temperature reduction
DX heat pump	>3.8 ISCOP @ AHRI conditions
Gas heat	Gas heat AFUE >80%, modulating
Boiler efficiency (see Table 5-26)	Condensing boiler, >92% efficiency
Water circulation pumps	VSD and NEMA premium efficiency <12 W/gpm at design

a. Minimum recommended levels per Air-Conditioning, Heating, and Refrigeration Institute (AHRI) standards.
b. Minimum recommended levels.
c. Minimum recommended levels per International Organization for Standardization (ISO) standards.

savings, we recommend this system for single-story floor plans with short duct runs. Multiple-story buildings, or those that have long duct runs, may better benefit from alternative systems presented in this Guide to achieve the best energy efficiency.

VAV terminal units are typically installed in the ceiling plenum above the occupied space or adjacent corridor. However, the equipment should be located to meet the acoustical goals of the space; fan power, ducting, and wiring should be minimized.

All the VAV terminal units served by each rooftop unit are connected to a common air distribution system (see Figure 5-52). Cooling is provided by the centralized rooftop unit. Heating is provided by a hydronic convection heater in each space.

The cooling equipment, heating equipment, and fans should meet or exceed the efficiency levels listed in Table 5-20. In climate zones 7 and 8, use condensing furnaces that have at least a 90% efficiency level as required by ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2016b) to provide morning warm-up. Requirements for hydronic zone heating are shown in Table 5-21. For systems using gas-fired boilers, condensing boilers should be used.

For packaged VAV DX systems, fan power is usually incorporated into the integrated energy efficiency ratio (IEER) calculation. To achieve the required level of energy efficiency, air supply and delivery systems for packaged VAV units should be designed to require no more than 2.0 in. w.c. external static pressure (ESP), should include static pressure reset in accordance with ASHRAE Guideline 36 (ASHRAE 2018c), and should include variable-speed drives (VSDs) or other features that result in improved part-load performance. A reduced design supply air temperature (SAT) of 50°F is used to lower system airflow and the resultant pressure drop. During periods when the outdoor air dew-point temperature is below 55°F, the SAT may be raised as high as is consistent with meeting space sensible load with the maximum allowable airflow in order to enhance economizer operation.

Units will have air-side economizers in all climate zones except climate zone 1, with control based on either dry-bulb temperature sensors or enthalpy sensors. See the recommendations in Table 5-29 for the control requirements in each climate zone.

Units will have exhaust energy recovery in all climate zones except climate zone 3C. Exhaust energy recovery should be incorporated into the VAV unit and should not prevent or limit air-side economizing. Units with energy recovery should have exhaust fans and avoid the use of return fans; using return fans with a system with exhaust air energy recovery greatly increases fan energy. For the amount of outdoor air required for office spaces, heat at the central unit is not needed with the exception of morning warm-up in cold climate zones. All the

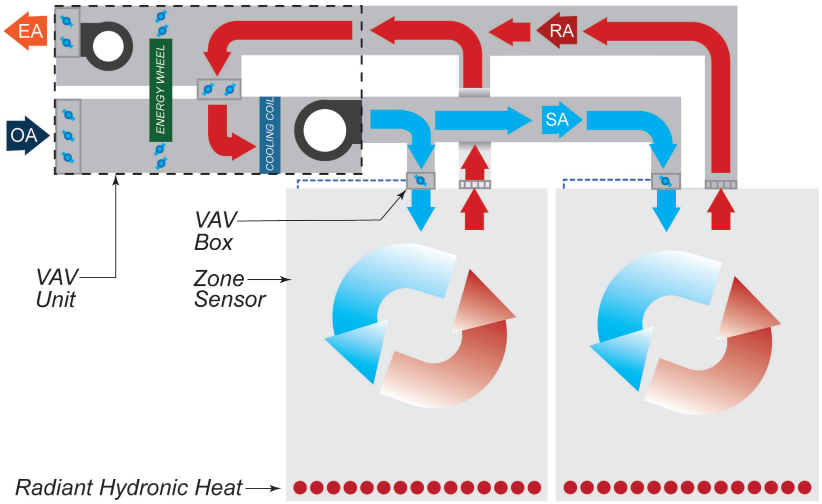

Figure 5-52 (**HV2**) **System A—Rooftop Multizone VAV with Hydronic Heating**

heat required during normal operation at the central rooftop unit can be recovered from the exhaust air with systems using energy recovery. The exhaust recovery exchanger should have means to reduce heat recovery to prevent overheating of the air. Energy-recovery-disabling controls should follow the economizer logic shown in Table 5-29. According to ANSI/ASHRAE Standard 62.1 (2016d), energy recovery can be ramped up until the mixed air temperature rises to the SAT set point if mixed return air and outdoor air fall below the supply air set point at any time while outdoor air is at minimum flow. To prevent overheating of outdoor air and recooling of mixed air, incorporate the energy recovery into the rooftop unit instead of a separate energy recovery ventilator. For systems that must use a separate piece of equipment to recover the exhaust energy, the BAS must interlock the energy recovery equipment with the VAV unit to prevent overheating and recooling of the air.

Zones that need additional heat should use hydronic heat in the zone. This heat is by either hydronic radiant heat or by a hydronic heating coil in the zone's VAV terminal unit. To minimize the likelihood of cooling and reheating, like zones should be grouped together. Internal zones and perimeter zones being served by the same unit should be avoided. In smaller offices it may be advantageous to use single-zone air-handling units (AHUs); these applications heat at the central unit.

For VAV systems, the minimum supply airflow to a zone must comply with local codes and the current editions of ASHRAE Standard 62.1 (for minimum outdoor airflow) and ASHRAE/IES Standard 90.1 (for minimum turndown before reheat is activated).

Ventilation optimization, a combination of zone demand-controlled ventilation (DCV) and system ventilation reset using the provisions of ASHRAE Standard 62.1, reduces outdoor air during operation (see HV25).

SYSTEM B—AIR-SOURCE VRF HEAT PUMP WITH DOAS

HV3 Overview—System B

This system is composed of a fan-coil in each thermal zone with air-source heat pump and heat recovery units located outside the occupied space. It is also called a *variable refrigerant flow (VRF)* system. This type of equipment is available in preestablished increments of capacity. The components are factory assembled and include a filter, fan, refrigerant-to-air heat exchanger, compressor, and controls. A system example is shown in Figure 5-53. Table 5-22 indicates the primary and secondary stages of heating for each of the climate zones with a DOAS and VRF system.

Table 5-21 (HV2) Recommendations for System A—Rooftop Multizone VAV System

CZ	System Designation	Central Equipment	
		VAV Rooftop Unit, Single Zone	VAV Rooftop Unit with Hydronic Heat
1	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Optional gas heat	Optional zone hydronic heat
2	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Optional gas heat	Optional zone hydronic heat
3	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery (not required in CZ 3C)	Exhaust energy recovery (not required in CZ 3C)
	Second-stage heating source	Gas heat	Zone hydronic heat
4	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Gas heat	Zone hydronic heat
5	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Gas heat	Zone hydronic heat
6	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Gas heat	Zone hydronic heat
7	Primary mechanical cooling source	Air-source DX	Air-source DX
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Gas heat	Zone hydronic heat + optional unit hydronic heat
8	Primary mechanical cooling source	Mechanical cooling not required; air-source DX if used	Mechanical cooling not required; air-source DX if used
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Gas heat	Zone hydronic heat + optional unit hydronic heat

Attributes that distinguish VRF from other DX system types are multiple indoor units connected to a common outdoor unit to achieve scalability, variable capacity, distributed control, and recovered-heat simultaneous heating and cooling (ASHRAE 2016a). The advantage is the ability to have individual zone control while also being able to transfer energy from one indoor space to another when both zones are on the same outdoor unit.

Terminal units are typically installed in each conditioned space, in the ceiling plenum within the space. However, the equipment should be located to meet the acoustical goals of the space, permit access for maintenance, and minimize fan power, ducting, and wiring. Consideration should also be given to any future modifications to the space. Piping supplying the terminal unit in the space will be refrigerant piping and will need trained technicians to reroute should any space reconfigurations require HVAC changes.

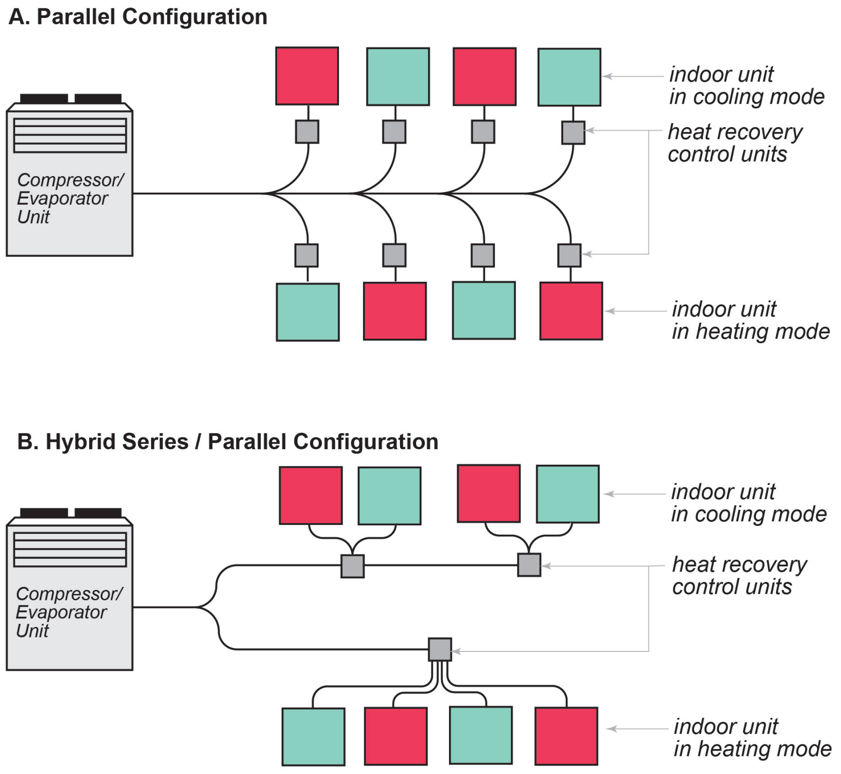

Figure 5-53 (HV3) **Heat Recovery VRF System Examples**

Adapted from Figure 4, Chapter 18, ASHRAE 2016a

Outdoor air for ventilation is conditioned and delivered by a separate DOAS. This may involve ducting the outdoor air directly to each occupied space. Depending on the climate, the dedicated outdoor unit may include components to filter, cool, heat, dehumidify, and/or humidify the outdoor air.

HV4 Sizing Indoor with Outdoor Units—System B

Outdoor units are sized based on the higher of the peak cooling load or the peak heating load. A consideration for supplemental heating is needed in climate zones where the outdoor ambient heating design temperature is below –4°F and needs to be included in the sizing of the outdoor condenser systems. Derating of the outdoor systems also needs to be taken into account on both heating and cooling sizes (ASHRAE 2016a). VSDs are highly recommended for at least one compressor on the outdoor unit. This will help with capacity control throughout the operating range of the equipment.

Indoor units are selected based on the design considerations for the space, which are primarily based on the sound considerations of the space. Sizing for indoor units takes into account the peak heating and cooling loads in the space as well as the ratio of the sensible to latent cooling load. Ventilation requirements and plans affect the sizing of the indoor unit; if cooler air is supplied to the space, this allows the indoor unit to focus primarily on the sensible cooling load (ASHRAE 2016a).

HV5 Refrigerant Safety—System B

All systems need to comply with ANSI/ASHRAE Standard 15 (ASHRAE 2016c) to provide safeguards to protect occupants from the dangers of leaked refrigerants. This requires that the smallest space in which any indoor unit or piping is located has the ability to safely

Table 5-22 (HV3) Recommendations for Zone Terminal Systems with DOAS

CZ	System Designation	System B—Air-Source VRF
1	Primary cooling source	Air-source DX
	First-stage heating source	Air-source DX
	Second-stage heating source	Not Required
2	Primary cooling source	Air-source DX
	First-stage heating source	Air-source DX
	Second-stage heating source	Not Required
3	Primary cooling source	Air-source DX
	First-stage heating source	Air-source DX
	Second-stage heating source	Not Required
4	Primary cooling source	Air-source DX
	First-stage heating source	Air-source DX
	Second-stage heating source	Optional perimeter-zone hydronic heat (radiant, convective in space)
5	Primary cooling source	Air-source DX
	First-stage heating source	Air-source DX
	Second-stage heating source	Perimeter-zone hydronic heat (radiant, convective in space)
6	Primary cooling source	Air-source DX
	First-stage heating source	Air-source DX
	Second-stage heating source	Perimeter-zone hydronic heat (radiant, convective in space)
7	Primary cooling source	N/A
	First-stage heating source	N/A
	Second-stage heating source	N/A
8	Primary cooling source	N/A
	First-stage heating source	N/A
	Second-stage heating source	N/A

disperse the entire refrigerant charge of the VRF system in the event of a leak or failure. Typical spaces that should be examined include restrooms, electrical rooms, closets, small offices, and egress spaces. As the engineer of record reviews the refrigerant safety applications for the equipment, they may make considerations of layout, condenser type, and efficiency to minimize the potential risk in small spaces.

Many options are available to address this requirement. Some spaces can be served by simple outdoor air ventilation. Multiple smaller spaces can be served by a single indoor unit, increasing the conditioned space under consideration. Multiple smaller spaces can be served by a single indoor unit, increasing the conditioned space under consideration by opening a smaller occupied space to an adjacent space that has a larger volume using a permanent opening. Details on compliance with ASHRAE Standard 15 are outside the scope of this Guide; however, additional guidance and references should be considered, including "Applying VRF? Don't Overlook Standard 15" (Duda 2012).

Long piping runs in this system can occur when design for minimizing pipe runs and heights is not taken into account. The advantage of several different outdoor condensers paired to several indoor systems should be used to minimize piping lengths and heights to reduce the amount of refrigerant within the system and ultimately the first cost of the system.

HV6 Ambient Condition Considerations—System B

It is important to note that in heating-dominated climate zones, the capacity of outdoor air-source condensers is decreased in cooler temperatures. Condensers are rated at about 60% capacity at –4°F (ASHRAE 2016a). Thus, systems requiring heat below 40°F design ambient conditions may need to include design considerations for low ambient conditions. This could mean including low ambient kits or baffles or locating the system in an enclosed space such as a parking garage or equipment room to ensure the condenser can provide enough heating during low ambient conditions. Furthermore, climates with operating temperatures below 0°F definitely need low ambient design considerations or a backup heating system. This would likely be electric resistance heating for simplicity of cost and controls. Low ambient design considerations should be implemented so as to not impact the cooling design conditions of the air-source condenser. That is, the air-source condenser needs unrestricted airflow in cooling mode.

During some temperature and humidity conditions, outdoor air-source condensers can accumulate frost. Defrost cycles are available and are manufacturer dependent. Without defrosting, the condenser will not have enough airflow over the condenser coil surface and will not perform as designed. Some systems, upon sensing frost, will reverse the refrigerant flow to heat the condenser for a period of time. Whether installing the system indoors or using a defrost cycle, considerations for heating during low ambient air conditions need to be a part of the design. Alternatively, a water-source unit may be considered, although such systems were not analyzed for this Guide.

SYSTEM C—WATER AND GSHP WITH DOAS

HV7 Overview—System C

A ground-source heat pump (GSHP) system consists of an exterior ground-coupled heat exchanger, either in a vertical borehole, in a horizontal trench, or submerged in a surface water feature; a water piping system connecting the ground heat exchanger to the GSHP heat pump unit; and thermal distribution to individual thermal zones. GSHP systems can be characterized as either "open loop" or "closed loop." The systems described in this Guide are all closed-loop systems. Open-loop systems, because they introduce ground water into the thermal circulating loop, present a number of additional challenges, mostly associated with groundwater chemistry. Design of an open-loop system should be done with the advice of experts, not only in ground thermal heat transfer but also in ground chemistry and in some cases ground microbiology. Open-loop systems are not discussed in this Guide.

A GSHP system offers several advantages for building owners when compared to conventional water-source heat pump (WSHP) systems. In most climate zones, a GSHP system eliminates the need for boiler/cooling tower maintenance and chemical treatment, services that owners must contract to multiple service vendors. The central plant is substantially reduced in size, which lowers building size and construction costs. The noise source of a cooling tower is also removed, along with the hazard of a boiler. These advantages must be evaluated against the added cost of the ground heat exchanger.

Table 5-23 shows the primary and secondary heating sources for each of the climate zones for a GSHP system. System efficiency requirements are shown in Table 5-20.

Table 5-23 (HV7) Recommendations for Zone Terminal Systems with DOAS

CZ	System Designation	System C Ground Source Heat Pumps
1	Primary cooling source	Water-source DX with cooling tower
	First-stage heating source	Ground-source DX
	Second-stage heating source	Not required
2	Primary cooling source	Water-source DX with optional cooling tower
	First-stage heating source	Ground-source DX
	Second-stage heating source	Not required
3	Primary cooling source	Ground-source DX
	First-stage heating source	Ground-source DX
	Second-stage heating source	Not required
4	Primary cooling source	Ground-source DX
	First-stage heating source	Ground-source DX
	Second-stage heating source	Not required
5	Primary cooling source	Ground-source DX
	First-stage heating source	Ground-source DX
	Second-stage heating source	Not required
6	Primary cooling source	Ground-source DX
	First-stage heating source	Ground-source DX
	Second-stage heating source	Not required
7	Primary cooling source	Ground-source DX
	First-stage heating source	Ground-source DX with supplemental boiler
	Second-stage heating source	Not required
8	Primary cooling source	N/A
	First-stage heating source	N/A
	Second-stage heating source	N/A

HV8 Types of GSHP Systems—System C

The simplest GSHP system uses multiple single-package WSHPs that are connected to the ground via a water circulating loop. Each thermal zone is provided with a separate GSHP terminal unit to provide zone cooling and heating. Supply and return ductwork connect the heat pump unit to the space for delivery of heating and cooling. GSHP units are available in preestablished increments of capacity. The components are factory assembled and include a filter, fan, refrigerant-to-air heat exchanger, compressor, refrigerant-to-water heat exchanger, and controls. The refrigeration cycle is reversible, allowing the same components to provide cooling or heating at any time, independent of the loop water temperature. Compressors and fans in the heat pump units should be variable speed to enhance energy efficiency.

Another popular option is to use water-source multi-split VRF heat pumps. Such a system employs a compressorized or “outdoor” unit that is connected to the ground circulating loop and to multiple fan-coils in the zones via refrigerant piping. This system has the advantage that the “outdoor” unit may be located outside the conditioned space, in a closet or mechanical room, isolating the compressor noise. Each fan-coil, or “indoor” unit, provides a separate thermal zone. The system can be configured with refrigerant-side heat recovery. With this system, when individual fan-coils, connected to an “outdoor” unit, are in different modes of operation (heating or cooling), the smaller of the two load modes may be met with very little additional energy consumption. This feature can be very beneficial with a large-floor-plate office building, in which the interior zones are almost always in cooling mode even when the perimeter zone is in heating mode. Depending on the floor-plate configuration, refrigerant-side heat recovery can be very beneficial in climate zones 2, 3, 4, 5, 6, and 7.

Both of the above options typically provide space conditioning through recirculated air. They are typically incorporated with separate DOASs to manage ventilation. Heat pump units within the DOAS that condition ventilation air may also be connected to the ground loop (ASHRAE 2012). See HV17 for additional information on DOASs.

One other option is to connect the ground circulating loop to one or more water-to-water heat pumps then circulate the hot or chilled water from the heat pumps to individual fan-coils, chilled beams, radiant panels, or thermally active floors located in the conditioned space. This system shares the advantage of locating the compressorized unit outside of the conditioned space and also has the additional advantage that no refrigerant is conveyed through the conditioned space, enabling the conditioning of very-small-volume spaces without a refrigerant purge system.

Hybrid heat pump systems are sometimes used in climate zones where achieving an annual thermal balance with the ground is not possible because of the load profile of occupancy. Hybrid systems are discussed briefly in HV12.

HV9 Thermal Storage in the Ground—System C

The primary means by which ground-coupled heat pump systems reduce energy is through increased refrigeration-system COP due to reduced temperature differential across which the system works. The annual ground temperature variations to which the heat exchangers are exposed are typically much narrower than the air temperature variations at the location. So, during cold weather, when the system is in heating mode, it will be extracting energy from a much warmer source than the air temperature. Similarly, in hot weather, when it is in cooling mode, it will be rejecting heat to a cooler sink than the air. Some ground-coupled heat pump systems may also save significant fan energy compared with centralized air distribution because the pressure drop through the fan-coil is significantly less than that for central AHUs.

It is important to remember that the ground is not an infinite heat source or sink and that heat rejected into the ground and extracted from the ground must be in approximate balance over time to avoid long-term migration of the average ambient ground temperature. This phenomenon is particularly important for large-scale, deep borehole fields, where heat transfer through the ground surface, across the lateral boundaries of the well field and downward to the soil below the boreholes, represents a very small percentage of the overall heat transfer into and out of the field. The ability of the ground to transfer and absorb heat is defined by three fundamental parameters—thermal conductance, specific heat, and density—and one calculated parameter—thermal diffusivity. Thermal diffusivity describes the rate at which the soil temperature changes over time in response to heat gain. Higher thermal diffusivity is weakly consistent with higher effective soil thermal resistance over time. In general, the greater the soil conductivity, the less length of ground heat exchanger is required for a given heat rejection or extraction capacity. Soils favorable to ground thermal storage should demonstrate both a high thermal conductivity, enabling heat to transfer from the heat exchanger far into the body of soil, and a high thermal capacity, resulting in reduced temperature change per unit of heat absorbed. Saturated ground typically shows both enhanced thermal conductivity and increased thermal capacity compared with dry soil. Table 5-24 shows typical values of thermal diffusivity and thermal conductivity for several types of soil.

Based on soil samples taken from a test bore, the thermal parameters of the soil can be established. Using those parameters, as well as detailed load profiles from the building energy

Table 5-24 (HV9) Thermal Properties of Different Soil Types

Soil	Thermal Conductivity	Thermal Diffusivity
Moisture/Texture	Btu/ft·h·°F	ft^2/day
Basalt	0.98	0.70
Shale	1.21	0.90
Limestone	1.62	1.26
Dry sand	0.23	0.27
Dry clay/silt	0.29	0.33
Dry loam	0.52	0.46
Saturated sand	1.39	0.89
Saturated clay/silt	0.98	0.54

model, the required length of ground heat exchanger can be calculated, using either the method described in *Geothermal Heating and Cooling: Design of Ground-Source Heat Pump Systems* (Kavanaugh and Rafferty 2014) or via detailed computer simulation of the ground.

HV10 Configuration of Ground Heat Exchangers—System C

Ground heat exchangers can be configured in vertical or horizontal boreholes or horizontal trenches as shown in Figure 5-54.

A typical vertical borehole ground heat exchanger includes many vertical pipe bores, each 200 to 500 ft deep. Multiple vertical pipe bores are circuited together with horizontal piping which is then routed to the building and the heat pump devices. An example of three different circuiting arrangements is shown in Figure 5-55, appropriate to different sizes of borehole fields.

Individual vertical borehole heat exchangers have typically been U-tubes, sized as shown in Figure 5-55. The sizing algorithms enable borehole sizing based on standard U-tube design or concentric heat exchangers (Kavanaugh and Rafferty 2014). Concentric or coaxial heat exchangers are designed to maximize the thermal coupling between the circulating fluid and the ground. These devices typically have an outer tube that is designed to fill the entire borehole so that grout is used only for void-filling between the borehole face and the tube. This arrangement minimizes the grout thermal resistance and maximizes the heat transfer area of tubing. The fluid flows down the length of the heat exchanger through an inner tube, made of a material with somewhat higher thermal resistance to minimize short-circuit heat exchange between the tubes. The fluid flows upward from the bottom of the heat exchanger between the outer wall and the inner tubing. Some products equip the outer wall of the inner tube with vanes to generate turbulent flow in the fluid flowing back to the surface, thus increasing heat transfer between the outer wall and the fluid. Testing of these devices indicates that the effective borehole length to achieve a certain capacity can be reduced by as much as 20% compared with standard U-tube heat exchangers embedded in thermally conductive grout (Kavanaugh and Rafferty 2014). Products using this strategy are available from multiple manufacturers.

Horizontal heat exchangers come in many configurations, but most examples seek to maximize the length of tubing that is inserted into a trench. As a result, the so-called “slinky” configuration is often used. While the adjacency of individual loops to one another results in a much less than optimal mass of soil influenced by each unit length of tubing, the very low cost of the tubing per unit length compared with the cost of trenching dictates this configuration. Horizontal heat exchangers are often used for projects with a large area of external grounds that will be disturbed for other reasons, such as construction of extended parking structures. An example of a “slinky” coil in a trench is shown in Figure 5-56.

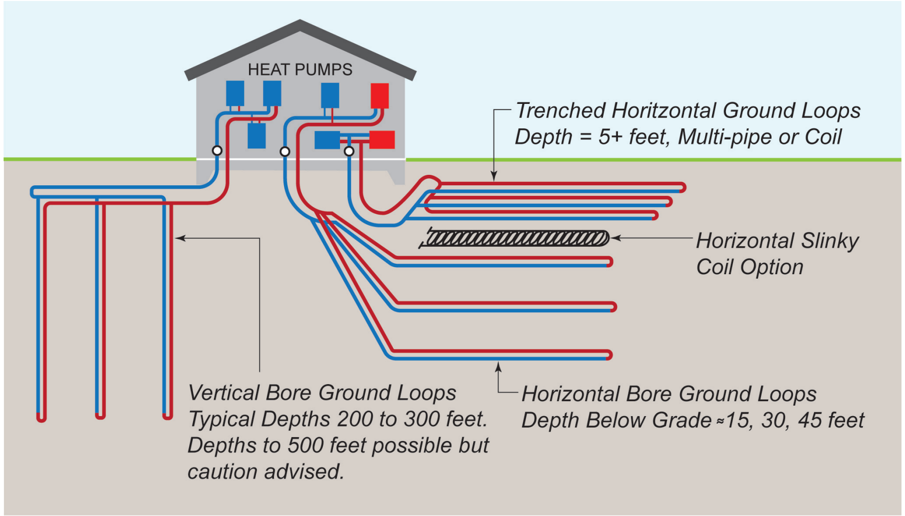

Figure 5-54 (HV10) GSHP Vertical Water Loop Diagram

Adapted from Figure 1.2, Kavanaugh and Rafferty 2014

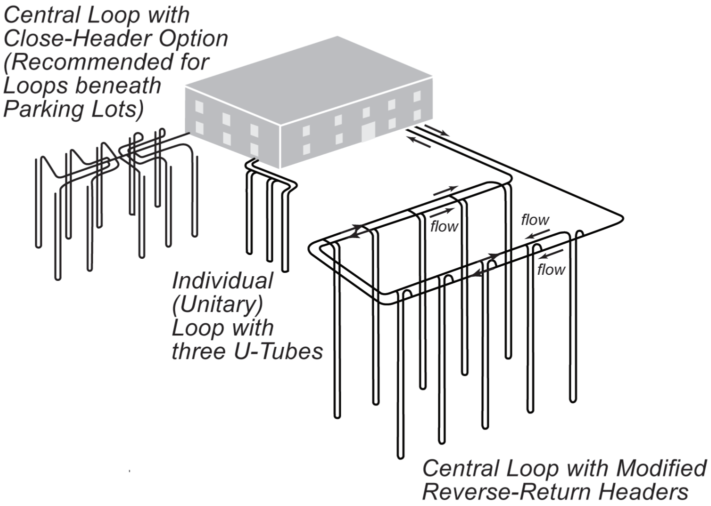

Figure 5-55 (HV10) Three Options for Closed-Loop Heat Pump Vertical Ground-Loop Circuits

Adapted from Figure 10, Chapter 34, ASHRAE 2015a

HV11 Water Piping and Pumping Strategies—System C

A 1995 GSHP survey conducted by Caneta Research reported that installed pumping power varied from 0.04 to 0.21 hp/ton of heat pump power (ASHRAE 1995). The piping material, pipe sizing, water velocity, and water solution used all effect the design efficiency. The piping system can be steel or various plastic materials. Good water quality is important to minimize fouling factor and avoid clogging of heat exchangers. A steel piping system requires chemical treatment to inhibit corrosion. The heat transfer fluid may be water with some additives or it may be a water/antifreeze mixture. Antifreeze should be included in the fluid only when design analysis indicates a danger of freezing because of high heating loads for the heat pump system along with a low undisturbed ground temperature. Successfully designed piping systems that can reduce the total system pressure drop below 46 ft w.c. flowing 3 gpm/ton are Graded as “A” by Chapter 34 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015a).

Figure 5-56 (HV10) Horizontal Heat Exchange Coil in a Trench

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Two water pumping strategies are most common: centrally pumped and distributed/decentralized pumped. A centrally pumped system should be configured with variable-speed pumps and heat pump devices should be equipped with shutoff valves to block flow when compressors are not active. Other options for increasing system part-load pumping efficiency are modulating valves for each heat pump device controlled to maintain a constant temperature differential for water flowing through the device (suitable for larger heat pumps) and using a controller that varies pump speed to maintain a maximum temperature differential across the heat pump device at greatest part load.

A decentralized water pumping system eliminates the central pumps and uses a small inline water pump at each heat pump unit. The water pump operates only when the heat pump unit compressor is operating. Variable water flow is accomplished without the need for variable-speed pumps and water-pressure controls, thus eliminating the additional system pressure drop imposed by the water pressure sensor. If the heat pumps are large, however, and of variable capacity, the dedicated pumps for each unit should be variable flow, controlled by temperature change across the heat pump unit.

HV12 Annual System Balance—System C

Very few climate zones strike a perfect balance between heat rejected to the ground heat exchanger and heat absorbed from it. A properly designed ground heat exchanger can accommodate an imbalance between heat rejected and heat absorbed. However, in extreme climate zones, larger imbalances exist and a hybrid system should be considered to ensure the ground heat exchanger does not deliver loop water that is too hot or too cold, which would impact the operation of the heat pump units.

For example, in a cooling-dominated climate (such as climate zones 1 or 2), a large amount of heat will be rejected to the ground during the cooling season and a smaller amount of heat will be extracted from the ground during the heating season. This imbalance can cause the temperature of the ground surrounding the ground heat exchanger to rise to levels that adversely affect system efficiency.

Conversely, in a heating-dominated climate (such as climate zones 6 or 7), a relatively small amount of heat will be rejected to the ground during the cooling season and a much larger amount of heat will be extracted from the ground during the heating season. In this case, the ground temperature may become too cold, adversely affecting both system efficiency and, sometimes, system capacity.

A hybrid approach involves adding a fluid cooler to the loop for a system that is installed in a cooling-dominated climate or adding a boiler to a system in a heating-dominated climate. Fluid coolers should be added to the ground circulating loop in series with and upstream of the ground heat exchangers, whereas boilers should be added to the building circulating system, in parallel or independent of heat pump supply to the space. A hybrid design reduces system efficiency, so design strategies that improve energy performance should first be considered.

HV13 Ground-Source System Success Factors—System C

The system efficiency of GSHP systems can be exceptionally high in larger buildings if

- high-efficiency, extended-range heat-pumps are used;
- the ground or surface-water heat exchangers are of sufficient depth and length and located in mediums so that liquid temperatures entering the heat pumps are much more moderate than the outdoor air temperature;
- the air distribution system is designed and installed so that the required fan power is small (<15% of total system power [heat pump + fan + pump power]); and
- the water distribution system is designed and installed so that the required pump power is small (<10% of total system power [heat pump + fan + pump power]) and that transport energy varies, through VSDs, with heating or cooling load on the system.

SYSTEM D—DOAS WITH SENSIBLE FAN-COILS AND CHILLERS WITH WATERSIDE ECONOMIZERS

HV14 Overview—System D

In this system, a separate fan-coil unit is used for each thermal zone. The fan-coil cools, removing sensible heat only, using warmer-than-traditional chilled water. The supply temperature of the chilled water is 55°F to 57°F. All the dehumidification is by the DOAS unit. There is no condensation in the space equipment. This can reduce zone filtration requirements and remove the need for zone condensate pumps. Components are factory assembled and include filters, a fan, heating and cooling coils, controls, and possibly outdoor air and return air dampers. An alternative to fan-coils for sensible conditioning of the space is a radiant system, either ceiling panels or floor slabs. Such systems must be used with a DOAS that is configured to provide all required dehumidification. Refer to the sidebar "Radiant Heating and Cooling" for additional information on this option.

All the fan-coils are connected to a common water distribution system. Cooling is provided by a centralized water chiller. The warmer chilled-water temperature required for sensible-only cooling can result in higher chiller efficiency and more waterside economizing hours. Heating is provided by either a centralized boiler, a heat recovery chiller, or electric resistance heat. In climate zones 1 and 2, where heating loads are quite low, the cost-effectiveness of a boiler heating system should be examined; it may be more cost-effective to use heat recovery chillers or solar hot-water heating in lieu of a hot-water heating system because of the minimal heating requirements. Table 5-25 indicates primary and secondary heating sources for this system.

Outdoor air for ventilation is conditioned and delivered by a separate DOAS. This may involve ducting the outdoor air directly to each fan-coil, delivering it in close proximity to the fan-coil intakes, or ducting it directly to the occupied spaces. Depending on the climate, the dedicated outdoor air unit may include components to filter, cool, heat, dehumidify, and/or humidify the outdoor air.

HV15 Chilled-Water Equipment—System D

The cooling equipment, heating equipment, and fans should meet or exceed the efficiency levels in Table 5-20.

Table 5-25 (HV14) Recommendations for Zone Terminal Systems with DOAS

CZ	System Designation	System D—Sensible-Cooling Hydronic Fan-Coils
1	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Electric resistance
	Second-stage heating source	Not required
2	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Electric resistance (perimeter zones)
	Second-stage heating source	Not required
3	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Hydronic (four-pipe perimeter zones)
	Second-stage heating source	Not required
4	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Hydronic (four-pipe perimeter zones)
	Second-stage heating source	Not required
5	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Hydronic (four-pipe perimeter zones)
	Second-stage heating source	Not required
6	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Hydronic (four-pipe perimeter zones)
	Second-stage heating source	Not required
7	Primary cooling source	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Hydronic (four-pipe perimeter zones)
	Second-stage heating source	Optional perimeter zone hydronic heat (radiant, convective in space)
8	Primary cooling source	Not required
	First-stage heating source	Hydronic (two pipe)
	Second-stage heating source	Perimeter zone hydronic heat (radiant, convective in space)

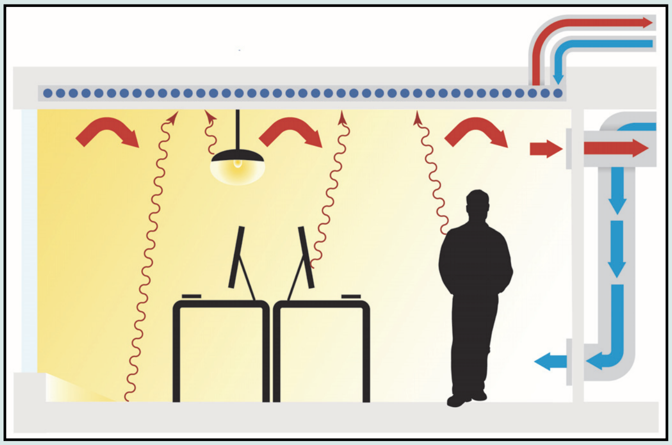
Chillers should include VSDs on the compressors to provide continuous unloading. Chillers should incorporate controls capable of accommodating variable evaporator water flow while maintaining control of leaving chilled-water temperature.

Water-cooled chillers and cooling towers were not analyzed for this Guide. A system including a water-cooled chiller, condenser water pump, and cooling tower all with sufficient efficiency and integrated controls may give the same or better energy performance as an air-cooled chiller. Large office buildings considering water-cooled chillers should follow the recommendations for chiller plant design outlined in *ASHRAE GreenGuide: Design, Construction, and Operation of Sustainable Buildings* (2018a).

HV16 Variable Primary Flow—System D

Variable-speed pumps in a chiller system offer significant operating-cost savings because the pumps will be optimized to respond to the changes in load conditions. Chillers need to be selected for the minimal flow requirement of the system plus a large turndown on the water side to ensure continued performance at lower flow rates. To optimize pump energy savings, reset the differential pressure to maintain discharge air temperature at the terminal units or air

Radiant Heating and Cooling



Radiant Ceiling System in an Office Space Showing Radiant Interchange between Ceiling and Heat Sources in the Space
Adapted from an Image © Caroline Karmann,
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Radiant heating and cooling systems are often considered for sensible conditioning because of the efficiency with which they can deliver heating or cooling to a space to maintain comfort conditions. These systems can cool using a relatively high-temperature cooling source and heat with a low-temperature heating source, thereby providing additional opportunity for energy efficiency at the heating and cooling source. Using these systems to maintain a comfortable mean radiant temperature in the space can allow greater variation in the space air temperature, potentially reducing the total amount of heating and cooling required. All of these reasons make such systems an attractive alternative for zero energy buildings.

A large surface area with a low temperature difference to the conditioned space provides thermal conditioning to maintain comfort. More conventional air-based delivery systems typically make use of a higher temperature differential to the space in order to reduce the amount of air required to deliver the heating or cooling. The amount of transport energy required to move the heat into or out of the space is dependent upon the quantity of air moved, creating a trade-off between low-temperature-difference heating and cooling sources and low transport energy. Radiant heating and cooling systems require no forced air movement at the space, eliminating that portion of the transport energy for the conditioning system.

Radiant heating and cooling systems do not ventilate or dehumidify. They are often coupled with a DOAS to provide fresh air. The controls for the air system must interlock with those of the radiant system to maintain comfort and to prevent the two systems from fighting to maintain set points. The airflow rate and discharge temperature of the air off the cooling coil must be carefully controlled during humid outdoor conditions to enable humidity control in the space and to prevent condensation on the radiant surfaces.

Radiant heating and cooling systems typically take advantage of a large surface in a space, usually the ceiling or floor. Ceiling-based systems typically have a greater cooling capacity than floor-based systems, unless the floor system falls in direct sunlight. In this case, the floor system is able to remove solar heat gain directly before it has an opportunity to heat the floor and indirectly heat the air in the space. On the other hand, floor-based systems have a greater heating capacity per unit area, although their maximum operating temperature is limited by comfort considerations.

Ceiling radiant systems are typically manufactured panels that are installed either as a suspended ceiling or as a surface-mounted panel on a structural ceiling. Piping conveys cool or warm water to the panel depending on the type of conditioning required. The system is often fairly low mass, so that heating and cooling changeover can occur about as rapidly as with a hydronic fan-coil system. Space conditions are maintained by modulating the water flow through the panel. The above figure shows how the ceiling system absorbs heat from internal heat sources through long-wave radiation interchange (Watson 2008).

Floor-based radiant systems typically involve polyethylene tubing embedded in the concrete floor slab of the space. Water flow through the tubing is modulated to maintain the floor slab at a set point that is consistent with maintaining comfort considering the types of loads imposed on the space due to envelope heat transfer and internal heat gains. Different control strategies are used in different types of spaces with different envelope configurations to ensure that the floor radiant system operates optimally to maintain comfort conditions in the space. Heating and cooling changeover is much more of a concern in these systems because of the thermal mass in which the tubing is embedded. By maintaining the slab at a relatively constant set-point temperature, however, the thermal mass of the slab is actively engaged to limit potential load swings and resulting air-temperature variation in the space. The following figure shows tubing laid out on a structural slab before the topping slab and floor finish material have been installed. This particular application was for a tall space with significant glass area. A greater discussion of radiant heating and cooling floor systems can be found in a three-part series published in *ASHRAE Journal* titled “Thermally Active Floors” (Nall 2013a, 2013b, 2013c).

Polyethylene Tubing for a Radiant Heating and Cooling System in an Atrium
Photograph Courtesy of WSP Flack + Kurtz

handlers with at least one control valve in a fully open condition. This will achieve flow to every unit while achieving pump savings at low load conditions (ASHRAE 2015b).

DEDICATED OUTDOOR AIR SYSTEMS

HV17 System Overview—DOAS

There are many advantages of using a dedicated outdoor air system (DOAS) with a zero energy office building. DOASs can simplify ventilation control and design, improve humidity control, and allow for sensible-cooling-only terminal equipment (ASHRAE 2017b). A DOAS also can be equipped with high-efficiency filtration systems with static pressure requirements above the capability of zone-terminal HVAC equipment. One of the energy-saving features of a DOAS is its separation of ventilation air conditioning from zone air conditioning and its ease of implementation of exhaust air energy recovery. Terminal HVAC equipment heats or cools recirculated air to maintain space temperature. Terminal equipment may include fan-coil units, water-source heat pumps (WSHPs), zone-level air handlers, or radiant heating and/or cooling panels. Table 5-26 illustrates how the DOAS and terminal systems work together to handle thermal load.

Table 5-26 (HV17) Recommendations for DOAS

CZ	Compatible Systems	DOAS Options			
		Air-Cooled DX Cooling	Air-Source Heat Pump	Ground-Source Heat Pump	Hydronic Fan-Coils
		System B System C System D	System B System C System D	System C	System D
1	Primary cooling source	Air-source DX	N/A	N/A	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Exhaust energy recovery	N/A	N/A	Exhaust energy recovery
	Second-stage heating source	Not required	N/A	N/A	Not required
2	Primary cooling source	Air-source DX	Air-source DX	Water-source DX with supplemental cooling tower	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Optional electric-resistance heat	Optional air-source DX	Ground-source DX	Optional electric-resistance heat
3	Primary cooling source	Air-source DX	Air-source DX	Ground-source DX with optional supplemental cooling tower	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Exhaust energy recovery (Not required in region 3C)	Exhaust energy recovery (Not required in region 3C)	Exhaust energy recovery (Not required in region 3C)	Exhaust energy recovery (Not required in region 3C)
	Second-stage heating source	Indirect gas furnace	Air-source DX	Ground-source DX	Condensing boiler
4	Primary cooling source	Air-source DX	Air-source DX	Ground-source DX	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Indirect gas furnace	Air-source DX	Ground-source DX	Condensing boiler
5	Primary cooling source	Air-source DX	Air-source DX	Ground-source DX	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Indirect gas furnace	Air-source DX	Ground-source DX	Hydronic heating coil

Table 5-26 (HV17) Recommendations for DOAS *(Continued)*

CZ	Compatible Systems	DOAS Options			
		Air-Cooled DX Cooling	Air-Source Heat Pump	Ground-Source Heat Pump	Hydronic Fan-Coils
		System B System C System D	System B System C System D	System C	System D
6	Primary cooling source	Air-source DX	Air-source DX	Ground-source DX	Air-cooled chiller or water-cooled chiller with cooling tower
	First-stage heating source	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Indirect gas furnace	Air-source DX + supplemental electric resistance	Ground-source DX	Condensing boiler
7	Primary cooling source	Air-source DX	N/A	Ground-source DX	Air-cooled chiller
	First-stage heating source	Exhaust energy recovery	N/A	Exhaust energy recovery	Exhaust energy recovery
	Second-stage heating source	Indirect gas furnace	N/A	Ground-source DX with supplemental boiler	Condensing boiler
8	Primary cooling source	Optional air-source DX	N/A	N/A	Optional air-cooled chiller
	First-stage heating source	Exhaust energy recovery	N/A	N/A	Exhaust energy recovery
	Second-stage heating source	Indirect gas furnace	N/A	N/A	Condensing boiler

A DOAS includes two ductwork systems, one to supply outdoor air to the thermal zones and the other to exhaust air from the thermal zones. The system is variable flow to help achieve energy targets. All building exhaust air is normally returned to the DOAS, including restroom exhaust. Special exhaust systems such as range hoods and fume hoods are ducted outdoors independently. Where possible, DOAS units should be located within the building thermal envelope to maximize the available roof area for solar systems.

DOASs can reduce energy use by decoupling the dehumidification and conditioning of outdoor air ventilation from sensible cooling and heating in a zone. The outdoor air is conditioned by a separate DOAS that is designed to dehumidify the outdoor air and to deliver it dry enough (with a low enough dew point) to offset space latent loads, thus providing space humidity control (Mumma 2001; Morris 2003).

There are many possible DOAS configurations (see Figure 5-59 for a few typical ones).

HV18 Sizing a DOAS for Dehumidification

A DOAS is sized to remove all the space latent load. This enables independent dehumidification control of a space and allows for energy-saving measures for the terminal cooling equipment.

The primary space latent load for most offices is from the space occupants. For example, a seated active office worker adds 0.19 lb/h of moisture to the space that must be removed (ASHRAE 2017c). Moisture added to the space by visitors and by outdoor air infiltration during humid weather must also be removed to maintain desired space humidity conditions (Harriman et al. 2001). The dew-point temperature of the supply air of the DOAS must be sufficiently below the desired dew-point temperature of the space to offset the moisture added to the space by these latent loads.

For system B (VRF) and system C (GSHP), the cooling coil in the terminal equipment will be cold enough for some coincidental dehumidification and condensate when there is a call for cooling. However, sizing and using the DOAS to control humidity will allow for the cycling of fan ON only for cooling needs. This will require the ventilation system to have separate delivery to the space from the terminal equipment (see HV19).

For system D (sensible-cooling fan-coil), the DOAS is sized to condition the space dew point below the chilled-water temperature of the terminal equipment. This prevents condensation on the terminal equipment. Keeping cooling coils dry reduces the energy required to cool the space. This also reduces the filtration requirements of the terminal equipment. Section 5.8 of ASHRAE Standard 62.1 (ASHRAE 2016d) requires MERV 8 or higher filters of devices with wetted surfaces through which air is supplied to an occupiable space. Not having these higher filtration requirements will reduce terminal fan energy to cool the space.

Because the DOAS does all the dehumidification, the chilled water to the terminal unit can be at a higher temperature (55°F to 57°F). This can improve the chiller efficiency >20% over a traditional 44°F chilled-water system, resulting in additional cooling energy savings.

HV19 Delivery for Zone-Level Demand-Controlled Ventilation (DCV)

DOASs can reduce energy use in primarily three ways:

- They often avoid the high outdoor air intake airflows at central air handlers needed to satisfy the multiple spaces equation of ASHRAE Standard 62.1 (ASHRAE 2016d) and enable zone-by-zone DCV.
- They eliminate (or nearly eliminate) simultaneous cooling and reheat that would otherwise be needed to provide adequate dehumidification in humid climates.
- With constant-volume zone units (heat pumps, fan-coils), they allow the unit to cycle with load without interrupting ventilation airflow.

To realize these savings, how the ventilation is delivered to the space needs to be considered. To control the amount of ventilation to each zone, a pressure-independent zone damper or air valve with flow measurement is needed. This allows for the outdoor air to be reduced during off-peak occupancy and is especially beneficial to office buildings, which often have a high variance of occupancy. In many cases, the outdoor air to the area during standby mode (occupied hours with no one present) can be reduced, and in some cases it may be reduced to zero (ASHRAE 2016d). Such an air valve may be in the DOAS ductwork before the diffusers serving the zone or it may be incorporated into the terminal equipment. Incorporating it into the terminal unit enables a broader range of ventilation control. Mixing in some return air will prevent airflow from falling below the diffuser's minimum recommended airflow and prevent the dumping of cool ventilation air. The DOAS unit delivers outdoor air to the zones as needed by their ventilation and dehumidification requirements. This is accomplished by the DOAS pressurizing the ductwork to the minimum pressure required to deliver the air. The static pressure set point in the system supply ductwork is reset based on the positions of the air valves in the system (see Figure 5-57). This ensures the minimum fan power is used to deliver ventilation to the space. The air valves' flow rates are recalculated based on number of occupants. Occupancy population can be measured by carbon dioxide (CO_2) sensors or occupancy sensors or both, depending on the zone. For more discussion of DCV calculations, see HV25.

Acceptable ways to deliver air to the zone are shown in Figure 5-58. In each case, ventilation is controlled by an independent-pressure air valve. The outdoor air should not be ducted to mix with return air to a unit that cycles fan ON for cooling or heating. Many traditional fan-coils and VRF terminals (system B) can operate this way. This type of equipment should have the

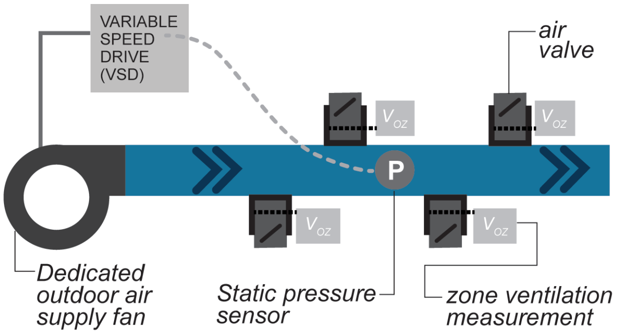


Figure 5-57 (HV19) DOAS Supply Fan Controlled with VSD

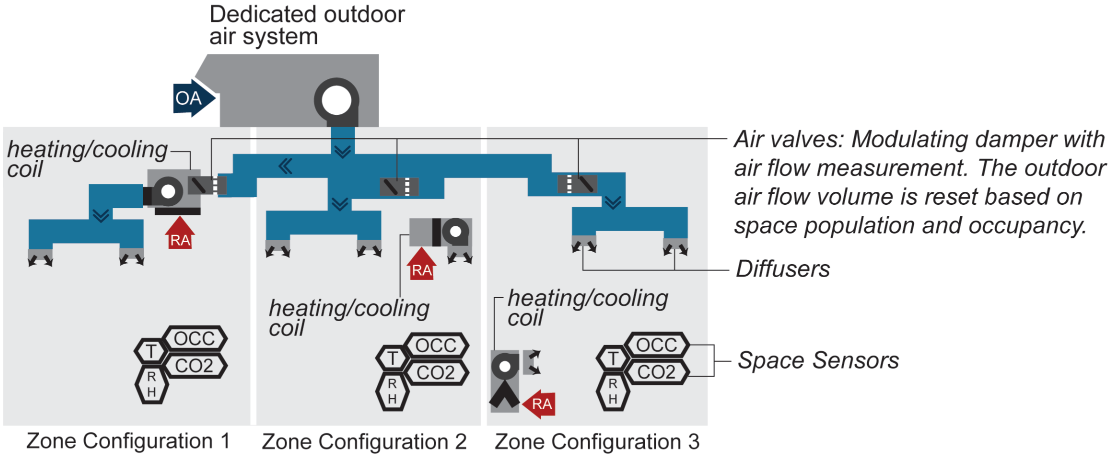


Figure 5-58 (HV19) DOAS Delivery for Zone-Level DCV

outdoor air delivered directly to the space through diffusers as shown in zone configuration 2 or 3 in Figure 5-58. An air diffuser will have a minimum airflow at which it is effective at diffusing the air; if DCV reduces the outdoor airflow below this minimum, the air may dump into space and cause cool spots and affect occupant comfort. To maximize the amount of ventilation turndown, the terminal unit can utilize a fan in series as shown in configuration 1 in Figure 5-58. In this type of system, the fan maintains the diffuser minimum airflow by drawing in recirculated air from the space. For system D, the sensible hydronic coil may be placed in the recirculating air path as shown in configuration 1 in Figure 5-58.

The DOAS equipment will have a minimum turndown limit. This turndown can be as low as 30% of design flow and should be confirmed with the manufacturer, as the limit depends on the fan, DX system, and other components in the DOAS. For proper building pressure control, the minimum ventilation rate should also not fall below the required exhaust sources. For offices this is often the restroom exhaust flow. The minimum positions set on the ventilation air valves should be set to not allow the DOAS to turn down below this minimum during occupied hours.

One of the disadvantages for systems that use a DOAS is the inability to get full utilization of air-side economizers, because the outdoor airflow rate is typically far below the flow rate required for full cooling. A DOAS can be designed to take advantage of using outdoor airflow volumes beyond the ventilation requirement to cool when it is advantageous. When cooling is required for the zones during economizing hours, DCV can be disallowed. In addition to disallowing DCV during economizing, the maximum outdoor airflow per zone may be oversized to allow for economizing airflows.

HV20 *Discharge Air Temperature Control for DOAS*

Consider delivering conditioned outdoor air cold (not reheated to neutral) whenever possible and reheat only when needed. For most offices, the amount of outdoor air required will not overcool the space if it is delivered cooler than the space temperature. When the discharge air temperature supplied from the DOAS unit is cooler than room temperature, the zone air distribution effectiveness is not penalized. Also, providing cold (rather than neutral) air from the DOAS offsets a portion of the space sensible cooling loads, allowing the terminal HVAC equipment to be downsized and use less energy (Shank and Mumma 2001; Murphy 2006). Adding reheat even if this reheat is from recovered energy wastes energy if cooling is needed in the space. Section 6.5.2.6 of ASHRAE/IES Standard 90.1 (ASHRAE 2016b) restricts heating the ventilation air above 60°F when a majority of zones served by the DOAS require cooling; zero energy buildings may lower this requirement even further to minimize reheat. However, there are cases when reheating the dehumidified air (to a temperature above the required dew point) may be warranted, such as the following:

- If the reheat consumes very little energy (using energy recovery, a solar thermal source, etc.) and none of the zones are in cooling mode.
- If all of the zones are in the heating mode.
- If, for those zones in cooling mode, the extra cooling energy needed (to offset the loss of cooling due to delivering neutral-temperature ventilation air) is offset by higher-efficiency cooling equipment and the reduction in heating energy needed for those zones in the heating mode (this is more likely to be true on an annual basis if the reheat in the DOAS is accomplished via air-to-air or condenser heat recovery).

In addition, implementing reset control strategies and exhaust air energy recovery (see HV21) can help minimize energy use.

HV21 *Exhaust Air Energy Recovery Options for DOAS*

Exhaust air energy recovery can provide an energy-efficient means of reducing the latent and sensible outdoor air cooling loads during peak summer conditions. It can also reduce the outdoor air heating load in mixed and cold climates. HVAC systems that use exhaust air energy recovery should to be resized to account for the reduced outdoor air heating and cooling loads (see ASHRAE 2017b).

Energy recovery devices should have a total effectiveness of 75% for climates where total energy recovery is required. For climates where sensible recovery is required, a sensible effectiveness of 75% is required. These minimum effectiveness values should be achieved with no more than 0.85 in. w.c. static pressure drop on the supply side and 0.65 in. w.c. static pressure drop on the exhaust side.

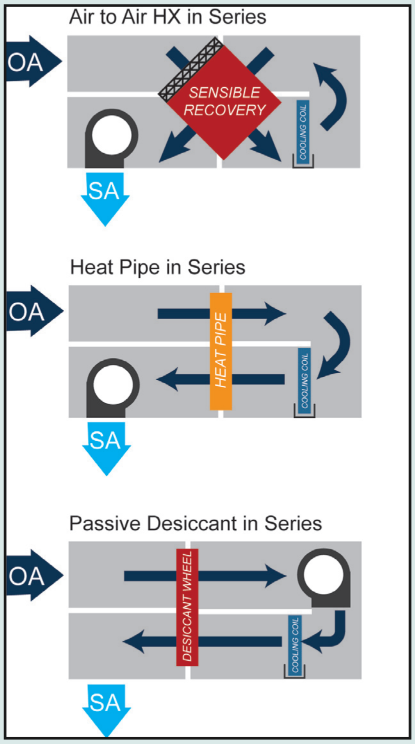
Sensible energy recovery devices transfer only sensible heat. Common examples include coil loops, fixed-plate heat exchangers, heat pipes, and sensible energy rotary heat exchangers (sensible energy wheels). Total energy recovery devices transfer not only sensible heat but also moisture (or latent heat)—that is, energy stored in water vapor in the airstream. Common examples include total energy rotary heat exchangers and fixed-membrane heat exchangers. Energy recovery devices should be selected to avoid cross-contamination of the intake and exhaust airstreams. For rotary heat exchangers, minimizing cross-contamination can be achieved by designing the intake outdoor air system pressure higher than the exhaust system pressure. The use of purge, flushing the rotary exchangers with excess outdoor air, should be avoided, as this will increase DOAS and exhaust fan energy.

For maximum benefit, the system should provide as close to balanced outdoor and exhaust airflows as is practical, taking into account the need for building pressurization. Office restroom exhaust will be a large portion of the exhaust air; this required toilet exhaust should be used along with the exhaust air needed for building pressure relief.

Air-To-Air Series Energy Recovery

Condenser reheat should be avoided for DOASs. Reheat at the DOAS unit should be used only if advantageous for overall building energy requirements. If this reheat at the DOAS is by a heating coil it will negate cooling. If this heat is recovered from a condenser or solar heat, the reheat energy is recovered but will still result in negating sensible cooling. One way to improve upon this is to recover the reheat in series with the cooling coil by using an air-to-air energy recovery device. The reheat energy can be recovered from air upstream of the cooling coil to reheat the air downstream of the cooling coil. This reheat energy is then used for precooling the air before the coil. The reheat energy is used to reduce cooling required by the cooling coil. For the same total amount of cooling accomplished, the ratio of dehumidification the coil performs will increase and the ratio of the amount of sensible cooling will be reduced. This may be a useful way to prevent overcooling for buildings with low cooling requirements.

Common heat exchangers used in this way are air-to-air plate heat exchangers, heat pipes, and passive type III desiccant wheels, as illustrated in the figure at right. Exhaust air energy recovery should be used in addition to series recovery. The outdoor air (OA) shown is air after it is preconditioned by the exhaust air energy recovery device.



Air-to-Air Series Energy Recovery

Conditioned ventilation air should be delivered to the space cold (not reheated to neutral) whenever possible; if space loads indicate reheat is required, adding a second exhaust energy recovery exchanger will reduce cooling energy. The reheat recovered in this configuration will result in precooling the outdoor air, reducing the amount of wasted sensible cooling that would occur by using a reheat coil (see Figure 5-59).

HV22 Advanced Sequence of Operation for DOAS

When outdoor air dew-point temperature is above the DOAS supply temperature set point, the DOAS unit will be in dehumidification and cooling mode. When the outdoor air has a dew-point temperature below the DOAS supply set point but a dry-bulb temperature above the supply set point, the unit will be in cooling mode; if the outdoor air dry-bulb temperature is below the supply air temperature (SAT), the unit will be in heating mode.

Figure 5-60 and Table 5-27 show the typical modes for a DOAS unit (ASHRAE 2017b). DOAS with exhaust energy recovery for outdoor air preconditioning should be controlled to prevent the transfer of unwanted heat to the outdoor airstream during mild outdoor conditions when cooling in the space is still required (shown as "ventilation only" mode in Figure 5-60). There should also be a mechanism to control the amount of heat recovered during heating mode to prevent overheating the air. When the outdoor air dry-bulb temperature falls below freezing, the energy recovery function can be re-initiated and controlled to maintain a minimum outdoor air supply temperature set point of 35°F to 40°F. The energy recovery function therefore serves as a preheat freeze protection function for the air-handling system. If warmer

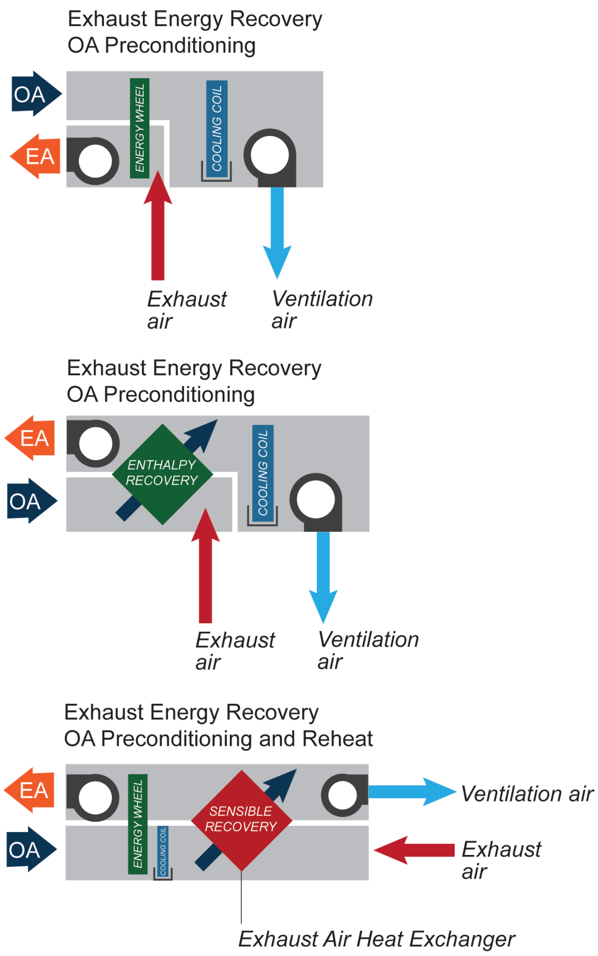


Figure 5-59 (**HV21**) **Example Exhaust Air Energy Recovery Configurations**

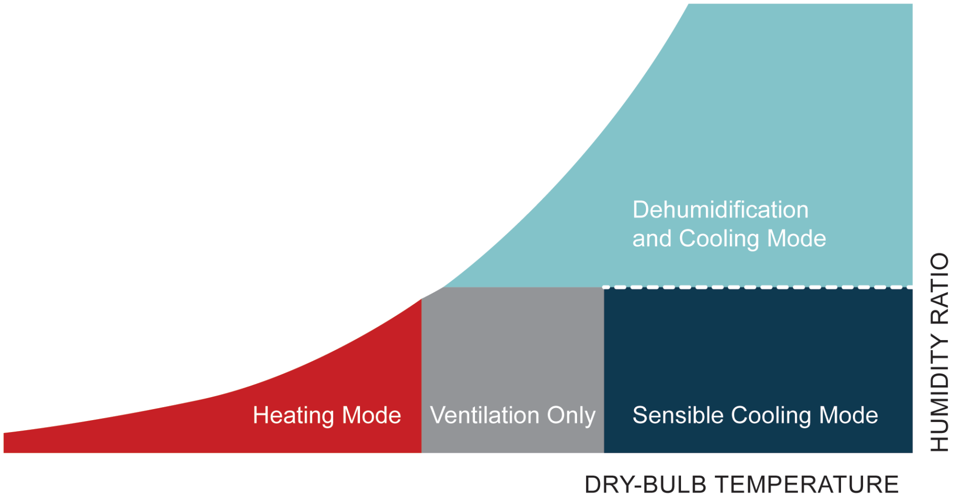


Figure 5-60 (**HV22**) **DOAS Unit Control Modes**

Adapted from Figure 5.3, ASHRAE 2017a

Table 5-27 (HV22) DOAS Unit Control Modes (ASHRAE 2017b)

Control Mode	Outdoor Conditions
Dehumidification and cooling	Outdoor air dew point > dehumidification set point
Sensible cooling	Outdoor air dew point ≤ dehumidification set point Outdoor air dry-bulb temperature > cooling set point
Ventilation only	Outdoor air dew point ≤ dehumidification set point Heating set point ≤ outdoor air dry-bulb temperature ≤ cooling set point
Heating	Outdoor air dew point ≤ dehumidification set point Outdoor air dry-bulb temperature > heating set point

air is required, this discharge air set point of the DOAS can be reset higher; however, heating of the space is controlled at the zone level.

A DOAS with exhaust energy recovery for outdoor air preconditioning and reheat (Figure 5-59) should be controlled similarly, with additional stages of control for reheat recovery (Moffitt 2015).

HV23 Part-Load Dehumidification Control

For the systems that use a DOAS (see Table 5-26), the DOAS should be designed to dehumidify the outdoor air so that it is dry enough (has a low enough supply air dew point) to offset the latent loads in the spaces. The DOAS should be dehumidifying and provide the ventilation air at this supply air dew-point set point whenever the outdoor air is above this condition. This helps avoid high indoor humidity levels without additional dehumidification enhancements in the zone terminal units. The BAS may reset the DOAS supply air dew-point set point if it finds the space is being over- or under-dehumidified. For systems with sensible-only cooling devices, it is critical to keep the space below the required dew point to prevent condensation from forming. For these systems it may be necessary to add limits to the DOAS turndown from DCV to keep the space dehumidified.

VAV systems typically dehumidify effectively over a wide range of indoor loads, as long as the VAV rooftop unit continues to provide cool, dry air at part-load conditions. One caveat: use caution when resetting the SAT upward during the cooling season. Warmer supply air means less dehumidification at the coil and higher humidity in the space. If SAT reset is used, include one or more zone humidity sensors to disable the reset if the relative humidity within the space exceeds 60%.

HV24 Ventilation Air Rate

The zone-level outdoor airflows and the system-level intake airflow should be determined based on the most recent edition of ASHRAE Standard 62.1 but should not be less than the values required by local code unless approved by the authority having jurisdiction. The number of people used in calculating the breathing zone ventilation rates should be based on known occupancy, local code, or the default values listed in Standard 62.1 (ASHRAE 2016d).

> ***Caution:*** The occupant load, or exit population, used for egress design to comply with the applicable fire code is typically much higher than the zone population used for ventilation system design. Using occupant load rather than zone population to calculate ventilation requirements can result in significant overventilation, oversized HVAC equipment, and excess energy use. Buildings with multiple-zone recirculating ventilation systems can be designed to account for recirculated outdoor air as well as system population diversity using the Ventilation Rate Procedure of ASHRAE Standard 62.1 (ASHRAE 2016d). In effect, the multiple-zone recirculating ventilation system design approach allows ventilation air to be calculated on the basis of how many people are in the building (system population at design) rather than the sum of how many people are in each space (sum-of-peak zone population at design). Using the Ventilation Rate Pro-

cedure can reduce the energy required to condition ventilation air in office buildings. Refer to *Standard 62.1 User's Manual* for specific guidance (ASHRAE 2016e).

For all zones, time-of-day schedules in the BAS should be used to introduce ventilation air. The DOAS should deliver the conditioned outdoor air directly to each zone, to the intake of each individual terminal unit or directly to the space as shown in Figure 5-58.

HV25 Demand-Controlled Ventilation (DCV) Strategies

Office buildings often have high variability in occupancy, and the amount of outdoor air should be controlled to minimize energy consumption for conditioning of outdoor air. Occupancy status can be determined by 1) a time-of-day schedule in the BAS or 2) an occupancy sensor (such as a motion detector) that indicates when a zone is occupied or unoccupied. The occupancy level is typically determined by a CO_2 sensor located within the space, and the sensed concentration is used as a proxy to modulate ventilation airflow to the space. The design ventilation rates for the occupied period should be based on full occupancy and should be calculated in accordance with Section 6 of ASHRAE Standard 62.1 (ASHRAE 2016d). This level then will be reduced based on actual occupancy as measured. The minimum ventilation rate during the occupied period should never drop below the rate required by the floor area of the space.

The required ventilation rate (V_{oz}), defined in Standard 62.1 (ASHRAE 2016d), can be written as the following equation:

$$V_{oz} = (R_p \times P_z) + (R_a \times A_z) / E_z$$

where

R_p = outdoor airflow rate required per person

P_z = zone population

R_a = outdoor airflow rate required per unit area

A_z = area of the zone

E_z = air distribution effectiveness of the zone

CO_2 sensors should be used in zones that are densely occupied and have highly variable occupancy patterns during the occupied period, such as conference rooms or meeting areas or open offices. For the other zones, occupancy sensors should be used to reduce ventilation when a zone is temporarily unoccupied. For all zones, time-of-day schedules in the BAS should be used to introduce ventilation air only when a zone is expected to be occupied.

Standard 62.1 (ASHRAE 2016d) allows a simplified control sequence for DCV; that sequence is fully explained in ASHRAE Guideline 36, *High-Performance Sequences of Operation for HVAC Systems* (ASHRAE 2018c). This sequence establishes the minimum required ventilation airflow to the space as the floor-area-dependent airflow in the equation above. The maximum ventilation airflow is defined as the airflow at design occupancy. Guideline 36 gives a target CO_2 concentration for the space and provides an algorithm for modulating ventilation airflow to the space based on the CO_2 concentration sensed in the space.

For a mixed air system with terminal units, such as system A, the minimum airflow for the terminal is a function of the required outdoor airflow and the outdoor air fraction at the AHU. Maximum airflow is also a function of V_{oz} and the outdoor air fraction at the AHU. Guideline 36 also provides an algorithm for modulating the outdoor air fraction at the AHU to meet the requirement of the most densely occupied space while minimizing overventilation in less densely occupied zones.

HV26 Carbon Dioxide (CO_2) Sensors

The number and location of CO_2 sensors for DCV can affect the ability of the system to accurately determine the building or zone occupancy. A minimum of one CO_2 sensor per zone is recommended for systems with greater than 500 cfm of outdoor air. Multiple sensors may be necessary if the ventilation system serves spaces with significantly different occupancy expectations. Where multiple sensors are used, the ventilation should be based on the sensor recording the highest concentration of CO_2.

Sensors used in individual spaces should be installed on walls within the spaces. Multiple spaces with similar occupancies may be represented by an appropriately located sensor in one of the spaces. The number and locations of sensors should take into account the sensor manufacturer's recommendations for their particular products as well as the projected usages of the spaces. Sensors should be located such that they provide a representative sampling of the air within the occupied zone of the space. For example, locating a CO_2 sensor directly in the flow path from an air diffuser would provide a misleading reading concerning actual CO_2 levels (and corresponding ventilation rates) experienced by the occupants.

The outdoor air CO_2 concentration can have significant fluctuation in urban areas. Outdoor air CO_2 concentration should be monitored using a CO_2 sensor located near the position of the outdoor air intake. CO_2 sensors should be certified by the manufacturer to have an accuracy to within ±50 ppm, be factory calibrated, and be calibrated periodically as recommended by the manufacturer.

HV27 Exhaust Air Systems

Zone exhaust airflows (for restrooms, janitorial closets, and break rooms) should be determined based on the most recent edition of ASHRAE Standard 62.1 but should not be less than the values required by local code unless approved by the authority having jurisdiction.

Central exhaust systems for restrooms, janitorial closets, and break rooms should be interlocked to operate with the air-conditioning system, except during unoccupied periods. Such a system should have a motorized damper that opens and closes with the operation of the fan. The damper should be located as close as possible to the duct penetration of the building envelope to minimize conductive heat transfer through the duct wall and avoid having to insulate the entire duct. During unoccupied periods, the damper should remain closed and the exhaust fan turned off, even if the air-conditioning system is operating to maintain setback or setup temperatures. Design exhaust ductwork to facilitate energy recovery from exhaust taken from spaces with air quality classification of 1 or 2 (e.g., restrooms) per Table 6.1 of Standard 62.1 (ASHRAE 2016d). This exhaust air and the relief air exhausted to properly pressurize the building should both be used to recover energy. The exhaust fan must have variable-speed capability. The zone exhaust airflows with required minimum flow per code, such as restrooms, should be measured and controlled with dampers to ensure these minimums are maintained as the exhaust fan speed is reduced to maintain building pressure (see Figure 5-61). This will occur when DCV is implemented.

The exhaust fan system should be controlled to minimize the pressure differential across the building envelope in all spaces. In a low-rise building with low stack effect, the intake outdoor and exhaust airstreams should be balanced to neutralize pressure differential. For taller buildings with significant stack effect, the topmost or bottom floors may need outdoor air to be either oversupplied or undersupplied to neutralize stack-effect-driven pressure differentials. Uncontrolled infiltration or exfiltration through the building envelope can cause cooling and heating loads to increase and do harm to the building. Each zone of the building with a DOAS or central VAV system will have a central relief fan that should modulate to maintain building pressure for that zone (see Figure 5-61). Controlling the zone pressure directly controls infiltration and exfiltration and also ensures that the exhaust energy available is recovered. The building envelope needs to be sealed properly (see EN27 through EN29) so the HVAC system and DOAS unit can work effectively. The demand-controlled system should also ensure flow is not unbalanced by not reducing the outdoor air flow rate below what the exhaust air flow rates are required to be by code.

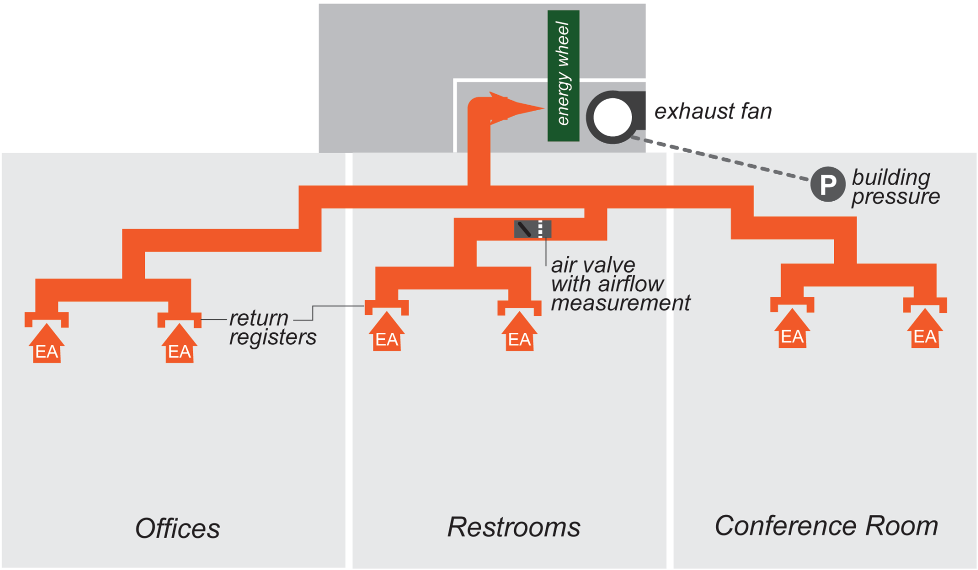


Figure 5-61 (HV27) **Exhaust Air Measurement**

HV28 Relief versus Return Fans

Relief (rather than return) fans should be used when necessary to maintain building pressurization during economizer operation. Relief fans reduce overall fan energy use in most cases, as long as return dampers are sized correctly, because overcoming the total pressure drop of the air supply and return system is more efficient when using one fan than when using two fans (supply and return) in series. The relief fan only moves enough air to keep the building from developing positive pressure, which typically is far less air than is moved by the return fan. Relief fans can be controlled to maintain neutral building pressure per ASHRAE Guideline 16, *Selecting Outdoor, Return, and Relief Dampers for Air-Side Economizer Systems* (ASHRAE 2018b).

HV29 Energy Recovery Frost Control

Energy recovery heat exchangers have a risk of frosting; this is especially a concern for climate zones 4–8. Frosting occurs when the exhaust air is cooled below the condensing point. Total recovery devices can help minimize this risk by transferring water vapor from the exhaust air to the supply air. The primary factor that causes frosting conditions is the humidity of the exhaust air from the space. To accurately predict frosting risk, entering exhaust air conditions at design should be calculated. Overestimating the indoor relative humidity of the office will reduce the amount of energy recovery and initiate frost prevention measures when not needed. Table 5-28 shows an example frost chart for a 75% total effective energy recovery wheel. Frost prevention is accomplished by either preheating the outdoor air to the predicted frost point or reducing the energy recovery capacity to reduce risk of exhaust air condensing. For example, when using electric preheat before the energy exchanger at an indoor design relative humidity of 30% rh, the outdoor air needs to be preheated to –3°F (not 32°F) to prevent frosting.

HV30 Indirect Evaporative Cooling

In dry climates, such as climate zones 2B, 3B, 4B, and 5B, incoming ventilation air can be precooled using indirect evaporative cooling. For this strategy, the incoming ventilation air (the primary airstream) is not humidified; instead, a separate stream of air (the secondary or heat rejection stream) is humidified, dropping its temperature, and is used as a heat sink to reduce the temperature of the incoming ventilation air.

Table 5-28 (HV29) Example Frost Point for Energy (with 75% Total Effectiveness and 70°F Space Conditions)

Indoor Relative Humidity	Outdoor Air Temperature
40%	5°F
30%	–3°F
20%	–14°F
15%	–22°F

The source of the heat rejection stream of air can be either outdoor air or exhaust air from the building. If the air source is exhaust air, this system becomes an alternative for HV27.

Sensible heat transfer between the ventilation airstream and the evaporatively cooled secondary airstream can be accomplished using plate or tubular air-to-air heat exchangers, heat pipes, or a pumped loop between air coils in each stream. For indirect evaporative coolers that use exhaust air as the secondary stream, the evaporative cooler can also function for sensible heat recovery during the heating season. If a runaround loop is used for heat transfer both for indirect evaporative cooling and heat recovery, the circulating fluid should incorporate antifreeze levels appropriate to the design heating temperature for that location.

Indirect evaporative cooling has the advantage that the indoor air quality (IAQ) is not affected, as the evaporative cooling process is not in the indoor airstream. Air quality is not as critical for the exhausted secondary airstream as it is for the ventilation stream entering the occupied space.

Indirect evaporative coolers should be selected for at least 90% evaporative effectiveness for the evaporatively cooled airstream and for at least 65% heat transfer efficiency between the two airstreams.

Indirect evaporative coolers should also be selected to minimize air pressure drop through the heat exchangers.

HV31 Evaporative Condensers

Evaporative condensers on rooftop DX packaged units (system A and DOAS units) can be considered in dry climates (i.e., climate zones 2B, 3B, 4B, and 5B) or low-wet-bulb climates to improve energy efficiency. These devices take advantage of the low ambient wet-bulb temperature in order to improve energy efficiency by coupling convective heat rejection with the evaporation of water off of wetted heat rejection condenser coils. In dry climates, up to 40% reduction in energy use can result.

Generally speaking, all of the wetted components and the condenser section should be designed for corrosion resistance to ensure reasonable equipment life. Some air-cooled package equipment can be retrofitted with evaporative precoolers before the condensing coils. A direct evaporative cooling media is placed before the condensing coil and sprayed with water pumped through nozzles. The extra pressure drop to the condenser fan airflow needs to be considered.

Drawbacks to this system include extra first costs, extra weight that arises from the extra equipment and the water in the sump, additional controls, and the need to provide water treatment regimens.

HVAC TIPS FOR ALL SYSTEM TYPES

HV32 Rightsize Equipment

Rightsizing of equipment requires consideration of all applicable load factors to correctly size an HVAC system. While oversizing can be an effective strategy for reducing energy, such as oversizing ductwork to reduce pressure drop losses, unplanned oversizing by relying solely on safety factors can lead to inefficiency. Safety factor multipliers should not be applied to calculations because they can enlarge loads for which the engineer has great confidence. Safety factors should also not be applied so that they serially expand previously applied safety factors. Applying a safety factor at the end of a calculation can also result in larger central equipment (e.g., chillers, boilers) but with no capability to deliver that capacity to conditioned spaces. Thus, the more that is known about the loads, the less safety factors need to be relied upon. The key to rightsizing systems and equipment is the application of strategic factors that will impact the load calculation process. These factors include the following:

- Critical service requirement—the selection of environmental design criteria that are inputs to the load calculation. This includes external and internal environmental conditions, ventilation rates, and other variables. While typical HVAC sizing criteria use 2% cooling conditions (conditions warmer than all but 2% of the hours at a location) and 99% heating conditions (conditions colder than 99% of the hours), certain functions may require different "strategic factors." For example, outdoor air systems with energy recovery should be designed to 1% wet-bulb conditions to recognize actual dehumidification requirements.
- Uncertainty factors should be applied to descriptive parameters when uncertainty exists. All known loads should be accounted for as accurately as possible. These might include the U-factor of a wall in an existing building. Analysis might reveal a range of U-factors for a given wall, depending on the exact material used, the exact dimensions, and the quality of the construction. For the load calculation, an informed decision should be made about the likely "worst" U-factors that might result from this construction. Uncertainty factors may also be applied to parameter estimations for future use and operation different form the initial program. They may also be applied to the diversity assumptions described in the next item in this list. As a general rule, uncertainty factors should be applied directly to parameters for which the designer has uncertainty concerning the actual parameter value. They should be directed at minimizing the risk of uncertainty for specific parameters that affect the load.
- Diversity assumptions include both the spatial and temporal aspects of diversity. Diversity factors reduce the magnitude of overall loads because they establish the extent to which peak-load component values are not applicable over the entire extent of the building operation. As an example, in an auditorium, either the hall or the lobby can have a certain maximum occupant density, but they almost certainly will not have maximum occupancy simultaneously. Similarly, certain areas of an office building may have equipment power densities as high as 3 or 4 W/ft^2, but almost certainly, the entire building will not. Determination of these diversity factors is an exercise that should involve the architect, engineer, and owner, to avoid future disagreement. It is important to note that diversity factors are independent of schedules and as such must be reviewed with the schedules to ensure that the appropriate level of fluctuation is accounted for only once (especially when the schedule is a percent-of-load type of schedule). While agreed-upon schedules capture known temporal variation of load components, diversity factors capture the uncertain variance of these components. Diversity assumptions, like uncertainty factors, should be applied to the actual parameters that are diversely allocated rather than any value that results from a subsequent calculation.

  Diversity factors may also be applied in sequence as the fraction of the building area to which they are applied becomes greater, because the likelihood that all served areas will be operating at peak intensity becomes less as the area grows larger. From a systems standpoint, this approach may mean that no diversity factor for plug loads is applied for single terminal units, while a moderate diversity factor (90%) is applied to sizing trunk ducts, a 70% plug-load diversity factor is applied for serving central AHUs, and a 50% factor is used for sizing the chiller plant.
- A redundancy factor reflects the need to upsize components or distribution systems to accommodate continued operation during a planned or unplanned component outage. A typical application of a redundancy factor is a design that meets the heating load require-

ment with two boilers each sized at 75% of the calculated heating load. Even if one of the boilers fails, the building will remain comfortable throughout most weather conditions and will be, at least, minimally habitable in the most extreme conditions. Redundancy factors almost always involve meeting capacity requirements with more than one piece of equipment. If the capacity requirement is met by a large number of units, as is often the case with a modular boiler plant, a prudent redundancy requirement may be met without upsizing the plant to any extent or affecting operating efficiency. Meeting the load with a greater number of smaller units may increase part-load operating efficiency. Once again, this factor is determined in concert with the entire project team, including the owner.

HV33 Economizer and Free Cooling

The extremely-high-performance building envelope required for zero energy office buildings results in very low heating loads, despite the very low user equipment power density implied by the EUI limitation. It also places the building in cooling mode even when the outdoor air temperature is very low. An important characteristic of the resulting load profile is a very low balance-point temperature, defined as the outdoor ambient dry-bulb temperature at which heat losses through the envelope balance internal and solar heat gains. Reduced infiltration is a significant contributor to this load reduction, through the use of continuous air barriers and architectural envelope details for minimizing infiltration. Figure 5-62 provides a qualitative illustration of relative values of balance-point temperature for different levels of building envelope performance.

The upshot of the low balance-point temperature is the need to exploit available free-cooling opportunities whenever exterior conditions permit to avoid excessive cooling energy consumption. In residential applications, operable windows might suffice, but for other types of applications, air-side economizers or waterside economizers can be very beneficial. Also, intelligent control of any energy recovery device on the ventilation air supply should maximize free cooling to the building when it is in cooling mode and when the outdoor conditions are beneficial.

Air-Side Economizer. Air-side economizing is more effective than waterside economizing because it provides free cooling at higher-enthalpy ambient conditions than waterside econ-

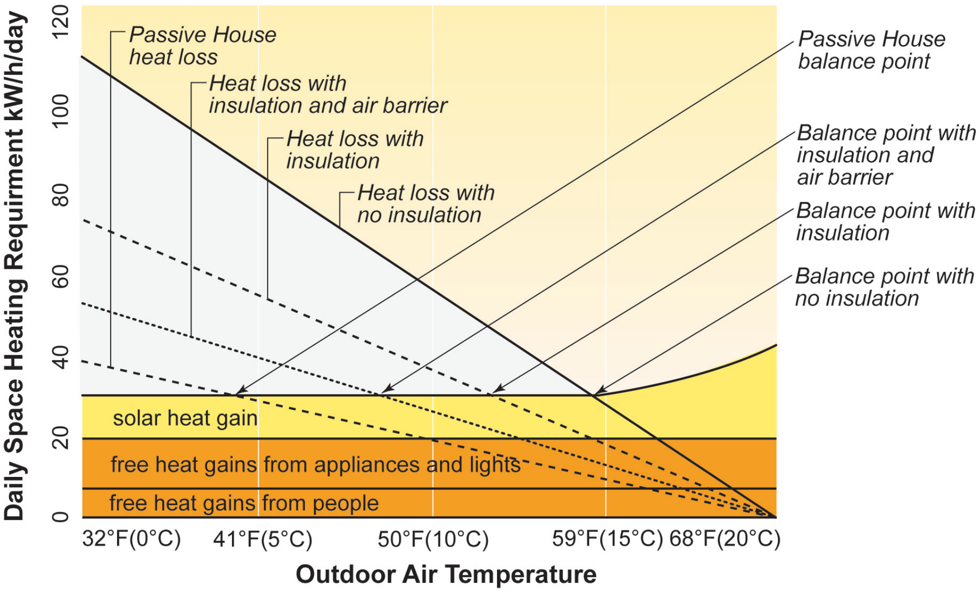


Figure 5-62 (HV33) Heating Requirements for Different Envelope Performance Levels as a Function of Outdoor Temperature

omizing and is more easily integrated into centralized systems such as system A. The strategy of air-side economizers is to substitute outdoor air for the recirculated air that returns from the space whenever that substitution results in a reduced load on the cooling coil. Air-side economizers increases energy efficiency because they are not subject to the same approach temperature as waterside economizers, do not entail water consumption, and have no cooling tower fans or water pumps required for operation.

Control of air-side economizers is a hotly contested issue, particularly with respect to the impact of sensor errors and calibration issues for enthalpy and humidity sensors. ASHRAE/IES Standard 90.1 (ASHRAE 2016b) publishes specifications for control of air-side economizers (see Table 5-29). The specifications in Table 5-29 have been truncated to include only those options that use dry-bulb temperature sensors, because owners and operators of small to medium office buildings may not wish to assume the burden of maintaining humidity sensors.

Waterside Economizer. Waterside economizing is only applicable for systems that incorporate water-cooled refrigeration and transport of cooling to space-cooling devices (AHUs, fan-coils, radiant panels, or chilled beams) using chilled-water cooling. This Guide does not discuss cooling towers, so the free-cooling option discussed here is a dry cooler attached to the air-cooled chiller for system D. The dry cooler reroutes the chilled water from the evaporator of the water chiller to the dry cooler when the outdoor air temperature is low enough that the dry cooler can generate chilled water at the required temperature.

The first step for determining waterside economizer performance is to establish the room sensible part-load fraction at waterside economizer conditions. For many buildings, the room sensible part-load fraction at low temperature, including the free cooling component of ventilation air, will be below 50% of the room sensible full load. Dry coolers are typically selected at about 20°F approach at full load. At 50% full load, that approach would be approximately 10°F, such that if 55°F chilled water is required, free cooling will be available when the outdoor air dry-bulb temperature falls to 45°F. Note that waterside economizer utilization likely entails addition of antifreeze (ethylene glycol) to the chilled-water loop, such that water flow and pump calculations should take into account the decreased specific heat and increased viscosity of the water/glycol solution

System D utilizes high-temperature (55°F) chilled-water fan-coils to provide sensible cooling only to the space, with all dehumidification provided by the DOAS unit. The fan-coils should be selected to increase the thermal coupling between the device and the space, minimizing the approach of the leaving SAT to the entering cooling-water temperature, minimizing the fan energy penalty of utilizing higher temperature chilled water. Because the coils in these fan-coils are not dehumidifying and are dry, pressure drop for any given coil will be reduced as much as 65% compared with wet coils. Using 8 row, 10 fpi coils, combined with reducing the coil face velocity to no more than 430 fpm, enables reduction of the approach of the coil leaving air dry-bulb temperature to the chilled-water entering temperature to 3°F. Radiant ceiling panels and chilled beams are also usually designed for a chilled-water temperature of 55°F or higher.

Table 5-29 (HV33) Recommended Control for Air-Side Economizers (ASHRAE 2016b)

Control Type	Allowed only in CZ at Listed Set Point	Required High-Limit Set Points (Economizer OFF when):	
		Equation	Description
Fixed dry-bulb temperature	0B, 1B, 2B, 3B, 3C, 4B, 4C, 5B, 5C, 6B, 7, 8	$T_{OA} > 75°F$	Outdoor air temperature exceeds 75°F
	5A, 6A	$T_{OA} > 70°F$	Outdoor air temperature exceeds 70°F
	0A, 1A, 2A, 3A, 4A	$T_{OA} > 65°F$	Outdoor air temperature exceeds 65°F
Differential dry-bulb temperature	0B, 1B, 2B, 3B, 3C, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, 8	$T_{OA} > T_{RA}$	Outdoor air temperature exceeds return air temperature

HV34 Natural Ventilation and Natural Free Cooling

Natural ventilation and natural free cooling should be recognized as separate but related functions. Ventilation is a regulated function, providing specific rates of outdoor airflow to specific occupancies and specific populations. Cooling is the maintenance of thermal conditions but, in most circumstances, is not a regulated activity. While both of these activities usually occur together, it is quite possible, and sometimes desirable, to have natural free cooling in concert with mechanical ventilation to achieve enhanced energy efficiency while ensuring that all space occupants have adequate ventilation.

Natural ventilation through operable windows, skylights, and operable vents in the building envelope can be a very effective energy-conservation strategy, but it requires either sophisticated and often expensive automatic control systems or well-trained and attentive building occupants to avoid using more energy than is saved. Clearly, excess outdoor air inflow to the building, when exterior conditionings are inopportune, increases building energy consumption. On the other hand, de-energizing the building conditioning system when exterior conditions can be used to maintain interior comfort requirements can result in significant energy savings.

The recognized limitations of ambient conditions being able to maintain interior comfort requirements through operable windows are an upper dry-bulb temperature limit of 68°F and a lower temperature limit of 48°F. Ambient temperatures higher than the upper limit cannot provide adequate cooling, especially to spaces significantly inboard of the building envelope, while temperatures below the lower limit result in diminished comfort conditions adjacent to the window. Another limitation to natural conditioning is the humidity content of the ambient air. If the dew-point temperature of the ambient air is greater than approximately 62°F, the interior relative humidity resulting from natural ventilation will likely be too high to maintain comfort.

If natural ventilation is being considered as a strategy for reducing energy consumption and providing a better work environment, it is recommended that the building design be modeled using a computational fluid dynamics (CFD) program. To successfully integrate this strategy, building orientation should align with prevailing wind patterns. (This may conflict with the best daylighting orientation.) Air inlet and outlet openings should be positioned to promote air flow through the rooms. The design team typically models several architectural design approaches to maximize thermal comfort in the zone. See Chapter 4 for an example of CFD analysis.

Natural conditioning can be used in office buildings in concert with interior thermal mass to reduce daytime cooling needs. If the overnight dry-bulb temperature falls below 60°F, the building can be “flushed” overnight to cool the internal thermal mass and the resulting cooling will be “stored” to reduce daytime cooling needs. The designer should recognize, however, that just as there is internal thermal mass, there is also internal moisture mass. The porous materials in the space, including carpets, fabrics, paper, and unsealed wood, have the ability to absorb moisture from humid air and slowly release that moisture when exposed to less humid air. In humid climates, overnight low dry-bulb temperatures may be coincident with very high relative humidity, so that overnight flushing may purge the building of sensible heat while charging it with moisture that will later appear as latent load for the air-conditioning system. In dry climates, overnight flushing in concert with thermal mass can result in significant energy savings.

Natural ventilation has less cooling capacity than mechanical cooling, so it is therefore even more important to design carefully to limit internal and envelope loads. Utilization of natural conditioning may also be limited by unusually poor outdoor air quality or high degrees of outside noise. Natural ventilation works best when the building owner and occupants are well educated about what to expect about the building performance and are willing to become an active and integral part of the building’s operation.

HV35 Minimizing Fan and Pump Energy

Transport energy can be up to 40% of the total amount of energy used to heat and cool a space. While zero energy building use less than typical buildings, this can be an area of concern for energy use and, left unchecked, an area that needs regular maintenance. Transport energy occurs in air systems through the ductwork and in hydronic systems through the piping. Both need to be systemically designed for zero energy buildings.

Filtration. Simply put, to reduce the amount of energy used by an air-side system, the air should be transported as efficiently as possible, and all the air should get to its required location, minimizing its loss of pressure drop, energy, and volume.

Filtration systems are typically selected for a peak design criterion. Pressure drop on filters is minimized by increasing the face area of the filter system. This can be accomplished by an angled filter rack in central equipment. Throughout the operation of the equipment, maintaining the design pressure drop is accomplished by regularly maintaining the filtration system. Use a filter differential pressure gage to monitor the pressure drop across the DOAS or VAV unit filters and send an alarm if the predetermined pressure drop is exceeded. Filters should be replaced when the pressure drop exceeds this alarm value. Using a pressure gauge may not be possible across the filters on the terminal units, such as heat pumps, VRF, and fan-coil units, because accurate sensing is not possible. For this equipment, scheduled filter changes should be in place to minimize fan energy for this equipment. The gages should be checked and the filters should be visually inspected at least once every three months.

Duct Design. Good duct design practices result in lower energy use. Low pressure loss and low air leakage in duct systems are critical to lowering the overall fan energy. Lowering the pressure needed to overcome dynamic pressure and friction losses will decrease the fan motor size and the needed fan energy. Refer to chapter 21 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2017d) for detailed data and practices.

In general, the following sizing criteria should be used for duct system components:

- Diffusers and registers, including balancing dampers, should be sized with a static pressure drop not to exceed 0.08 in. w.c. Oversized ductwork increases installed costs but reduces energy use due to lower pressure drop.
- Supply ductwork should be sized with a pressure drop no greater than 0.08 in. w.c. per 100 lf.
- Return ductwork should be sized with a pressure drop no greater than 0.04 in. w.c. per 100 lf.
- Exhaust ductwork should be sized with a pressure drop no greater than 0.05 in. w.c. per 100 lf.
- Flexible ductwork should be of the insulated type and should be
  - limited to connections between duct branches and diffusers or between duct branches,
  - limited to 5 ft (fully stretched length) or less,
  - installed without any kinks,
  - installed with a durable elbow support when used as an elbow, and
  - installed with no more than 15% compression from fully stretched length.
- Hanging straps, if used, need to use a saddle to avoid crimping the inside cross-sectional area. For ducts 12 in. or smaller in diameter, use a 3 in. saddle; those larger than 12 in. should use a 5 in. saddle.
- Long-radius elbows and 45° lateral take-offs should be used wherever possible. The angle of a reduction transition should be no more than 45° (if one side is used) or 22.5° (if two sides are used). The angle of expansion transitions should be no more than 15° (laminar air expands approximately 7°).

Duct Insulation and Testing. Duct insulation should be installed to ensure conditioned air reaches the space with as minimal loss as possible. All ductwork should be insulated, and for zero energy buildings, no ductwork should be located outside the thermal envelope such as in attics, in crawlspaces, or on the roof.

The ductwork should be sealed to ensure all air is supplied to the conditioned space. All duct joints should be inspected to ensure they are properly sealed and insulated, and the ductwork should be leak tested at the rated pressure. The leakage should not exceed the allowable cfm/100 ft^2 of duct area for the seal and leakage class of the system's air quantity apportioned to each section tested.

After the system has been installed, cleaned, and placed in operation, the system should be tested, adjusted, and balanced in accordance with ANSI/ASHRAE Standard 111 (ASHRAE 2017a) or the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) TAB manual (2002).

Piping Considerations. Hydronic systems should be designed for variable flow and be capable of reducing pump flow rates to 30% or less of the design flow rate. Care should be taken to maintain the minimum flow through each chiller as defined by the chiller manufacturer.

Using a smaller pipe size increases the pressure drop through the pipe, increases the velocity through the pipe, and may cause erosion to occur if the velocity is too high. A larger pipe size results in additional pump energy savings but increases the installed cost of the pipe. In systems that operate for longer hours, larger pipe sizes are often very economical.

Energy use and installed costs are typically both reduced by selecting a chilled-water ΔT of 12°F to 20°F rather than the traditional 10°F (ASHRAE 2015b). This saves pump energy, permits the reduction of pipe sizes (reducing installation costs), and minimizes pump heat added to the water because of the use of reduced pump horsepower, but it also affects cooling-coil performance. This can be overcome by lowering the chilled-water temperature to deliver the same air conditions leaving the coil. Chilled-water temperature set points should be selected based on a life-cycle analysis of pump energy, fan energy, and desired air conditions leaving the coil.

HV36 Electronically Commutated Motors

Electronically commutated motors (ECMs) electronically control voltage and current. They have a permanent magnet applied to the motor and a stator with electrical windings that generate a rotating magnetic field. As the rotor moves, it commutates the stator windings (i.e., switches phases of the magnetic poles) (Roth et al. 2004). ECMs operate without slip-losses, as opposed to alternating-current (AC) induction motors, and therefore are inherently more efficient. In addition, the electronic commutation provides a convenient means for speed control. Minimum full-load efficiency requirements for a permanent split capacitor (PSC) motor, per ASHRAE/IES Standard 90.1 (ASHRAE 2016b) range from 65% to 85% depending on motor size, while the full-load efficiency of an ECM ranges from 70% to 90%. However, the efficiency of a PSC motor drops dramatically in part-load conditions, often falling below 40%, while the efficiency of an ECM remains high. Market factors have driven down the cost and price of these motors, and manufacturers now manufacture ECMs up to 15 hp. These motors are also more reliable, have an inherent soft start, and have a longer motor life (Nall 2016). Wherever possible, ECMs should be specified to improve energy efficiency, especially in fractional horsepower motor sizes.

HV37 Thermal Zoning 🔒 $

The HVAC systems discussed in this Guide simplify thermal zoning because each thermal zone has a respective terminal unit. The temperature sensor for each zone should be installed in a location that is representative of the entire zone.

Thermal zoning should also consider building usage during the unoccupied hours. Depending on the office schedule, the building may be used for alternative events and/or include non-regular-schedule-work-hour programs. It is important to identify the spaces that may typically be used for these events and arrange the building design so that these spaces are isolated in one area. This will minimize the equipment needed to operate during these atypical hours and limit the DOAS unit ventilation air supplied during these periods.

Arranging similar occupancies on the same building exposure provides the design team with the option of using one terminal unit to serve two offices. Each office can be provided with a temperature sensor, and the unit will respond to the average condition. This design approach is often used to reduce first costs and long term maintenance costs.

HV38 System-Level Control Strategies

System-level control strategies exploit the concept that conditioning and ventilation are for the health and comfort of the occupants and control set points may be modified in pursuit of energy savings when occupants are not present. Having a setback temperature for unoccupied periods during the heating season or a setup temperature during the cooling season can help save energy by avoiding the need to operate heating, cooling, and ventilation equipment. A good design approach is to equip each zone with a zone temperature sensor and then use a system-level controller that coordinates the operation of all components of the system. This system-level controller contains time-of-day schedules that define when different areas of the building are expected to be unoccupied. During these times, the system is shut off and the temperature is allowed to drift away from the occupied set point. Similarly, when occupants are not present, ventilation may not be required, and DOAS system delivery to the space may be eliminated. This control strategy is different from DCV in that some ventilation is required during the occupied period even if no occupants are present.

Optimal start uses a system-level controller to determine the length of time required to bring each zone from the current temperature to the occupied set-point temperature. The controller waits as long as possible before starting the system so that the temperature in each zone reaches the occupied set point just in time for occupancy. This strategy reduces the number of hours that the system needs to operate and saves energy by avoiding the need to maintain the indoor temperature at the occupied set point when the building is unoccupied. Controlling energy usage outside of normal operating hours is most successful when the usage culture can be changed. Refer to Chapters 2 and 3 for more information on achieving culture change.

Control systems should include the following:

- Control sequences that easily can be understood and commissioned.
- Use of a room motion sensor to set back temperatures during the occupied period when no usage is occurring in the room. Also, many times a room may be scheduled ON during the unoccupied period for a function. The room motion sensor will ensure the unit operates only when the room is occupied.
- A user interface that facilitates understanding and editing of building operating parameters and schedules.
- Optimal-start systems as a means to limit demand during start-up so the peak demand is not inadvertently set during start-up.
- Sensors that are appropriately selected for range of sensitivity and ease of calibration.
- Means to effectively convey the current status of systems operation and of exceptional conditions (faults).
- Means to record and convey history of operations, conditions, and efficiencies.
- Means to facilitate diagnoses of equipment and systems failures.
- Means to document preventive maintenance.

HV39 Employing Proper Maintenance

Continued performance and control of operation and maintenance (O&M) costs require a maintenance program. O&M manuals provide information that the O&M staff uses to develop this program. Detailed O&M system manual and training requirements are defined in the Owner's Project Requirements (OPR) and executed by the project team to ensure the O&M staff has the tools and skills necessary. The level of expertise typically associated with O&M staff for buildings covered by this Guide is generally much lower than that of a degreed or licensed engineer, and staff typically need assistance with development of a preventive maintenance program. The CxP can help bridge the knowledge gaps of the O&M staff and assist the owner with developing a program that will help ensure continued performance. The benefits associated with energy-efficient buildings are realized when systems perform as intended through proper design, construction, operation, and maintenance.

HV40 Commission Systems and Equipment

After the system has been installed, cleaned, and placed in operation, it should be commissioned to ensure that the equipment meets the intended performance and that the controls operate as intended. While ASHRAE/IES Standard 90.1 requires testing, balancing, and Cx (ASHRAE 2016b), the recommended level of Cx should go further. The CxP should provide a fresh perspective that allows identification of issues and opportunities to improve the quality of the construction documents and verify that the OPR is being met. Issues identified in the design review can be more easily corrected early in the project, providing potential savings in construction costs and reducing risk to the team.

Performance testing is essential to ensure that commissioned systems are properly implemented. Unlike most appliances these days, none of the mechanical/electrical systems in a new facility are “plug and play.” Functional test procedures are often written in response to the contractor’s detailed sequence of operations. The CxP will supervise the controls contractor running the equipment through its operations to prove adequate automatic reaction of the system to artificially applied inputs. The inputs simulate a variety of extreme, transition, emergency, and normal conditions.

If it is possible to do, it is useful to operate and monitor key aspects of the building for a one-month period just before contractor transfer to verify energy-related performance and the final set-point configurations in the O&M documents. This allows the building operator to return the systems to their original commissioned states (assuming good maintenance) at a future point, with comparative results.

Final acceptance generally occurs after the CxP’s issues noted in the issues log have been resolved, except for minor issues the owner is comfortable with resolving during the warranty period.

HV41 Noise Control

Acoustical requirements may necessitate attenuation of the supply and/or return air, but the impact on fan energy consumption should also be considered and, if possible, compensated for in other duct or fan components. Acoustical concerns may be particularly critical in short, direct runs of ductwork between the fan and supply or return outlet (see Figure 5-63).

Avoid installation of the air-conditioning or heat pump units above occupied spaces. Consider locations above less critical spaces such as storage areas, restrooms, corridors, etc. (see Figure 5-63).

Chapter 48 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015c) is a potential source for recommended background sound levels in the various spaces that make up office buildings.

THERMAL MASS

HV42 Thermal Mass Concept Overview

The thermal mass of the building structure can be incorporated into the building conditioning system in several ways, both to improve comfort and to reduce energy consumption by shifting heating and cooling loads. The overall success of using thermal mass to shift cooling or heating loads is directly related to how much internal heat gain there is to how much mass the building has, along with the control strategies used by the heating and cooling system to exploit the effects of the thermal mass. Utilization of passive thermal mass both inside the building and external to the building thermal envelope is discussed extensively in EN9 through EN11.

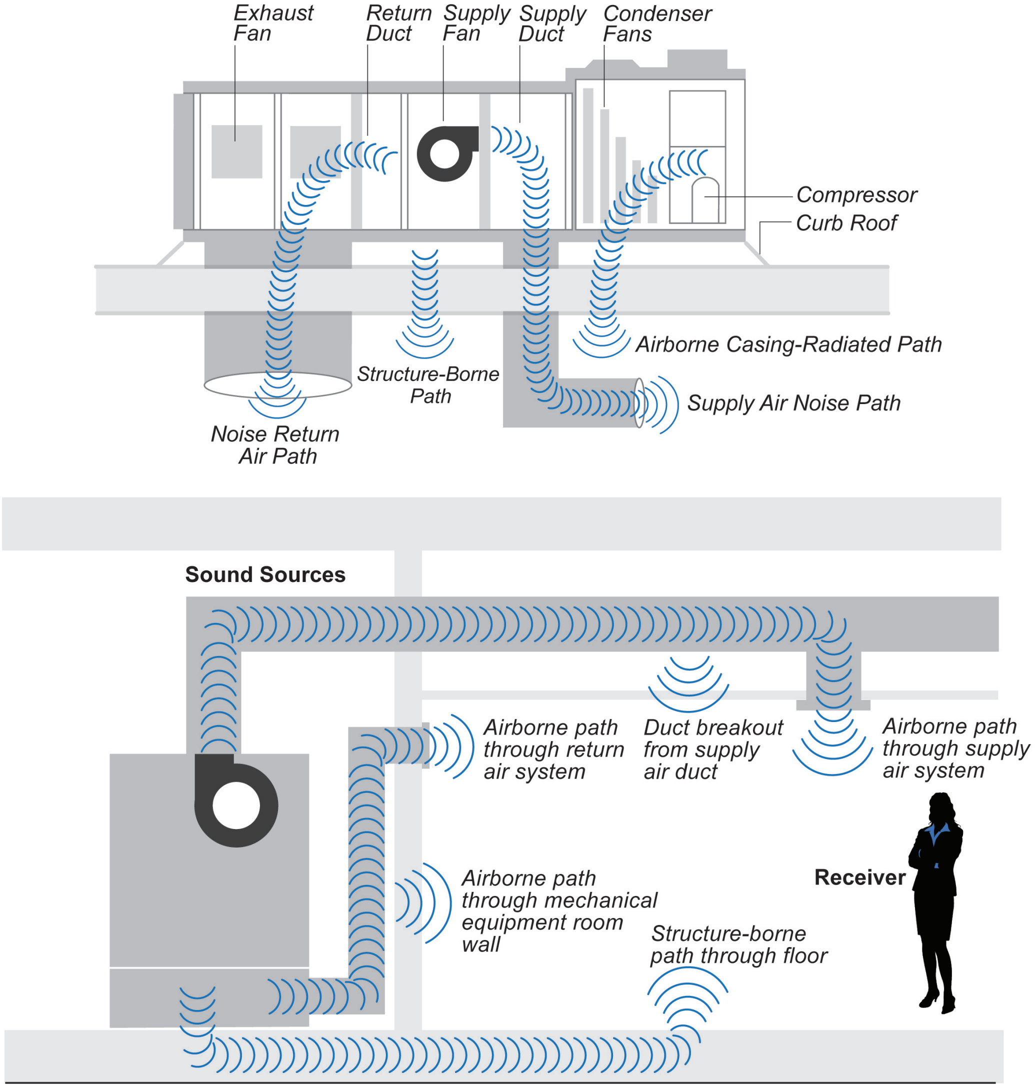


Figure 5-63 (HV41) **Typical Noise Paths for Interior-Mounted HVAC Units**

HV43 Active versus Passive Thermal Mass $

Passive thermal mass is thermal mass whose temperature is driven by convective or radiant interaction with the air or the sun. Heat transfer into or out of the mass is not under active control and is usually driven by variation in air temperature or radiant flux. Exploitation of internal thermal mass, therefore, usually requires a larger variation of internal air temperature than the variation of temperature in the thermal mass.

Active thermal mass, on the other hand, can be used to moderate interior air temperature variations. Typically, the active thermal mass is charged or discharged with embedded hydronic tubes or air passages. Conditioning fluid is passed through these conduits to control the temperature of the thermal mass independently of the air temperature. Examples of active thermal mass elements include floor slabs, ceiling slabs, and even the entire internal horizontal structures of buildings. The thermal mass can dampen significant variations in thermal loads, resulting in less variation of comfort conditions. Thermal mass can be precooled before the start of the day to mitigate daytime cooling requirements. Conditioning to the thermal mass can be terminated before the end of the day, and the thermal mass will maintain space conditions until the end of the operating period. Using natural ventilation at night to precool building spaces for daytime use is discussed in HV34. Active thermal mass can be used as the primary vehicle to maintain the heat balance of a space and constrain internal temperatures within the comfort range. Note that active thermal mass neither ventilates nor, hopefully dehumidifies, so that air systems are required to provide these two functions of the building environmental system. The heating and cooling sources for active thermal mass may require a significantly lower deviation from the average interior temperature because of the extensive surface area of the massive element available. Commonly, active thermal mass elements are cooled with chilled water no cooler than 60°F and heated with hot water no warmer than 110°F—enabling heating and cooling sources to operate with much greater efficiency than when they are generating the more extreme heating and cooling temperatures required by conventional heating and cooling delivery methods.

Thermal storage is a special case of active thermal mass wherein both the charging of the thermal mass is actively controlled and the coupling of the thermal mass to the space is also controlled. This strategy can be used to create conditioning potential independently of space operation and to apply the conditioning to the space in the most energy-efficient way.

Active thermal mass is particularly effective when natural conditioning assets do not occur simultaneously with building conditioning requirements. Examples of these assets include low overnight dry-bulb temperatures, which might allow the active thermal mass to store cooling to be used during the day, and solar heat gain, which might allow heat to be stored during a sunny day to be used for warming the space on the following morning.

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RENEWABLE ENERGY

OVERVIEW

The final step in the process of producing a zero energy building is to include on-site energy generation to offset the remaining building consumption and loads. In most cases, the main focus should be to reduce consumption and loads through energy efficiency and design, since these remain the most effective use of owners' financial resources.

The cost of renewable energy has dropped rapidly in the last decade, driven by declining costs of wind and solar power generation. The focus of this Guide is to provide solutions for the building to achieve zero energy at near or slightly higher than market rates.

For most building owners, photovoltaics (PVs) are a highly versatile renewable on-site energy source and provide the capability for buildings to become zero energy. For this guide, PV systems are considered the primary renewable energy source for getting to a zero energy building.

While some small-scale wind, micro-hydro, and biomass systems are available, they are fairly limited. These renewable energy sources are not discussed in this Guide. Designers should evaluate whether these sources are economically viable for each specific project. Note that wind turbines large enough to produce power for a zero energy building are usually difficult to site on the property, especially in urban and suburban areas.

Since 2010, the cost of PV power generation has dropped more than half as the prices of PV panels and systems equipment have decreased due to worldwide implementation and manufacturing improvements (Fu et al. 2016). The use of solar energy is increasing rapidly. As of 2018, the installed capacity was in excess of 500 GW, having increased over 99 GW in the previous year (IEA 2019). Market prices of most on-site PV installations have achieved grid price parity in many areas of the country. Rates will continue to drop as markets adjust to demand globally.

Other renewable energy systems, such as biomass systems, and the purchase of renewable energy certificates (RECs) do not meet the definition of on-site renewable energy and thus are not considered for this Guide.

RE1 Common Terminology

Photovoltaic systems are made up of an array of PV modules that use sunlight to produce electricity. This electricity is generated as direct current (DC) and must be converted to alternating current (AC) and synchronized with the local utility grid in order to be used in commercial power applications like an office building. PV power generation can be configured in any size to suit the loads of the facility. Besides the PV modules that combine to make the PV array, other equipment is required, such as inverters to convert DC to AC, maximum power point trackers (included in many inverters), disconnecting and combining equipment, mounting hardware, metering equipment, and monitoring equipment. In some cases energy storage devices may be used to help match PV production with actual building loads or for uninterruptible power during a utility outage. A diagram of a typical PV AC system is shown in Figure 5-64.

Understanding common terms from the renewable energy field is useful when discussing the use of renewable energy for a zero energy building. The following definitions are general definitions and may differ from specific definitions provided in zero energy standards or certification programs.

Renewable energy refers to energy that is produced from a fuel source that cannot be exhausted, like sunlight or wind. Coal and natural gas are two fuel sources that have limited supplies and are considered nonrenewable.

Photovoltaic (PV) refers to a type of energy production that uses light to directly generate electricity. Sunlight striking a semiconductor material is converted directly to electricity. More about PV panels and the materials used in creating PV panels can be found at the

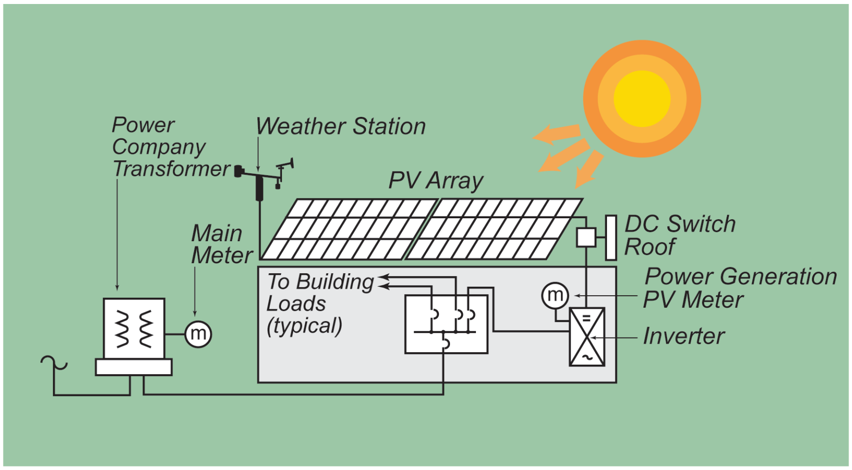

Figure 5-64 (RE1) Typical PV AC System Diagram

National Aeronautics and Space Administration (NASA) Science webpage "How Do Photovoltaics Work?": https://science.nasa.gov/science-news/science-at-nasa/2002/solarcells (NASA 2019).

Interactive or *grid-tied PV systems* are those that operate with the AC utility grid. Grid-tied PV systems must be synchronized with the grid voltage and phase to ensure that issues of flicker, harmonic distortion, frequency, and voltage fluctuation do not occur. The PV system is disconnected from the grid whenever voltage and frequency do not meet utility requirements or when there are utility power outages.

Standalone PV systems are not connected to the building power infrastructure. They are typically used for small applications and often use battery storage to operate when the solar energy is not available. Though not widely used in commercial buildings, they are sometimes used for smaller loads such as traffic signs, street lights, and bus shelters.

Wind power is the production of electricity from wind. More information about wind power production can be found at the EERE "Wind Energy Basics" webpage: https://www.energy.gov/eere/wind/wind-energy-basics (EERE 2019).

Energy storage devices are devices with the capability of storing energy, such as batteries.

Net metering is where the renewable energy generated offsets power consumption at the facility. When on-site generation is more than the building consumption, the excess power is sent to the utility. The utility bill shows the net energy flow, or the difference between the energy supplied from the utility and the energy sent to the utility. The amount of energy purchased (or sold if the facility overgenerates) is used as the basis for the billing (NREL 2019a). Note that for a facility to claim the renewable attributes, the facility must retain the RECs. A typical PV single-line diagram illustrating a net metered system is shown in Figure 5-65.

Sell-all metering is metering of the PV system where all of the power generated is sold to the utility and is not used to directly offset facility electricity consumption. Compensation is an important component of the sell-all system.

Renewable energy certificates (RECs) are also sometimes called *renewable energy credits*, *renewable electricity certificates*, *green tags*, or *tradable renewable certificates* and provide a mechanism for purchasing the renewable attribute of the energy from the electricity grid. A certificate documents that one megawatt-hour of electricity has been generated by a renewable energy source and fed into a shared electric grid that transports electricity to

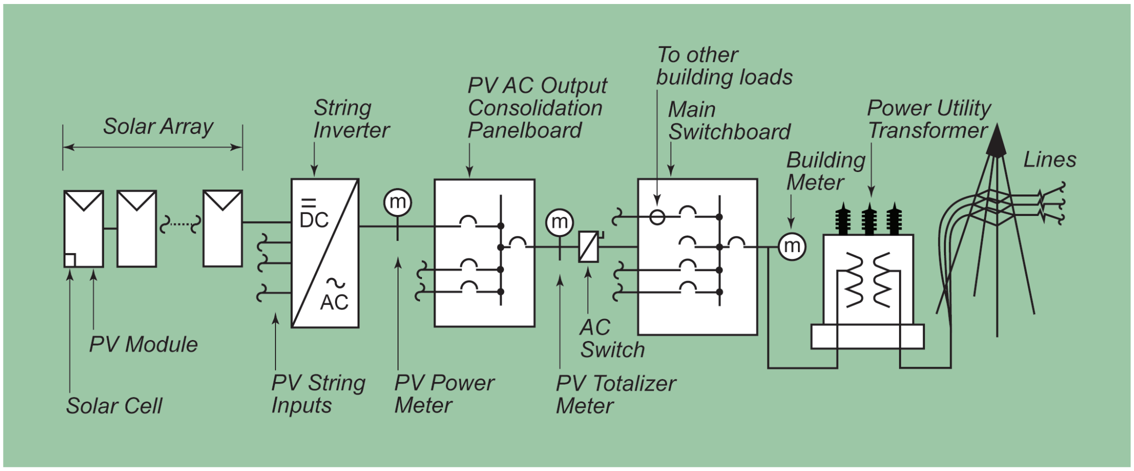

Figure 5-65 (RE1) Typical PV Single-Line Diagram

customers. They are also known as *SRECs* when solar energy is the source of the renewable energy power generation.

Solar renewable energy certificates (SRECs) are RECs specifically generated by solar energy. See *Renewable energy certificates (RECs)* above.

Ground-mounted refers to solar energy PV systems that are mounted at grade level, commonly on "tables" that are structurally anchored to the ground by concrete or pinned foundations that hold the PV panels in place. Ground-mounted PV systems may also include parking canopies and building canopies that provide protection from weather elements such as sun and rain. Typically, the use of ground-mounted solar for building applications is limited to sites with large areas of available ground for installation of the PV panels. PV panels that are ground mounted are usually installed at an angle of around 30°, whereas roof-mounted PV panels are mounted at approximately a 10° tilt to minimize array cost and minimize uplift. From a cost optimization point, it is less expensive to add extra panels to make up for the non-optimal tilt than to pay for additional structures.

DESIGN STRATEGIES

RE2 System Design Considerations

PV panels are specified with two distinct guarantees: performance and manufacturing. Performance guarantees are for a power output over time. A PV panel will degrade slightly over a nominal 25-year system life, so it is important to compare different manufacturers' warranties for degradation of power production over the same time period.

Other considerations include the following:

- Types of PV panels, efficiencies, and quality
- Orientation and panel tilt
- Number of inverters and number of panels
- Rebates and tax credits, if any are applicable
- Type and quality of inverters
- Type and quality of energy storage, if any
- Type of wire and conduit and wire management systems
- Point of connection to building main power switchboard or at utility transformer
- Size and configuration of customer or utility transformers to accommodate PV power input
- Accessibility of roof
- Remote shutdown from building fire alarms and by code officials in order to disconnect all power generation sources
- Type of roof (flat, standing seam metal, or other)
- Additional architectural or structural engineering associated with mounting of PV panels on roof
- Code-required disconnects
- Location of inverters on roof or in the electrical room
- Shading, including trees

Solar-ready design is rooted in determining the optimal placement of potential future solar technology. See BP12 through BP19 for additional information regarding how building orientation, roof form, and shading considerations affect system design.

Panel-mounted inverters are small inverters mounted at each individual panel. These inverters can increase the performance of the system via multipoint panel power tracking (MPPT), which allows panels in the same string to produce varying power without degrading the production of the string and can be used in semi-shaded areas to increase the array's production. These systems should be carefully compared with the costs of centralized inverters to make the best economic decision.

Consider the use of metering separate from the inverter meter. As a best practice, a two-directional meter should be installed on the renewable energy system to capture parasitic losses when the renewable energy system is not generating. An external metering system is an important part of the overall monitoring and measurement and verification (M&V) system for the building. Having this meter allows for verification of performance of the renewable system compared to the modeling.

RE3 *Sizing Renewables for the Zero Energy Goal*

The objective when sizing a renewable system is to balance the energy consumption of the building with the renewable energy. The lower the EUI, the smaller the required renewable system. The size is also limited by the available locations for the PV system, including roof area, façades, or ground. See Chapter 3 for information on setting energy targets and BP14 for infor-mation on calculating the amount of PVs required based on a target EUI and to determine the roof area required. BP15 provides information on maximizing available roof area.Modeling can often predict PV performance based on orientation, weather, and shading. An additional allowance should be made if batteries are included, to account for their inefficiencies.

The design team, in conjunction with the owner, should set a production expectation for the renewable system. Many teams elect to design a renewable energy system to produce at least 110% of the predicted EUI of the building. PV panel degradation over the life of the panel can be offset by overproduction of the system array during the first handful of years. PV systems also have many safeguards that may result in temporary shutdown of the array, reducing its production. Inverter shutdown issues can be caused by lightning strikes leading to blown fuses or moisture penetration into combiner boxes. Electronic notification systems can be installed to notify maintenance staff of issues. In areas where snow is prevalent, long periods of time may exist when snow and ice cover the panels; this is often not modeled, but it will reduce energy output. A slightly larger PV system also covers situations where the building might use a little more energy than anticipated.

NREL's PVWatts® Calculator and System Advisor Model (SAM) are online, interactive tools that can be used to explore system sizing and output potential (NREL 2019b, 2014). See Chapter 4 for more information on these modeling tools.

RE4 *Battery Energy Storage*

Battery storage can be an effective means of reducing peak demand charges and can contribute to a project's overall goals for resiliency. Life expectancy of current technology (lithium ion batteries) is about ten years, depending on the number of discharges.

The use of energy storage is currently at a 15- to 20-year payback period dependent on system design and is trending downward. Until the payback period reaches less than ten years, battery storage may not be financially desirable for reducing utility bills. It does have some other merits, however, such as providing uninterruptible services, demand response, and potential building operations without the utility grid. Many of these attributes are not financially quantifiable but are nevertheless important to building owners.

Battery systems are required to meet UL 924 battery systems (UL 2016) if used for life safety systems including lighting. Once battery storage systems are UL 924 compliant, elimination of redundant generation systems will aid in the reduction of the payback period.

RE5 *Mounting Options*

Once the size of the renewable energy system is determined, the building site can be evaluated for PV panels. Determining whether there is adequate space for the PV modules and equipment is the next most important consideration after sizing considerations. The PV system can be mounted many different ways on the building property.

The most-used location is the roof of the building (Figure 5-8). The type of roof system used can affect the cost of solar installations. In optimizing PV system costs, which include mounting and the PV panels, a tilt of 5° to 10° is common. The reduction in production from the non-optimal tilt is compensated by additional panels—because of the reduced structure, including wind loading, the overall system is less expensive. This also minimizes the shading of the PV panels on other PV panels.

Ballasted systems are much heavier than standoff systems and are used for flat-roof-mounted systems. The roof must be specifically engineered for the number of ballasts, ballast locations, types, effect on roof structural sizing, seismic concerns, and wind loading. The weight distribution tends to be uniform in this type of system. Uplift is a primary concern for PV arrays, especially in high-wind areas like tornado alleys or hurricane zones. The effect of the PV arrays and their attachment points must be considered when designing the roof and building structure. The typical tilt for a flat-roof-mounted system is 5° to 10° to minimize uplift. Maintenance access to the roof should be considered.

Standoff mounting is often used for pitched roofs. In these situations, standoffs are attached to the roof for support rails, to which the PV modules are mounted. Standoff arrays with panels typically add anywhere from 3 to 5 lb/ft^2 of weight; however, they can be designed to coincide with the roof structure. Be cautious that the thermal integrity of the roof is not compromised by the PV system.

Roof-mounted systems should be planned around the replacement of the panels at 25 years and around future roof replacement. The roof selection should be made with the consideration that the PV panels will be covering a large portion of the roof for the life of the PV system. Access should be provided to the roof for periodic maintenance of the PV system. See BP12 through BP19 for more information on roof form, area, durability, longevity, safety, and maintaining solar access.

Ground-mounted and parking-canopy-mounted PV installations are two relatively straightforward applications that can be planned as part of the PV system. While the mounting and racking approach will vary, these installations often use the same types of PV modules (monocrystalline and polycrystalline, and even bifacial modules), with similar solar orientations to roof-mounted applications. However, there is the potential to increase the module tilt (particularly with ground-mounted installations), gaining additional energy-generation performance.

Ground-mounted PV systems are common in larger PV power-generation systems but are only an option where other uses of the land are not anticipated or with complementary uses such as parking or shade structures. A rough rule of thumb is that 2.5 acres is necessary for a 500 kW system, depending on shading factors, module efficiency, location, and orientation. It is not a long-term solution to place a PV system on a piece of land that will be developed. If the land is redeveloped, the PV system is no longer available to the building. See Figure 5-66 for an example of a ground-mounted PV installation.

Covered parking areas may provide another location for siting PV systems. In addition, in hot, sunny climates, parking canopies created by PV panels can serve the additional purpose of shading cars, which reduces fuel consumption for air conditioning. See Figure 5-67 for an example of a parking-canopy-mounted PV system.

RE6 Interconnection Considerations

PV systems on commercial buildings can be configured many ways depending on rate tariffs, regulations, and utility interconnection agreements. In a sell-all mode, all electricity is sold to the utility company and then electricity is purchased from the grid. In other cases, the PV system is on the customer side of the meter; PV energy can be used in the building and any excess is sent (or *sold*) to the utility. When there is insufficient PV power available, power is

Figure 5-66 (RE5) Ground-Mounted PV Installation

Photograph by Paul Torcellini, NREL 55603

Figure 5-67 (RE5) Canopy-Mounted PV System

Used with Permission from CMTA, © Dish Design

drawn from the grid (or *purchased* from the utility). Some rate tariffs use a net metering arrangement where the sold price and the purchased price are the same; some rate tariffs compensate the two power flow directions differently.

In most PV systems, the inverters disconnect the system from the grid during grid failures to prevent electricity from traveling to a grid that is not functioning. In limited cases, inverters can provide power to a building much like an emergency generator—but batteries and emergency circuits must be designed for this application.

For many buildings, the interconnection point must be sized for a solar energy production that operates only a few hours per day yet provides enough energy for the entire year. As soon as the system size has been determined, the utility should be engaged for discussions about electrical configuration, transformer sizes, and rate tariffs. Larger transformers may impact fault currents and impedance on the building's electrical power distribution systems. If the building site is using net metering, the point of interconnection is usually made at the main switchboard, with the PV connection made ahead of the main breaker for the building. The switchboard will need to be sized properly to accommodate the power from the renewable energy system. Space for AC inverters will need to be accommodated, either on the roof, on the ground, or in the main electrical room. Bus connection ampacity sizing must take into consideration building load as well as demand load and PV load. If the building has a maximum demand as part of the rate structure, strategies should be deployed to minimize the peak monthly demand or the value and return on investment (ROI) of the PV system will be diminished. Time-of-use rate structures are becoming more prevalent and can reduce the ROI for PV systems.

> ***Caution:*** Work with the utility early on the interconnection agreement. It can often take several months for agreements to be placed with large systems.

RE7 Utility Considerations

Coordinate with the local utility company to determine the proposed demand for the project. This will be based on the design team's load calculation for the building from the energy model with all loads considered.

Initiate discussion with the local utility company as soon as the decision is made to build a zero energy building to understand the grid connection and Public Utility Commission (PUC) requirements. Coordinate with the local utility to understand the local rates, including demand charges, and discover any restrictions to connecting the grid or whether there are zoning issues regarding ground-mounted PV systems or wind turbines.

The interconnection agreement with the utility will be affected by the size of the PV system, the grid characteristics, and how much energy will be exported to the grid. Verify with the utility the fees charged for the utility interconnection fee, the feasibility study, and the metering charges. The term of the agreement should be specifically addressed, such as 10, 15, or 25 years. Understand the implications of a long-term utility rate agreement as part of the contract demand agreement.

Easements may be required by the utility company. The requirements vary from state to state but must be filed prior to construction of the PV system.

Questions to ask the utility company include the following:

- Can power be exported to the grid?
- Is there a power limit for exporting electricity to the grid?
- What additional facility charges, if any, will there be if the PV system ties directly to the utility transformer?
- What will the utility pay for excess power exported to the grid?
- How will having a PV system affect the building's electricity rate?
- When does the utility require the filing of a report on the planned construction with their distribution department?

It is important to get answers in writing. Staff may change and PUC rules and regulations may change, but original agreements are usually honored if in writing.

> ***Caution:*** Legal agreements are more durable than a written memorandum of understanding between an owner and a utility company.

RE8 Utility Rates

Questions to ask the utility company regarding utility rates include the following:

- What is the rate type: time of use, flat, peak demand charges, uninterruptible, or interruptible?
- What are peak and off-peak demand charges?
- What are peak and off-peak electric rates?

- When do the peak and off-peak rates and demand charges occur in the summer and winter? Time of day?
- Is there a minimum contract kilowatt-hour demand consumption clause in the utility contract? (Typically this is the contract demand established by the energy model, design team, owner, and utility.)

These answers should be communicated to the design team as part of the energy modeling efforts.

IMPLEMENTATION STRATEGIES

RE9 Purchasing Options

Determine whether to purchase the PV system outright or to enter into a power purchase agreement (PPA) with a solar developer, who will furnish, install, and maintain the PV system under a lease or lease purchase agreement. Before entering into any agreements, verify that PPAs are legal in the jurisdiction where the building is located, as PPAs are illegal in some states.

> ***Caution:*** If using a lease or purchase agreement, remember to maintain ownership of the RECs. Owners do not have rights to claiming that renewable energy is powering the building unless the certificates are retained.

Determine maintenance staff capabilities and current and projected maintenance workload for providing ongoing maintenance for the PV system. Consider contracting with the PV installer for an ongoing maintenance contract. Decide whether a performance bond will be included for the term of the PV system guarantee and warranty.

Consider an insurance policy to cover damage from high winds, hail, baseballs, and target practice.

RE10 Purchasing the System

Write the technical specs and request for proposals (RFP) for the PV system. Include a checklist for panel and inverter efficiencies, AC and DC system sizing, number of inverters, metering, monitoring, approximate layout, interconnection point, and warranty and power production guarantee requirements. Consider using a template PPA RFP such as that available from the Solar Energy Industry Association (SEIA 2019).

Negotiate and bid the system, including doing homework on the warranty and guarantee offered, PV products, technologies, equipment efficiencies, metering, monitoring, system configuration, and guaranteed power production.

Verify system provider qualifications, including certifications and references. Some questions to ask to verify contractor qualifications include the following:

- Are they accredited with an electrical contracting license in the state, with adequate liability insurance?
- Do they have workers compensation insurance and are they OSHA-compliant, with safety policies in effect and a designated safety officer?
- Does the bid tabulation include the RFP checklist, the equipment included in the bid, and a schedule of values for the equipment, installation, metering, monitoring, and maintenance agreement?
- Are there system performance estimates included for daily, weekly, monthly, and annual performance?
- Are they members of industry associations?
- How many similarly sized systems have they installed?
- Are they experienced in working with the local utility company?
- Will any of the work be subcontracted to another firm?
- What specific equipment are they proposing for the project?
- Does the proposed equipment meet the requirements of the RFP?

- What exceptions did they note with their bid?
- Has a detailed analysis of the load generation been included to confirm sizing is adequate to achieve zero energy, taking into account specific project limitations and conditions?
- Is the metering and monitoring system sufficiently detailed in the bid?
- What is the monitoring and metering agreement?
- Has a complete project team, including contact information and team structure, been included?
- Have they provided a simulation model, such as one created using PVWatts® (NREL 2019b), for the system that includes the panels, their orientation, and the design PV inverter size (which might be significantly smaller than the DC panel output)?

RE11 Negotiating Procurement

There are many system considerations open for negotiation during the procurement process.

Output-limiting factors include the following:

- DC versus AC system sizing (Typically use a 15% efficiency factor when converting from DC to AC power. Module efficiencies are improving and some reports of well over 46% efficiency are being achieved in laboratories. Present commercial efficiency is about 20%.)
- Safety considerations
- Lightning protection
- System sizing for optimal energy production
- System sizing for peak reduction
- Flicker and why it matters—power quality considerations
- Grid interactive only
- Grid interactive with battery storage
- Energy storage
- Battery types

Educational factors include the following:

- Monitoring of power production
- Graphics display
  - PV system and how it works
  - Carbon production showing the reduction in carbon from the energy strategies for lighting, HVAC, and renewable energy versus the baseline energy consumption
  - Solar irradiance
  - Weather station
  - Carbon reduction
  - Impact on natural environment
  - Carbon trading
  - Real-time monitoring

Installation considerations include the following:

- Maintenance considerations for roof replacement
- Maintenance considerations for PV panel replacement
- Maintenance and location of inverters and combiner boxes
- Fire safety and signage considerations
- Electrical fusing and protection
- Financing models
  - Solar developer
  - Tax breaks
  - Private-public partnerships

- Bidding methods
    - Included with construction documents
    - Included as stand-alone contract
    - Bid with construction versus as post building completion

RE12 Commissioning the System

Once the system is installed, provide independent Cx of the PV system to verify performance, grounding, overcurrent protection, and overall functionality. Perform a reconciliation of predicted energy production versus actual production at monthly and one-year intervals. Analyze factors affecting energy production such as weather, cleanliness of panels, inverter performance and component failure, and meter drift. Perform remediation to return the PV system to peak operating performance.

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DPR CONSTRUCTION—RETROFITTING BUILDINGS FOR ZERO ENERGY

DPR is helping to pioneer a movement that will make zero energy buildings the new normal in sustainable design and construction, and they are demonstrating that these goals can apply to building retrofits as well as to new construction. These retrofitted buildings serve as living laboratories showcasing the latest in sustainable technologies and strategies.

For more information, visit https://www.dpr.com/media/review/fall-2016/white-paper-watch-the-path-to-net-zero-energy and https://www.dpr.com/assets/case-studies/DPR-Reston-Case-Study.pdf.

San Diego, California, Regional Office

CLIMATE ZONE 3B

Completed in 2010, this project served as the launching pad for DPR's net-zero initiatives. DPR purchased the 34,000 ft^2, 25-year-old suburban tilt-up industrial office building in 2008. The resulting design includes open office space with 14 ft ceilings, conference rooms, a training center, a video conference room, and a space devoted to building information modeling (BIM) technology. The easy-viewing building dashboard features data from building submeters and the PV system to keep employees engaged and informed.

EUI
14

Project Data

Building area: 24,414 ft^2
Building type: Commercial office
Year completed: 2010

Project Team

Owner: DPR Construction
Architect: CallisonRTKL
MEP engineers: DNV KEMA

Energy Data

Actual EUI: 14 kBtu/ft^2·yr
RE type and size: PV system

Certifications

LEED-NC Platinum 2010
ILFI Living Building Challenge ZE Status 2016

KEY ENERGY-EFFICIENCY MEASURES

- Rooftop tubular daylighting devices
- Rooftop daylight-harvesting light wells
- High-efficiency LED fixtures
- Expanded occupancy thermal comfort zone
- Low-velocity ceiling fans
- Natural ventilation—operable windows
- Passive ventilation with stack effect
- Passive evaporative cool towers—solar chimney
- Passive infrared occupancy controls
- Integrated building management
- Building energy use dashboard
- Energy end-use submetering

Phoenix, Arizona, Regional Office

CLIMATE ZONE 2B

With a desire to transform an underutilized, existing building in an area accessible to public transportation, DPR located an older retail building with obvious potential. The overall structure was sound and 94% of the original shell and structure was maintained in the retrofit. Large expanses of glass were added to the east and north façades to bring in natural light, and shading devices were used to minimize direct solar gain. The ten-month project timeline required a highly collaborative environment for the integrated project team.

EUI
26

Project Data

Building area: 16,533 ft^2

Building type: Commercial office

Year completed: 2013

Project Team

Owner: DPR Construction

Architect/engineer: SmithGroup

Energy Data

Actual EUI: 26 kBtu/ft^2·yr

RE type and size: 78.96 kW PV

Certifications

LEED-NC Platinum 2013

ILFI Living Building Challenge ZE Status 2013

KEY ENERGY-EFFICIENCY MEASURES

- Rooftop tubular daylighting devices
- Rooftop daylight-harvesting light wells
- High-efficiency LED fixtures
- Expanded occupancy thermal comfort zone
- Low-velocity ceiling fans
- Passive ventilation with stack effect
- Passive evaporative cool towers
- Natural ventilation—operable windows
- Exterior window shading
- Passive infrared occupancy controls
- Nonoccupied circuit shut-off system
- Integrated building management
- Building energy use dashboard
- Energy end-use submetering

San Fransisco, California, Regional Office

CLIMATE ZONE 3C

After outgrowing their office space, DPR moved into a an existing two-story, 24,000 ft^2 structure in San Francisco. The building had to be retrofitted to net-positive energy on a budget and a tight schedule in an urban environment with uncertain, foggy weather. The resulting building houses 50 DPR employees, 20+ subtenant employees, conference rooms, a central atrium, a break area, a kitchen, and a fitness center. One lesson learned is that design, construction, and operation issues are ultimately caused or solved in the nontechnical sphere.

EUI
23

Project Data

Building area: 24,010 ft^2

Building type: Commercial office

Year completed: 2014

Project Team

Owner: DPR Construction

Architect: FME Architects

MEP engineers: Integral Group

Energy Data

Actual EUI: 23 $kBtu/ft^2 \cdot yr$

RE type and size: 118 kW PV system

Certifications

ILFI Living Building Challenge ZE Status 2016

KEY ENERGY-EFFICIENCY MEASURES

- Rooftop tubular daylighting devices
- Rooftop daylight-harvesting light wells
- Thermochromatic tinting windows
- High-efficiency LED fixtures
- Expanded occupancy thermal comfort zone
- Low-velocity ceiling fans
- Passive ventilation with stack effect
- Passive ventilation—operable skylight
- Passive infrared occupancy controls
- Nonoccupied circuit shut-off system
- Occupant plug-load management system
- Integrated building management
- Building energy use dashboard
- Energy end-use submetering

Reston, Virginia, Office (DC Metro Area)

CLIMATE ZONE 4A

Needing greater accessibility to public transportation, DPR moved their inaccessible northern Virginia location to a location accessible to the metro and a biking path. They chose to renovate a 20,000 ft^2 space that had been vacant for more than seven years. The project demonstrates that a Class C office space with an average building envelope can become a zero energy Class A building. In order to make decisions based on actual data, the project team did a total cost analysis of rent, construction costs, energy savings, systems, components, finishes, and employee commutes.

pEUI
29

Project Data

Building area: 20,000 ft^2

Building type: Commercial office

Year completed: 2016

Project Team

Owner: DPR Construction

Architect: SmithGroup

MEP engineers: SmithGroup & Southland Industries

Energy Data

Predicted EUI: 29 $kBtu/ft^2 \cdot yr$

RE type and size: 141 kW rooftop PV system

Certifications

LEED-CI v4 Platinum 2018

WELL Gold Certification 2018

KEY ENERGY-EFFICIENCY MEASURES

- Rooftop tubular daylighting devices
- Interior glass walls and reflective surfaces
- Thermochromatic tinting windows
- High-efficiency LED fixtures
- Expanded occupancy thermal comfort zone
- Exterior window shading
- Radiant panels for heating and cooling
- Energy recovery from hot/cold water loops
- Passive infrared occupancy controls
- Nonoccupied circuit shut-off system
- Occupant plug-load management system
- DOAS
- Integrated building management
- Building energy use dashboard
- Energy end-use submetering

Envelope Thermal Performance Factors

A

The envelope information in Tables 5-4 and 5-6 of this Guide presents a prescriptive or target construction option for each of the opaque envelope measures discussed. Table A-1 presents U-factors for above-grade components and F-factors for slab-on-grade floors that correspond to the prescriptive construction options.

Procedures to calculate U-factors are presented in Chapters 26 and 27 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2017), and expanded U-factor, C-factor, and F-factor tables are presented in Normative Appendix A of ASHRAE/IES Standard 90.1 (ASHRAE 2016). These alternative constructions provide an equivalent method for meeting the specifications of this Guide provided that they are less than or equal to the thermal performance factors listed in Table A-1.

Table A-1 Opaque Construction Options

Walls, Above Grade			
R	**U**	**R**	**U**
Mass Walls		**Steel Framed**	
5.6 c.i.	0.163	6.0 c.i.	0.113
10.0 c.i.	0.106	13 + 5.0 c.i.	0.077
12.5 c.i.	0.089	13 + 8.0 c.i.	0.062
16.8 c.i.	0.071	13 + 9.0 c.i.	0.059
17.5 c.i.	0.067	13 + 11.0 c.i.	0.052
22.4 c.i.	0.056	15 + 13.0 c.i.	0.047
28.0 c.i.	0.046	15 + 20.0 c.i.	0.035
33.6 c.i.	0.039	**Metal Building**	
Wood Framed		7.5 c.i.	0.120
11	0.096	16 + 6.5 c.i.	0.077
11 + 3.0 c.i.	0.073	16 + 9.8 c.i	0.062
11 + 5.0 c.i.	0.063	30	0.052
13 + 5.0 c.i.	0.059	25 + 10	0.047
13 + 8.0 c.i.	0.050	25 + 13 c.i.	0.035
13 + 9.0 c.i.	0.047		
15 + 15.0 c.i.	0.035		

Roof Assemblies	
R	**U**
Insulation Above Deck	
20 c.i.	0.048
25 c.i.	0.039
30 c.i.	0.032
35 c.i.	0.028
40 c.i.	0.025
Metal Building	
19 +10 FC	0.041
19 +11 Ls	0.037
25 + 8 Ls	0.037
25 + 11 Ls	0.031
30 +11 Ls	0.029
25+11+11 Ls	0.026

Slabs	
R-in. (vertical)	**F**
Unheated	
0	0.73
15–36	0.480
30–54	0.400
Heated—Fully Insulated	
7.5	0.64
15	0.44
20	0.373

Note: All information in this appendix is in Inch-Pound (I-P) units. For slabs, "in." refers to the depth of the vertical slab edge insulation. See ASHRAE/IES Standard 90.1 for additional explanation. All units used in the table are defined in the Abbreviations and Acronyms section of this Guide.

REFERENCES

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B

International Climatic Zone Definitions

ANSI/ASHRAE Standard 169, *Climatic Data for Building Design Standards* (ASHRAE 2013a), has 60 pages of tables that indicate the climate zones for locations throughout the world. That information is reproduced in Annex 1 of ANSI/ASHRAE/IES Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2016). Standard 169 indicates that those are the climate zones that should be used for those locations. The methodology shown in this chapter comes from Section A3 of Standard 169 and provides climate zone definitions for locations that are not listed in the standard. Weather data are needed in order to use the climate zone definitions for a particular city. Weather data by city are available for a large number of international cities on the 2013 *ASHRAE Handbook—Fundamentals* CD (ASHRAE 2013b).

Table B-1 International Climatic Zone Definitions (ASHRAE 2013a)

CZ	Name	Thermal Criteria
0	Extremely hot	10,800 < CDD50°F
1	Very hot	9000 < CDD50°F ≤ 10,800
2	Hot	6300 < CDD50°F ≤ 9000
3	Warm	CDD50°F ≤ 6300 and HDD65°F ≤ 3600
4	Mixed	CDD50°F ≤ 6300 and 3600 < HDD65°F ≤ 5400
5	Cool	CDD50°F ≤ 6300 and 5400 < HDD65°F ≤ 7200
6	Cold	7200 < HDD65°F ≤ 9000
7	Very cold	9000 < HDD65°F ≤ 12600
8	Subarctic/arctic	12600 < HDD65°F

CDD50°F = cooling degree-day to a base temperature of 50°F.
HDD50°F = heating degree-day to a base temperature of 50°F.

DETERMINING CLIMATE ZONES

For locations not listed in Standard 169, use the following information to determine climate zone numbers and letters: first determine the thermal climate zone, 0–8, from Table B-1, using the heating and cooling degree-days for the location, then determine the moisture zone (Marine, Dry, or Humid) using the following steps:

a. If monthly average temperature and precipitation data are available, use the Marine, Dry, and Humid definitions below to determine the moisture zone (C, B, or A).
b. If monthly or annual average temperature information (including degree-days) and only annual precipitation (i.e., annual mean) are available, use the following to determine the moisture zone:
    1. If thermal climate zone is 3 and CDD50°F < 4500, climate zone is Marine (3C).
    2. If thermal climate zone is 4 and CDD50°F < 2700, climate zone is Marine (4C).
    3. If thermal climate zone is 5 and CDD50°F < 1800, climate zone is Marine (5C).
c. If only degree-day information is available, use the following to determine the moisture zone:
    1. If thermal climate zone is 3 and CDD50°F < 4500, climate zone is Marine (3C).
    2. If thermal climate zone is 4 and CDD50°F < 2700, climate zone is Marine (4C).
    3. If thermal climate zone is 5 and CDD50°F < 1800, climate zone is Marine (5C).

MARINE (C) ZONE DEFINITION

Marine (C) zones are locations meeting all four of the following criteria:

a. Mean temperature of coldest month between 27°F and 65°F.
b. Warmest month mean < 72°F.
c. At least four months with mean temperatures over 50°F.
d. Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

DRY (B) DEFINITION

Dry (B) zones are locations meeting the following criteria:

a. Not Marine (C).
b. If 70% or more of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is $P < 0.44 \times (T - 7)$.
c. If between 30% and 70% of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is $P < 0.44 \times (T - 19.5)$.
d. If 30% or less of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is $P < 0.44 \times (T - 32)$, where

P = annual precipitation, in.
T = annual mean temperature, °F
Summer or high sun period = April through September in the Northern Hemisphere and October through March in the Southern Hemisphere
Winter or cold season = October through March in the Northern Hemisphere and April through September in the Southern Hemisphere

HUMID (A) DEFINITION

Humid (A) zones are locations that are not Marine (C) and not Dry (B).

REFERENCES

ASHRAE. 2013a. ANSI/ASHRAE Standard 169-2013, *Climatic data for building design standards*. Atlanta: ASHRAE.

ASHRAE. 2013b. *ASHRAE handbook—Fundamentals* [CD]. Atlanta: ASHRAE.

ASHRAE. 2016. ANSI/ASHRAE/IES Standard 90.1-2016, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

Quantifying Thermal Transmittance Impacts of Thermal Bridges

C

Quantifying thermal transmittance through materials, assemblies, and details requires applying one-dimensional, two-dimensional, and three-dimensional steady-state heat transfer calculations/simulations, depending on the spatial complexity of the assembly or detail.

ONE-DIMENSIONAL HEAT TRANSFER

Fourier's law of heat conduction can also be used to calculate one-dimensional heat transfer through different materials:

$$q = kAdT/s$$

where

q = heat transfer, Btu/h
k = thermal conductivity of a material, Btu/(h·ft·°F)
A = heat transfer area, ft^2
dT = temperature gradient, °F
s = material thickness, ft

The thermal conductivities of various materials are outlined in Table C-1. Material densities are provided to help define the actual building material. In some cases, the density has an impact on the thermal conductivity. See Chapter 26 of *ASHRAE Handbook—Fundamentals* for more information (ASHRAE 2017).

TWO-DIMENSIONAL HEAT TRANSFER

Methods for estimating two-dimensional heat transfer and effective thermal resistances for assemblies can be found in ASHRAE Handbooks and other industry resources. It is also possible to model two-dimensional heat transfer with software such as THERM (freely available from Lawrence Berkeley National Laboratory; LBNL 2019).

Table C-1 Envelope Material Conductivity

Material	Density, lb/ft^2	Thermal Conductivity, Btu·in/h·ft^2·°F
Polyisocyanurate	1.6–2.3	0.15–0.16
Extruded polystyrene	1.4–3.6	0.20
Expanded polystyrene	1.0–1.5	0.24–0.26
Cellulose	1.2–1.6	0.27–0.28
Polyurethane foam	0.45–0.65	0.26–0.29
Glass fiber batts	0.47–0.57	0.32–0.33
Wood	25	0.74–0.85
Gypsum sheathing	40	1.1
Brick—common	120	5.0
Brick—face	130	9.0
Concrete—sand/gravel	150	10–20
Stainless steel	494	96
Carbon steel (mild)	489	314
Aluminum (alloy 1100)	171	1536

THREE-DIMENSIONAL HEAT TRANSFER

Thermal bridges at interface details are more complex than one-dimensional or two-dimensional heat transfer methods. Three-dimensional heat transfer has traditionally been measured through the testing of actual assemblies, but it can also be modeled. While three-dimensional heat transfer testing and modeling is complex, there are industry resources available to streamline the quantification of the common interface thermal bridges. A paper reporting findings from ASHRAE Research Project RP-1365 provides for such a simplified methodology (using linear and point thermal transmittances) and includes a catalog of 40 common details with corresponding thermal transmittance factors that can be applied to modify the U-factors of assemblies (Roppel et al. 2012). Figure C-1 illustrates output from three-dimensional heat transfer modeling. A similar resource is BC Hydro's *Building Envelope Thermal Bridging Guide* (BC Hydro 2016) and its accompanying material data sheet catalogs. The section below summarizes this method; refer to the above-mentioned resources for more detailed background and explanation.

ASSEMBLY U-FACTOR ADJUSTMENTS FOR THREE-DIMENSIONAL THERMAL BRIDGES USING LINEAR AND POINT THERMAL TRANSMITTANCE FACTORS

The following method provides for a simplified approach to the adjustment of assembly U-factors for the simulation of thermal bridges. For the purpose of incorporating the effects of thermal bridges, the clear-field U-factors of modeled assemblies need to be modified in accordance with the following equation:

$$U_{tot} = ([(\Sigma\psi_i \cdot L_i) + (\Sigma\chi_i \cdot n_i)]/A_{total}) + U_o$$

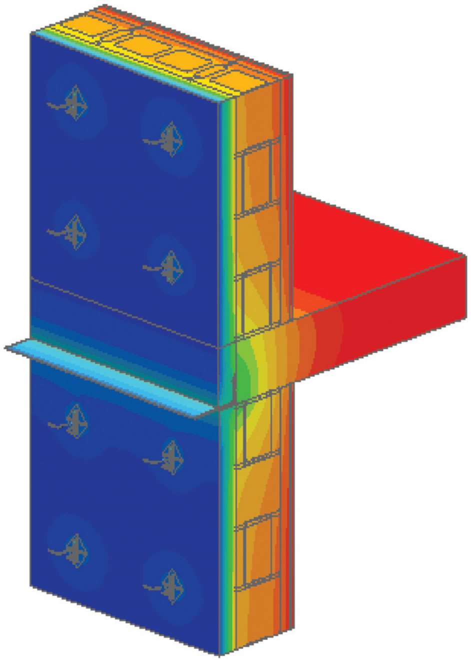

Figure C-1 Three-Dimensional Heat Transfer Modeling
Figure 4, Roppel et al. 2012

where

U_{tot} = overall thermal transmittance including the effect of linear thermal bridges and point thermal bridges not included in the assembly's U_o value, Btu/(h·ft^2·°F)

ψ_i = Psi-factor, thermal transmittance for each type of linear thermal bridge, Btu/(h·ft·°F)

L_i = length of a particular linear thermal bridge as measured on the outside surface of the building envelope, ft

χ_i = Chi-factor, thermal transmittance for each detail type of point thermal bridge, Btu/(h·°F)

n_i = number of occurrences of a particular type of point thermal bridge

A_{total} = total opaque projected surface area of the assembly, ft^2

U_o = clear-field thermal transmittance of the assembly, Btu/(h·ft^2·°F)

Psi-factor (ψ_i) and Chi-factor (χ_i) values representative of an as-built thermal bridging condition as shown in Table C-2 are determined by one of the following ways:

- With values derived from models compliant with ISO 10211 (ISO 2017) using details representative of the actual construction and modeling assumptions consistent with accepted practice.
- By testing the assembly in accordance with ASTM C1363 (ASTM 2011) with and without the presence of the thermal bridge condition to determine a linear transmittance value or point transmittance value for the thermal bridge condition.
- Using values from the Roppel et al. (2012) paper or other published detail catalogs or tables.

Table C-2 Thermal Bridging Default Psi-Factors and Chi-Factors for Thermal Bridges

Class of Construction—Wall, Above Grade	Thermal Bridge Type	Unmitigated		Default	
		Psi-Factor, Btu/(h·ft·°F)	Chi-Factor, Btu/(h·°F)	Psi-Factor, Btu/(h·ft·°F)	Chi-Factor, Btu/(h·°F)
Steel Framed	Parapet	0.289	N/A	0.151	N/A
	Floor to wall intersection	0.487		0.177	
	Relieving angle	0.314		0.217	
	Wall to vertical fenestration intersection	0.262		0.112	
	Shading device	0.402		0.117	
	Other element	N/A	1.73	N/A	0.91
Mass	Parapet	0.238	N/A	0.126	N/A
	Floor to wall intersection	0.476		0.118	
	Relieving angle	0.270		0.186	
	Wall to vertical fenestration intersection	0.188		0.131	
	Shading device	0.352		0.140	
	Other element	N/A	0.91	N/A	0.19
Wood-framed and Other	Parapet	0.032	N/A	0.032	N/A
	Floor to wall intersection	0.336		0.049	
	Relieving angle	0.186		0.043	
	Wall to vertical fenestration intersection	0.150		0.099	
	Shading device	0.083		0.072	
	Other element	N/A	0.33	N/A	0.07

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Advanced Energy Design Guide for Small to Medium Office Buildings—Achieving Zero Energy

This Guide was prepared under ASHRAE Special Project 140.

Advanced Energy Design Guide for Small to Medium Office Buildings—Achieving Zero Energy is the second in a series of guides for achieving zero energy and is tailored to the design and creation of zero energy office buildings. It builds on the popular 50% AEDG series with new and updated recommendations on energy efficiency along with guidance about on-site renewable energy sources. The Guide establishes a set of energy performance goals for achieving zero energy. The goals are provided for all ASHRAE climate zones, in both site and source energy.

Strategies on how to achieve these energy targets are provided throughout the Guide and include setting measurable goals, hiring design teams committed to those goals, using simulation throughout the design and construction processes, and being aware of how process decisions affect energy usage.

As in previous AEDGs, the how-to tips in this Guide address specific project aspects—building and site planning, envelope, daylighting, lighting controls, electric lighting, plug loads and power distribution systems, service water heating, HVAC systems and equipment, and renewable energy. Each section contains multiple tips that move the design incrementally toward the zero energy goal.

Finally, case studies and sidebars show how the energy goals are achievable within typical construction budgets as well as at demonstrating the technologies in real-world applications.

Find us on Twitter **#ZeroAEDG**

For more information on the entire Advanced Energy Design Guide series, please visit www.ashrae.org/AEDG.

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