Note to Reviewers:

This the third in the series of Zero Energy Advanced Energy Design Guides. This series of guides differs from previous guides in that it is based on an energy goal of zero energy. This shift represents a balance of energy consumption and energy supply in order to achieve a target EUI for energy consumption and ultimately a zero energy building with that balance.

GENERAL NOTES:

- *With this technical refinement review, the Project Committee is interested in feedback on specific details and recommendations in the Guide.*
- *Comments on any and all of the content/text in the document is solicited and appreciated.*
- *Chapters 2 and 3 continue to be refined to address this specific building type. Feedback on what is missing from these chapters would be very helpful to the project committee.*
- *Where appropriate specific questions are interspersed throughout the document in red text and brackets.*
- *Please provide your comments on the input form and note the referenced text by line number.*

CASE STUDIES:

- *The Project Committee is actively looking for Case Studies to include in the final document. Names of buildings whose energy use meets the EUI targets in Table 3.1 are appreciated*

FIGURES:

- *Many figures in the document are preliminary sketches and are currently being professionally redrawn for the final publication document.*
- *The figures have been compressed for this document in order to make the document small enough to email and easily download – this affects the appearance and quality of the graphics – but is not indicative of the final publication quality.*
- *Where indicated, some figures are placeholders only and do not accurately reflect the information in this document. These will be updated with accurate data prior publication.*
- *There is currently no particular rhyme or reason to the numbering of the tables and figures other than to connect them to the appropriate text. All numbering in the document will be updated to a consistent numbering system prior to publication.*

EDITORIAL NOTES:

- *This draft has not been copy edited for typographical or punctuation errors. These will be addressed prior to publication by ASHRAE's editorial staff.*
- *References to other sections of the Guide will be added, updated, and corrected prior to publications.*

Advanced Energy Design Guide For Multifamily Buildings – Achieving Zero Energy

90% Technical Refinement Draft
February 2019

NOT FOR DISTRIBUTION

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
The American Institute of Architects
Illuminating Engineering Society
U.S. Green Building Council
U.S. Department of Energy

This is an ASHRAE Design Guide. Design Guides are developed under ASHRAE's Special Publication procedures and are not consensus documents. This document (SP 140) is an application manual that provides voluntary recommendations for consideration in achieving greater levels of energy savings relative to minimum standards

Project Committee
Paul Torcellini, *Chair*

Daniel Nall
AIA Representative

Carol Marriott
ASHRAE Representative

Michael Lane
IES Representative

Stet Sanborn
USGBC Representative

Zach Craun
Member-at-large

Rois Langner
Analysis Support

Lilas Pratt
Staff Liaison

Steering Committee
Tom Phoenix, *Chair*

Daniel Nall
AIA Representative

Mark Lien
IES Representative

Brendan Owens
USGBC Representative

Bill McQuade
ASHRAE Representative

Sarah Zaleski
DOE Representative (Ex-Officio)

Lilas Pratt
Staff Liaison

1

Table of Contents

Acknowledgements

Note: Acknowledgements will be added prior to publication

Abbreviations and Acronyms

Abbreviations and Acronyms will be updated as part of the publication process

ACCA	- Air Conditioning Contractors of America
ADA	- Americans with Disabilities Act (United States)
A/E	- Architectural/Engineering
AFUE	- Annual Fuel Utilization Efficiency - dimensionless
AIA	- American Institute of Architects
ASE	- Annual sunlight exposure
ASTM	- American Society for Testing and Materials
ANSI	- American National Standards Institute
BOD	- Basis of Design
Btu	- British Thermal Unit
CBECS	- Commercial Building Energy Consumption Survey
CD	- Construction Documents
CHW	- Chilled Water
c.i.	- Continuous Insulation
Cx	- Commissioning
CxA	- Commissioning Authority (See also preferred term CxP)
CxP	- Commissioning Provider
CFM	- Cubic Feet per Minute
CM	- Construction Manager
CMH	- Ceramic Metal Halide
COP	- Coefficient of Performance - dimensionless
CRI	- Color Rendering Index
CRRC	- Cool Roof Rating Council
D	- Diameter - ft
db	- Dry Bulb - °F
DCKV	- Demand Control Kitchen Ventilation
DL	- Advanced Energy Design Guide Code for Daylighting
DOAS	- Dedicated Outdoor Air System
DOE	- Department of Energy (United States)
DX	- Direct Expansion
E_c	- Efficiency, combustion - dimensionless
ECM	- Electronically Commutated Motor
EEPR	- Electronic Evaporator Pressure Regulator
EEV	- Electronic Expansion Valves
EER	- Energy Efficiency Ratio - Btu/W-h
EF	- Energy Factor - dimensionless
EIA	- Energy Information Agency
E_t	- Efficiency, thermal - dimensionless
EL	- Advanced Energy Design Guide Code for Electric Lighting
EN	- Advanced Energy Design Guide Code for Envelope
EPR	- Evaporator Pressure Regulator
EUI	- Energy Use Intensity
EX	- Advanced Energy Design Guide Code for Exterior Lighting
F	- Slab Edge Heat Loss Coefficient per Foot of Perimeter – Btu/h·ft·°F

FC	- Filled Cavity
FPI	- Fins per inch
FPT	- Functional Performance Testing
GC	- General Contractor
GSHP	- Ground Source Heat Pump
Guide	- Advanced Energy Design Guide
HC	- Heat Capacity - Btu/(ft$^{2}\cdot$°F)
HGR	- Hot Gas Reheat
HSPF	- Heating Season Performance Factor – Btu/W·h
HV	- Advanced Energy Design Guide Code for HVAC Systems and Equipment
HVAC	- Heating, Ventilating and Air-Conditioning
HW	- Hot Water
HX	- Heat Exchange
IES	- Illuminating Engineering Society
in	- Inch
IPLV	- Integrated Part Load Value - dimensionless
kBtu/h	- Thousands of British Thermal Units per Hour
kW	- Kilowatt
LBNL	- Lawrence Berkeley National Laboratory
LED	- Light Emitting Diode
LPD	- Lighting Power Density - W/ft^{2}
Ls	- Liner Systems
LSHX	- Liquid Suction Heat Exchanger
LT	- Low-temperature
N/A	- Not Applicable
MA	- Mixed Air
MBMA	- Metal Building Manufacturers Association
MT	- Medium-temperature
NEMA	- National Electrical Manufacturers Association
NFRC	- National Fenestration Rating Council
NR	- No Recommendation
NREL	- National Energy Renewable Laboratory
NZEB	- Net Zero Energy Buildings
O&M	- Operation and Maintenance
OPR	- Owner’s Project Requirements
PC	- Project Committee
PF	- Projection Factor - dimensionless
PL	- Advanced Energy Design Guide Code for Plug Loads
PPA	- Power purchase agreement
ppm	- Part per million
psf	- Pounds per square foot
PV	- Photovoltaic
QA	- Quality Assurance
R	- Thermal Resistance - h·ft$^{2}\cdot$°F/Btu
SCT	- Saturated Condensing Temperature
sDA	- Spatial daylight autonomy
SEER	- Seasonal Energy Efficiency Ratio – Btu/W-h
SET	- Saturated Evaporator Temperature

SHGC - Solar Heat Gain Coefficient - dimensionless
SP - Special Project
SRI - Solar Reflectance Index - dimensionless
SSPC - Standing Standards Project Committee
SST - Saturated Suction Temperature
Std. - Standard
SWH - Service Water Heating
SZCV - Single Zone Constant Volume
SZVAV - Single Zone Variable Air Volume
TAB - Test and Balance
TC - Technical Committee
TD - Temperature Difference - °F
TXV - Thermostatic Expansion Valve
U - Thermal Transmittance - Btu/h·ft^2·ºF
UPS - Uninterruptible Power Supply
USGBC - U. S. Green Building Council
VSD - Variable Speed Drive
VT - Visible Transmittance - dimensionless
W - Watts
wb - wet bulb
”wg - Inches of Water Gauge
w.c. - Water Column
WH - Advanced Energy Design Guide Code for Service Water Heating
WSHP - Water Source Heat Pump
ZE - Zero Energy
ZEB - Zero Energy Building

Foreword: A Message to Building Owners/Managers

Note: Foreword will be added prior to publication

Chapter 1 Introduction

Buildings account for 40% of total energy consumption in the United States and for a similar percentage total global energy consumption (EIA 2019). 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 building at a cost that is comparable to buildings built to typical energy codes in use today.
Zero energy multifamily building can provide increased resilience, utility cost stability, and contribute to reduced or eliminated utility costs for tenants and property owners. The majority of zero energy multifamily projects also eliminate combustion appliances within the units, which increases indoor air quality (IAQ) significantly and results in a healthier home. Beyond the energy savings and health benefits, more and more families are looking for housing that reduces their climate impacts. Zero energy homes provide a means to demonstrate and live a commitment to sustainability and can attract higher rental rates.

For multi-family buildings which exceed 4-6 stories, on-roof renewables may not enough to offset 100% of onsite energy use, but often can offset house common loads. For shorter multi-family buildings, on roof renewables, utilizing virtual net metering, may be enough to offset common loads as well as tenant loads, resulting in dramatically reduced tenant energy costs.

GOALS OF THIS GUIDE

The goals of this Guide are to demonstrate that zero energy multifamily buildings are attainable and to provide direction through recommendations, strategies, and solution packages for designing and constructing zero energy multifamily buildings in all climate zones. Like the zero energy Advanced Energy Design Guides (AEDG) for small to medium offices and 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 buildings can be achieved today within the budget of conventional buildings and is also possible in building retrofit work. 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; engagement of occupants; 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. The goal for the building is to achieve energy use targets in order to create a zero energy ready building. Renewable energy may then be added on site, if available, or procured off site, if desired. In dense urban areas, the guide can still be used to create (ultra-efficient) low-energy buildings that help support zero energy communities. 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 BUILDING

SOUND FISCAL MANAGEMENT

Zero energy buildings often have substantially reduced energy bills compared to traditional buildings. These lower energy bills make typically volatile energy costs a much smaller percentage of operational budgets and therefore more manageable. Zero energy 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 utility prices. One way to think about this is that today's investment "locks in" future energy costs through the savings.

Zero energy buildings can also have lower maintenance costs. Many energy-efficiency strategies result in less operational time for mechanical and electrical equipment, and allows for more operation within optimal parameters, which may extend the life of the 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 buildings should have lower life-cycle costs than other buildings and continue to conserve resources throughout the lifetime of the building.

OCCUPANT SATISFACTION

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. Critically important for zero energy multifamily buildings is a focus on Indoor Air Quality (IAQ), as it is one of the most important factors for occupant satisfaction in housing. Many factors contribute to increased IAQ, from materials selection, exhaust design and HVAC system selection to air-sealing and compartmentalization. Often, there are co-benefits between designing for zero energy and high IAQ. The ASHRAE Residential Indoor Air Quality Guide: Best Practices for Acquisition, Design, Constructions, Maintenance, and Operation and the EPA Indoor Air Quality Guidelines for Multifamily Building Upgrades (EPA 2016) provide excellent guidance on IAQ strategies which are beyond the scope of this guide. ASHRAE Standard 55-2017 *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017) and ASHRAE Guideline 10-2016, *Interactions affecting the achievement of acceptable indoor environments* (ASHRAE 2016) are other resources for guidance and strategies on occupant satisfaction.

ENVIRONMENTAL STEWARDSHIP

Completing a zero energy multifamily building, or a multifamily 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. Investing in a zero energy building is one of the most impactful things an organization can do to impact communities, protect natural resources, and mitigate climate change (Terrapin 2012).

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 multifamily 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 buildings.

While this Guide cannot specifically address all possible configurations of buildings, the recommendations apply to multifamily buildings covered by ASHRAE Standard 90.1 up to twenty floors. The Guide covers buildings with independent tenant living spaces with units ranging from one to three bedrooms where each unit has kitchen space, bathroom(s), bedroom(s), and living spaces. The also covers a first floor containing common meeting spaces, workout room, and staff/management offices or containing low-energy density mixed use spaces such as light retail and leased offices. The Guide includes consideration of vertical transportation, laundry facilities, as well as energy management systems and controls. The Guide does not consider specialty spaces with extraordinary heat generation, large ventilation requirements, food service, pool, vehicle and other maintenance areas, domestic water well pumping, sewerage disposal, medical equipment as in skilled nursing facilities, or smaller residential buildings not covered by ASHRAE Standard 90.1.

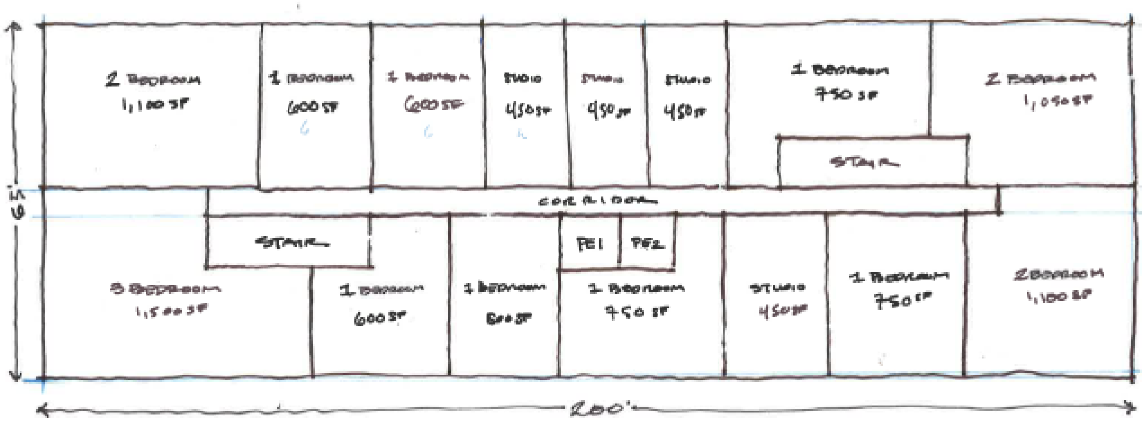
Much of the Guide may also be applicable to buildings undergoing complete or partial renovation, additions, and or changes to one or more building systems; however, upgrading existing exterior building envelopes as is required to achieve the low EUIs needed to reach zero energy can often be challenging. With that in mind, any time changes are made to a building, there is an opportunity to move that building toward zero energy. Planned changes may include 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 a design decision is made is an opportunity to save energy.

While this Guide focuses on reducing energy consumption in a building, there are also 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 is to create a zero energy building that is cost-effective and also designed with all these parameters in mind.

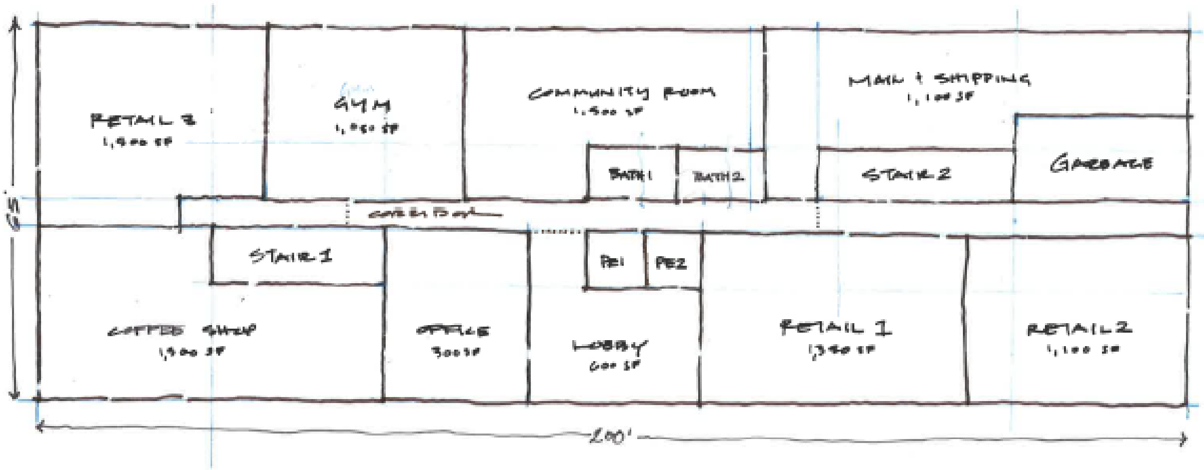
DEVELOPING THE GUIDE

To establish reasonable energy targets for achieving zero energy performance in all climate zones, a prototypical multifamily building was modeled and analyzed using hourly building simulations. The prototype building was carefully assembled to represent multifamily building construction, with information drawn from several sources. Typical floor plan layouts for a multifamily building are shown in Figure 1-1.

[Note to Reviewers: Floor plans will be professionally redrawn for final publication.]



(a) Typical Resident Floor Plan



(b) Typical Lobby Floor Plan

Figure 1-1 Typical Multifamily Floor Plans

[Note to Reviewers: Floor plans will be professionally redrawn for final publication.]

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

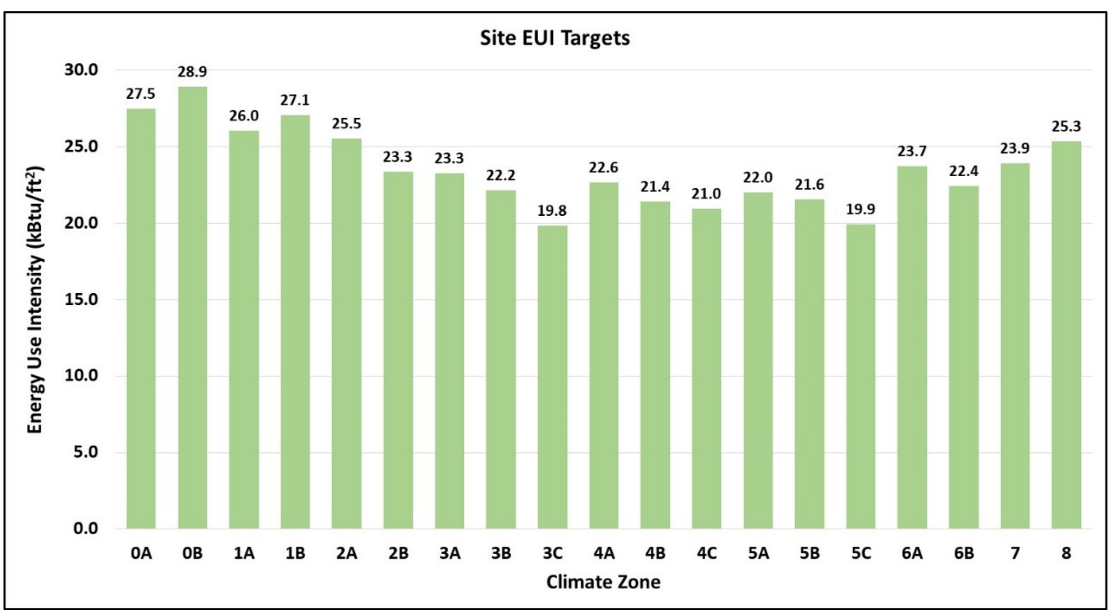


Figure 1-2 (a) Site EUI Comparison by Climate Zone

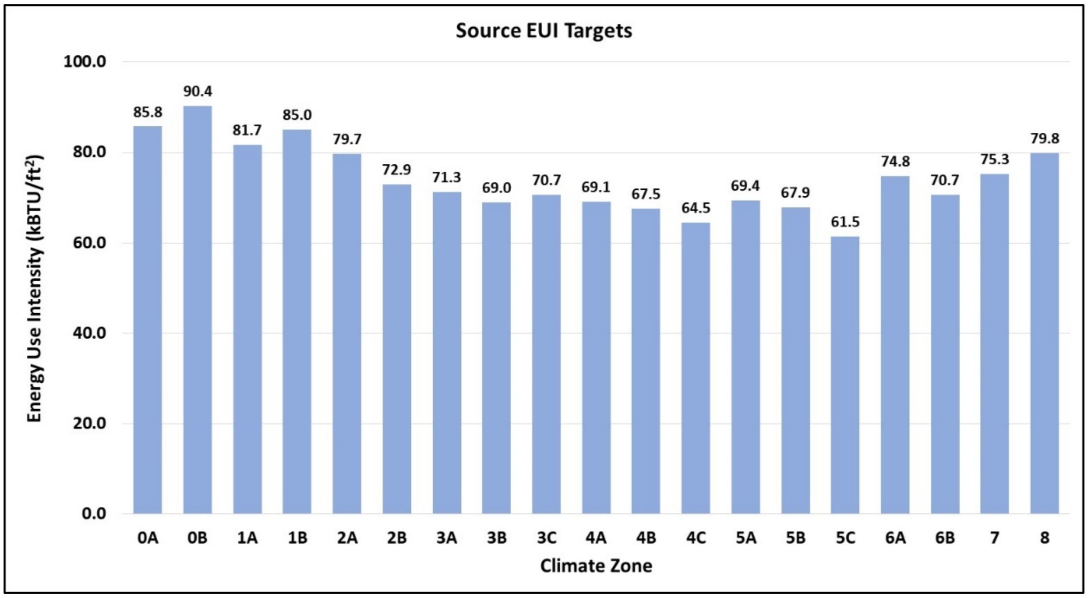


Figure 1-2 (b) Source EUI Comparison by Climate Zone

To facilitate reaching these EUI targets, the Guide provides recommendations for the design of the building configuration and of building components, including the building envelope, fenestration, lighting systems (including interior and exterior electric 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, Data Driven Approach to Success, 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 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 in chapter 5 highlight strategies that contribute to four different categories. These icons and categories are:

(GA) Reducing peak demand and increasing alignment with the electricity grid

(RS) Energy resilience

(CC) Capital cost savings

(RT) Building retrofit strategies

Appendices provide additional information:

- Appendix A—Envelope Thermal Performance Factors
- Appendix B—International Climatic Zone Definitions

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.

REFERENCES AND RESOURCES

ASHRAE. 2017. ANSI/ASHRAE Standard 55-2017, *Thermal environmental conditions for human occupancy*. Atlanta: ASHRAE.

ASHRAE. 2016. ASHRAE Guideline 10-2016, *Interactions affecting the achievement of acceptable indoor environments*. Atlanta: ASHRAE.

DOE. 2015. *A common definition for zero energy buildings*. DOE/EE-1247. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://energy.gov/eere/buildings/downloads/common-definition-zero-energy-buildings.

EIA. 2019. Frequently asked questions, EIA website. Last updated May 2019. Washington, DC: U.S. Energy Information Administration. https://www.eia.gov/tools/faqs/faq.php?id=86&t=1.

EPA 2016. Energy Savings Plus Health Indoor Air Quality Guidelines for Multifamily Building Upgrades. EPA Publication 402/K-16-01, January 2016.

NREL and DOE. Zero energy buildings resource hub. National Renewable Energy Laboratory and U.S. Department of Energy. www.zeroenergy.org.

Terrapin. 2012. *The economics of biophilia: Why designing with nature in mind makes financial sense*. New York: Terrapin Bright Green, LLC. https://www.terrapinbrightgreen.com/report/economics-of-biophilia/.

Chapter 2 Principles for Success

[Note to Reviewers:** This chapter is intended to convey the importance of zero energy and how to be successful in delivering a zero energy building. It should also cover the barriers to getting an owner on board with the zero energy goal and how to overcome those barriers.**]

There are many stakeholders in a 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

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 used by building occupants and operations staff, who, in turn, 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 environmental performance goals for a building project. Many sustainability and green-building goals may be simultaneously pursued. These could include:

- *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 annual energy use has been a key performance metric historically, the time of day that energy is being used is important. Shifting loads to avoid peak utility times can help minimize utility infrastructure. In addition, shifting loads to align with when grid-renewables are available helps to increase penetration of these resources. Buildings, collectively, can have a large influence on utility infrastructure development and the fuels power generator use.
- *Water Efficiency*. Reduction of water consumption for all end uses has both energy and environmental impacts. The consumption of indoor, outdoor, and process water requires energy—both to heat indoor hot water and 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. The energy embodied in the production and transportation of those material is another consideration for the project.

- *Indoor Environmental Quality.* High-performance buildings integrate air quality, lighting, views, acoustics, and the overall indoor occupant experience into the design. Improvements in indoor environmental quality have been linked to increased satisfaction in building occupants. Improved comfort, user control of their environment, and reductions in environmental stresses can also reduce demands on building operations staff, thus reducing total cost of ownership and improving building energy performance.
- *Carbon Reduction.* Many owners are interested in tracking carbon emissions. These are calculated based on the fuels used in the building as well as fuels used to produce electricity on the grid. Owners can use these metrics to reduce their carbon impact. In some jurisdictions policy and local laws are requiring carbon tracking.

MOVING TO ZERO ENERGY

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:

- Reduction of utility costs as a percentage of annual operating expense
- Improved marketing potential and reduced vacancy rates
- Increased affordability of units due to lower utility bills for tenants
- Increased resiliency of the building (see also Resiliency section below)
- Sustainability as part of the organization's mission
- Interest in mitigating impact of climate change
- Potential carbon credit value in communities adopting carbon policies
- Legislation/code requirements for reduction in energy consumption

Successful zero energy projects have buy-in and commitment from all stakeholders including the Owner, Design Team and Contractor, all of whom support the zero energy goal with the attitude that it can be done. Some factors involved in this success include:

- Identifying incentives/subsidies available to offset capital costs.
- Identifying lenders willing to underwrite operational savings.
- Educating owners and residents to dispel misconceptions about high-performing buildings (such as "you can't open windows) and encourage behavior changes needed to achieve zero energy (such as "you can open windows").
- Educating code officials and regulatory agencies on the preservation benefits and improved health/safety factors of zero energy buildings.

PRINCIPLES FOR SUCCESS

In every zero energy 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 following subsections are critical to achievement.

DEVELOP THE CULTURE AND MINDSET

The first key to success is creating a “can-do” mindset that a zero energy project is achievable within budget; is a good financial investment; is good for climate and carbon reduction goals; and can signify excellence, improve the marketability of a project, invoke a sense of community, and invigorate and inspire building occupants. To support this, the development of a culture that priorities the zero energy goal must start in a project’s infancy and extend through design and construction into operations.

To help create 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. One potential resource for such a strategy is 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 building will automatically cost more than a typical high-performance building 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 engraining 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 successful solutions, thereby disputing these myths. Leveraging results and experiences from previous projects supports the zero energy goal. The case studies in this Guide provide projects that also challenge these myths.

IDENTIFY A CHAMPION

Establishing an energy champion from within the broader integrated project team and giving them authority on the project team will help maintain the zero energy priority. This individual must have the authority to make decisions and oversight throughout construction in order to navigate the project through potential roadblocks. 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, ideally, 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 the goals 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 buildings 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 buildings, finding synergies through an integrated process is an essential strategy for achieving the target EUI 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.

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. It is important that team members recognize the impacts their decisions have on other building elements. The repeated cycles through building simulation analyses to optimize the design are illustrated in Figure 2-3. The feedback continues into occupancy through post occupancy evaluations (POE) as the occupants engage in and develop the most effective and efficient ways to run the building.

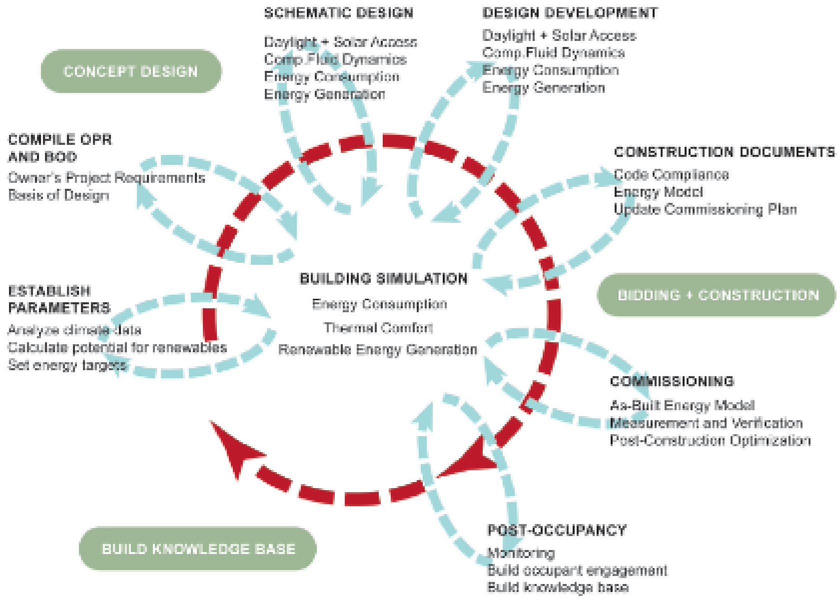


Figure 2-3 Integrated Design Process for a Zero Energy

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. The accuracy of the energy model is critical as it allows for right-sizing of the renewable energy systems. Inaccuracies or conservative input will force systems to be larger than necessary and increase first cost.

In an integrated process, these steps are typically iterative (as illustrated in Figure 2-3). Through these 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)**.**

HIERARCHY OF DECISION MAKING

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. ***Financial Strategies.*** Before a project can begin, there needs to be a plan to work through utility incentives, tax breaks, insurance rates, vacancy rates, and financing for the project. Building the business case and pro forma are especially important in multifamily projects so as to highlight the benefits that a zero energy provides. For additional details, see the *Establish the Finance Model* section in Chapter 3.
2. ***Passive Strategies.*** This category includes optimizing the static elements of the building for maximum energy efficiency including the building form and configuration, including the building orientation and layout. The building envelope separates the conditioned spaces from weather elements. 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. Other passive strategies include passive solar heat and natural cooling which can be applied to individual dwelling units. Measures in this category should be prioritized and employed as extensively as possible.
3. ***Plug and Process Loads (PPLs).*** Determining the amounts and schedules for the plug loads should be done early in the design process as overestimating plug loads can impact the ability to cost effectively achieve a zero energy building Setting watt density targets will determine the heat generated from these devices. Plug load levels need to be set with an understanding of occupant needs and expectations. Understanding plug loads will help identify possible plug load reductions strategies. An engagement plan will help ensure that strategies are successful. Building level PPLs are specified by the design team for items such as security systems, elevators, and secondary transformers..
4. ***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.
5. ***Operations, Set Points, and Controls.*** Items 2 through 4 focus on the building design and the ability to create the potential for a building to save energy. Ultimately, the ability for a building to achieve a zero energy performance or EUI target is dependent on the actual energy consumed by the building. Operations is a critical piece to achieve success including appropriate set points and control sequences. Controls can help maintain appropriate setpoints from temperature setbacks to ventilation levels to lighting level to meet the needs of the building occupants. The design team should strategize on how to effectively use controls to minimize building energy consumption. The team starts with a detailed definition of the strategies and sequences of operations needed to achieve desired outcomes. As the design progresses, these are enhanced with detailed sequences

of operations, component specifications and performance metrics, and initial setpoints. These are detailed in the construction documents, which become the means of communicating the intent of the design and the strategies for operation…

6. ***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.

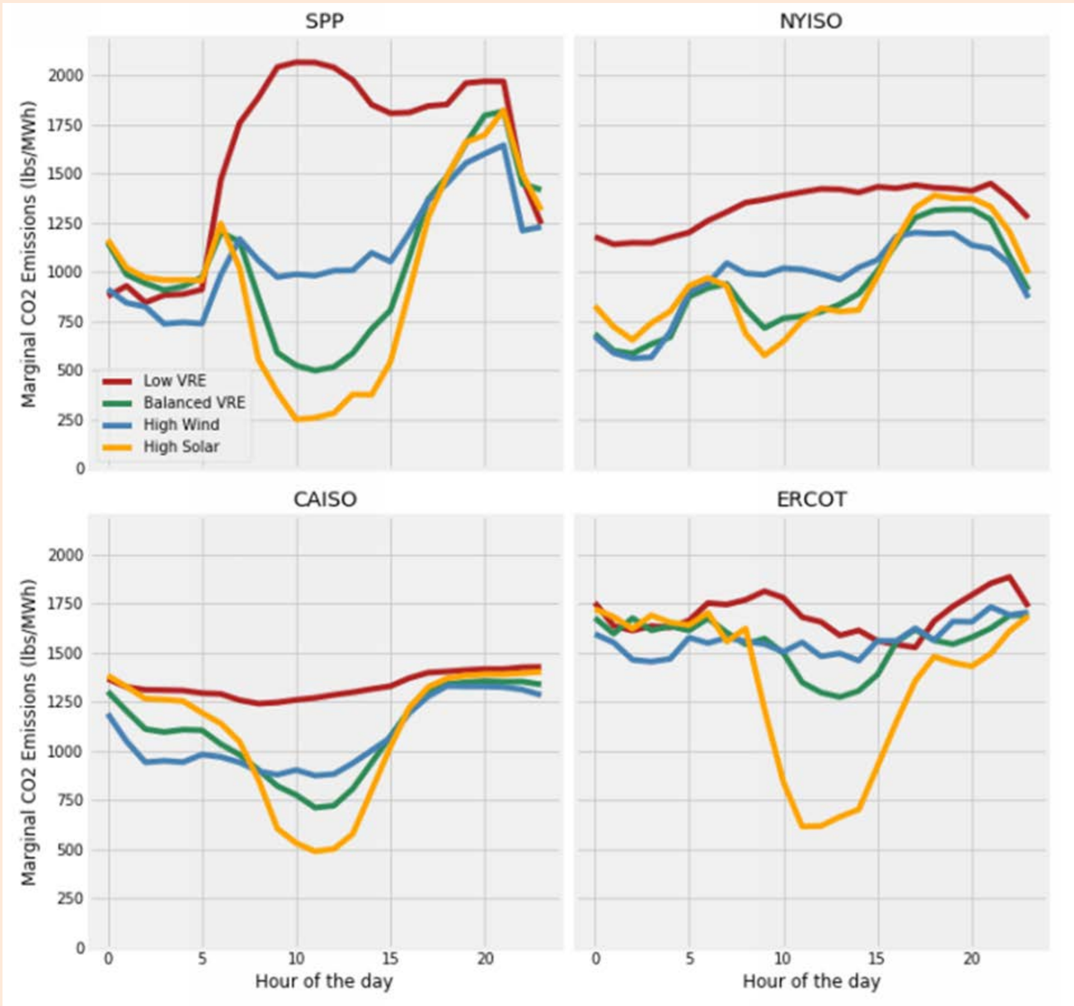
Following the above priority for design decision making will usually result in larger reductions in the project EUI for the least capital expenditure. Each project must find its own specific design solution based on building program, climate, owner preferences, and other core building goals, but pursuit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

Grid Considerations and Energy Storage

Most zero energy projects are connected to their local electric grid, using the grid as a to provide energy at moments when their on-site renewable energy generation does not cover demand. In some ways, the grid can be viewed as a giant-battery even though there is no physical storage occurring. 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 requirement that someone else can use the energy creates this notion of a virtual battery. 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 the 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. This issue is often referred to as the "Duck Curve" and is illustrated in Figure 1, by the diurnal carbon emissions profiles of several grid segments, especially the "High Solar" curves for the Southwest Power Pool (SPP) and the California Independent Systems Operator (CAISO) pool. As the grid adds more renewable generation assets, both utility scale and grid-connected asset from individual customers, it runs the risk of overgeneration during hours of renewable availability. During periods of rapid fall-off of renewable production, such as late afternoon, approaching sunset, grid operators must rapidly dispatch nonrenewable assets to replace the rapidly dropping renewable supply.



Diurnal Marginal Carbon Emissions Profiles (Mean) for Weekdays in Four Regions - Southwest Power Pool (SPP), New York (NYISO), California (CAISO) and Texas (ERCOT)

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 import demand from utilities., and to shift that demand to periods of low marginal carbon emissions for the grid. They can generally be categorized into passive load-reduction strategies and active load-management strategies. Passive load-reduction strategies minimize electric demand during a period that might have high marginal carbon emissions (the head of the duck), such as between 5:00 pm and 9:00 pm when cooling loads are still high but photovoltaic (PV) generation is fading. Passive strategies, by their nature, however, tend to have a static pattern of load reduction and load shifting, so that they are adapted to a specific diurnal marginal carbon emissions profile. These strategies include minimization of solar heat gain from west exposures while optimizing electric lighting reduction from daylight penetration. Active demand response techniques, on the other hand, are designed to be controllable to allow building operators to shift loads out of he high marginal emissions periods to times with lower marginal carbon emissions. These techniques include control of discretionary loads, that must be accomplished at some point during a day, but are not specific to an exact time, and various forms of energy storage, which allow energy to be accumulated during periods of high renewable production to be used during periods of low renewable production. Discretionary loads in a multi-family residential building might include charging of electric vehicles, defrosting a refrigerator and operating a washing machine or dishwasher.

The most common form of energy storage in multi-family residential buildings is the tank-type domestic water heater that is an example of thermal storage. It is almost universally controlled to enable the system to meet large short-term hot water demands, while limiting the instantaneous energy (gas or electric) demand but is not controlled to time- shift energy demand. Actively controlled 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 is 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 grid-aligned buildings, cooling is generated during any period of high renewable energy generation (such as in the late morning) when cooling loads are less than the peak load. The stored cooling energy is, then, 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.

Direct electrical storage is a very 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.

In multifamily buildings, super-insulating the façade and including modest thermal mass, in the form of mass walls or more massive interior finishes, such as tile or paver flooring, can enable users to pre-cool their apartments during mid-day and then turn off their cooling systems well into the night, using the stored “coolth” to maintain comfort and avoid energy use during the neck of the duck. Any negative impact of super-insulation for increasing cooling requirements in mild weather can be offset for free-cooling through operable windows. During the heating season, such strategies can be used to load shift heating energy as well, to better time the use of heat pumps with more favorable daytime temperatures.

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.

ADAPTING TO FUTURE NEEDS

A final consideration is the ability of the building to adapt to future needs and changes and to minimize current and future risks and impacts. Adapting 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)
- 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
- Capacity and infrastructure for electric vehicle (EV) charging stations

RESILIENCY

The concept of resiliency includes hazard preparation, mitigation and recovery. 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-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 such as natural ventilation, daylighting and thermal envelope
- On-site renewable energy
- Energy storage to operate the building when the grid is not available or is at reduced capacity
- Subsurface or ground-level spaces designed to provide protection or to recover quickly after flooding from storms or sea-level rise.

The RELI Reference Brief is an online resiliency action list and credit catalog that provides additional information on how to incorporate resilience into your building design (Pierce 2014).

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 and energy storage is available in the sidebar "Grid Considerations and Energy Storage."

RETROFIT-READY

Buildings can be designed to allow them to achieve zero energy via future retrofits with thoughtful planning during design and construction. Providing the infrastructure for these future retrofits during initial construction is typically far easier and less costly than completing the work after occupancy. Many cities are adopting retrofit ready energy codes, requiring buildings to be ready to be zero energy in the future with minimal renovation. These codes typically prepare buildings to be ready for all-electric building systems, which are better able to have their energy use offset by on-site renewables. Some strategies include:

- Planning for the location of renewables to be added and including conduits to those locations
- Allowing space for future switchgear, transformers and inverters
- Including empty conduits for future routing of conductors
- Installing electric infrastructure for all appliances and building systems including power for heat pump water heaters and heat pump based HVAC systems

OTHER FACTORS

Other important factors to be considered in adapting to future needs include:

- Facility Operator training and education
- Restructuring of utility tariffs
- Volatility of natural gas costs
- Embodied carbon
- Electrification

REFERENCES AND RESOURCES

EIA. 2017. *Utility-scale solar has grown rapidly over the past five years*. Washington, DC: U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=31072.

NBI. 2018. *2018 Getting to zero status update and list of zero energy projects*. Portland, OR: New Buildings Institute. https://newbuildings.org/wp-content/uploads/2018/01/2018_GtZStatusUpdate_201808.pdf.

NBI. 2019. Getting to zero database. Portland, OR: New Buildings Institute. https://newbuildings.org/resource/getting-to-zero-database/.

Pierce. 2014. *Resilience Action List and Credit Catalog*. Reference Brief. RELI. http://c3livingdesign.org/?page_id=13783

Pless, S., and P. Torcellini. 2010. *Net-zero energy buildings: A classification system based onrenewable energy supply options*. Technical Report NREL/TP-550-44586. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy10osti/44586.pdf.

USGBC. 2014. Green building 101: What is an integrated process? USGBC website. Washington, DC: U.S. Green Building Council. https://www.usgbc.org/articles/green-building-101-what-integrated-process.

Chapter 3: A Process for Success

[Note to Reviewers: This chapter is intended to provide guidance on how to navigate the design and construction process in order to achieve zero energy.]

In comparison to a traditional project process, a zero energy goal requires that the owner maintain the focus on zero energy and comfort goals during all planning, design, and operation decisions. The steps in this process include the following:

- Establishing zero energy as a goal
- Establishing the financing model for the project
- Selecting the right contracting process and the right team
- Determining 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

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. If necessary, the owner should work with a zero energy expert in setting the goals and parameters to be included in the RFP.
- ***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. It is important to consider the impact of removing or modifying a building system/element on other building systems/elements before making changes.
- ***Construction.*** Potential cost overruns, delayed schedules, and change orders due to scope creep could threaten the zero energy goal throughout the construction process. Using contractors familiar with high-performance construction is a helpful approach.
- ***Occupancy/Energy Verification.*** Effective owner, operator, and occupant training is necessary to achieving and maintaining the zero energy goal. Proper training and monitoring allow for the evolving needs of the building occupants and for the detection and correction of system failures or maladjustments that might inhibit achievement of the

zero energy goal. An additional strategy is to add metering/monitoring with permanent instructional signage. Providing free energy monitoring and feedback devices to tenants helps engage them post occupancy. Additional information on engaging tenants is provided in the *Educate and Engage Occupants* section later in this chapter.

Creating a zero energy building is about making good design decisions to deliver a finely tuned product that supports the people within the building. 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 and be continually reinforced throughout the organizational layers. 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. 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.

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.

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.
- Build confidence in the EUI target 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).
- 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. In addition to a total building EUI, that table also breaks out the lobby floor (common areas and commercial space) EUI separately from the residential floors EUI.

Table 3-1 Target Energy Use Intensity (EUI)

Climate zone	SITE ENERGY (kBTU/ft^2/yr)			SOURCE ENERGY (kBTU/ft^2/yr)		
	Resident Floors	Lobby Floor	Total	Resident Floors	Lobby Floor	Total
0A	28.9	23.2	27.5	90.0	73.1	85.8
0B	29.4	27.6	28.9	91.5	86.9	90.4
1A	26.9	23.4	26.0	84.3	73.9	81.7
1B	27.5	25.7	27.1	86.3	81.1	85.0
2A	26.7	22.2	25.5	82.9	69.9	79.7
2B	23.5	22.8	23.3	73.3	71.8	72.9
3A	23.9	21.4	23.3	72.7	67.3	71.3
3B	22.5	21.1	22.2	69.8	66.6	69.0
3C	21.1	16.0	19.8	77.5	50.2	70.7
4A	23.0	21.7	22.6	69.4	68.5	69.1
4B	21.7	20.6	21.4	68.4	64.9	67.5
4C	22.2	17.3	21.0	67.8	54.4	64.5
5A	21.6	23.2	22.0	68.1	73.0	69.4
5B	21.1	22.9	21.6	66.5	72.0	67.9
5C	20.7	17.5	19.9	63.6	55.2	61.5
6A	22.4	27.7	23.7	70.6	87.3	74.8
6B	21.7	24.7	22.4	68.3	77.8	70.7
7	21.8	30.3	23.9	68.6	95.5	75.3
8	21.8	36.0	25.3	68.6	113.5	79.8

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.

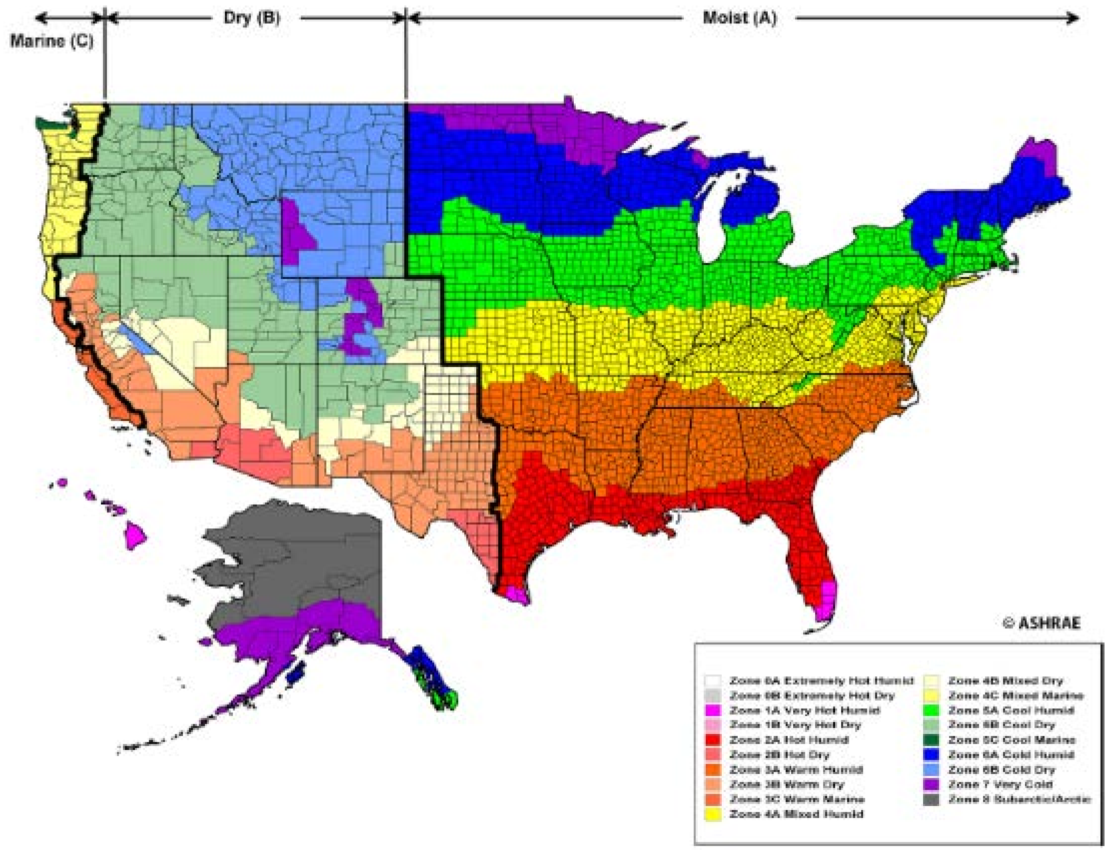


Figure 3-1 Climate Zone Map for U.S. States and Counties (Figure B-1, ASHRAE 2013)

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.

ESTABLISH THE FINANCING MODEL

Building the business case for zero energy buildings is especially important in multifamily building investment, as most investors are not familiar with the benefits that a net zero energy building can bring to their pro forma. There are many factors that play into the development of a pro forma for a multifamily building, including but not limited to the following:

- 5-10 year pretax cashflow model including operating expenses
- Loan to Value Ratio, Debt Service and Maximum Supportable Loan
- Gross Rent Multiplier
- Cash on Cash Return, Internal Rate of Return, and Net Present Value
- Vacancy Stress Scenarios for Cash Flow and debt service coverage impact

Each of the portions of a pro forma above can be impacted by the strategies deployed for a zero energy building, especially the cash flow models and return models. With simple payback of PV systems dropping to 7-years or sometimes less, the net present value of these systems can be significantly positive.

Even insurance costs and vacancy rates can be impacted by zero-energy design. Because zero-energy multifamily buildings offer utility cost reductions along with health improvements and more sustainable living, they can attract higher occupancy rates than traditional multifamily buildings, reducing the risk of vacancy stresses on cash flow modeling (USGBC 2015). Insurance companies are also starting to look at new insurance products with lower premiums for all-electric zero energy buildings due to the reduced risk of fire during seismic events or from tenant misuse of combustion appliances.

SELECT A PROJECT DELIVERY METHOD

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. Cost control can be maintained through competitive bids of the subcontractors.

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

- Understanding and 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
- Transparency of actual construction costs by all trades

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

[Note to Reviewers: Examples will be added.]

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 per ASHRAE Standard 209. 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 and proven, verifiable results. Requesting references and 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. 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 representative facility management groups and the perspectives of tenants. Each of these viewpoints 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 PROJECT REQUIREMENTS

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. While this type of information is often contained in a developer's prescribed development standards, there is still value in creating the project specific OPR and BOD documents for use by the project team. ANSI/ASHRAE/IES Standard 202-2018 *Commissioning Process for Buildings and Systems* includes detailed information on these documents.

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 living 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 describes what the owner wants or requires, and the BOD is the detailed description of the means by which those requirements will be fulfilled including an explanation of how the proposed solutions meet the requirements of the OPR.

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.

CONFIRM AND VERIFY

Design and construction of a new 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.

A project's failure to reach a zero energy goal can be the result of roadblocks that occur at any stage in the process. 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.

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 revisions 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

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.

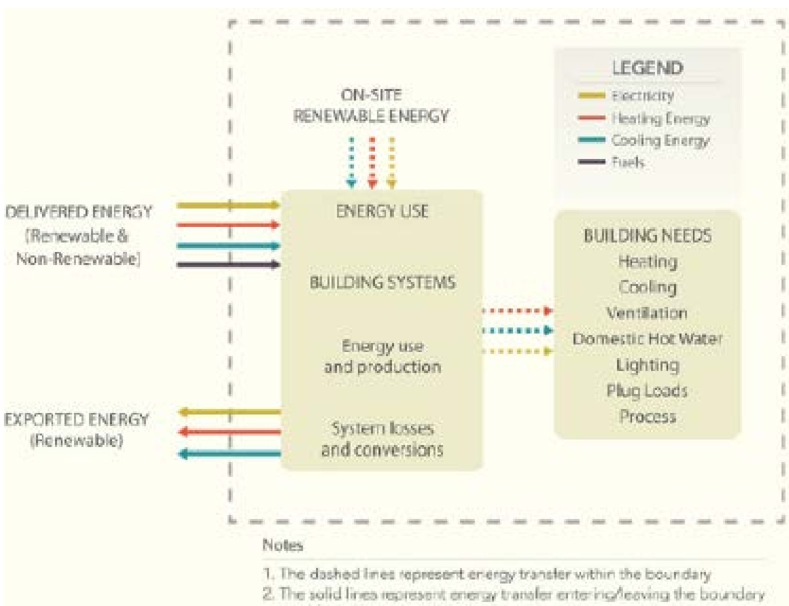


Figure 3-2 Energy Balance Diagram
(Figure 1, DOE 2015)

Two points are worth noting in regard 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 as 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.

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.

CONFIRM THROUGH COMMISSIONING

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.

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 Commissioning (Cx) process. The QA and Cx work should be included in early contractual documents with the project team.   Including these in the scope and in contracts from the start of the project, help ensure that the work gets done as required.

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 Commissioning Provider (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); domestic water heating, 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.

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.
- Pre-functional 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.
- Resolution of unresolved issues uncovered during Cx and of any delayed tests.

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, thermal bridging, 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 envelope 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. Whole building testing is more difficult to conduct in multifamily buildings because they are broken into small spaces. One strategy is to test apartment by apartment. One current methodology is to pressurize the spaces on each plane of the apartment (e.g., adjacent apartments, corridors, etc.) being tested in series to measure the leakage on each plane individually. Testing individual apartments also supports compartmentalization and air sealing between apartments. It is very difficult to do this type of testing in occupied buildings, so ideally, these are conducted prior to occupancy and at a point in time that allows for easy correction issues, 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. Inexpensive thermal cameras are now widely available.

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 (CO2), 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, air velocity, 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.

EDUCATE AND ENGAGE BUILDING OCCUPANTS

Engaging occupants is one of the most critical strategies to achieving actual energy use reductions in multifamily buildings. There are several key engagement strategies depending on the stage of design or tenant occupancy. Because each resident tends to have personal autonomy over their home, top down forced efficiency measures are often counterproductive and overridden by tenants who have not bought into the strategy. The following are some key engagement strategies to increase the effectiveness of efficiency measures with tenants:

- Offering educational programs
- Engaging with building management
- Identifying and partnering with trusted community members
- Instituting incentive programs
- Initiating floor by floor competitions
- Providing free energy monitoring and feedback devices to tenants

A key requirement for effective engagement and success is the inclusion of sufficient data monitoring equipment to provide actionable information to tenants. Real-time feedback systems provide much more influence over users than relying on end-of-month utility bills. Visual indicators and dashboards that can help interpret energy use in easily understood ways (red light, yellow light, green light) tend to help achieve for substantial energy reductions.

These types of feedback systems are sometimes available from controls vendors as well as third parties. The scope for developing these feedback systems should be included in the budget. It is also important that building owners, operators, and tenants are made aware of the opportunities 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.

VERIFY AND TRACK AFTER OCCUPANCY

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 begins 12 to 24 months after substantial completion of the building and continues indefinitely into the future to encourage and document continual improvement. 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

It takes at least 12 months of post-occupancy 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. It is important to continue to maintain the level of efficiency, if not improve on it, year over year. Successful multifamily projects often incorporate the following strategies:

- Create a measurement plan to capture the energy consumption of the building. This has to be coordinated with the utility as often each dwelling unit is monitored separately. In some cases, a building level meter can be installed. In others the leasing agreement should have a provision to provide the building owner with unit by unit data which can be aggregated to the whole building.
- Measure and evaluate specific components that are common to the building such as ventilation systems and hot water systems. With tenant permissions, data can be collected to help diagnose unit-based HVAC equipment and provide feedback in real time. Value based services such as dashboards can help tenants save energy and money.

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. Reward maintenance staff and occupants for meeting energy targets with strategies such as prizes or rent rebates.

REFERENCES

ASHRAE. 2013. ANSI/ASHRAE Standard 169-2013, *Climatic data for building design standards*. Atlanta: ASHRAE.

ASHRAE. 2015. ASHRAE Guideline 0.2-2015, *Commissioning process for existing systems and assemblies*. Atlanta: ASHRAE.

ASHRAE. 2018a. ANSI/ASHRAE/IES Standard 202-2018, *Commissioning process for buildings and systems*. Atlanta: ASHRAE.

ASTM. 2016. ASTM E2947-16a, *Standard guide for building enclosure commissioning*. West Conshohocken, PA: ASTM International.

ASTM. 2018. ASTM E2813-18, *Standard practice for building enclosure commissioning*. West Conshohocken, PA: ASTM International.

DOE. 2015. *A common definition for zero energy buildings*. DOE/EE-1247. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://energy.gov/eere/buildings/downloads/common-definition-zero-energy-buildings.

USGBC. 2015. *The business case for green building*. Washington, DC: U.S. Green Builiding Council. https://www.usgbc.org/articles/business-case-green-building.

Chapter 4: Leveraging Analysis to Drive Success

INTRODUCTION

The design process should include mechanisms for assessing the energy performance of the proposed design with real-world operating assumptions. The tool used to assess the energy performance should be capable of modeling the performance of the building systems, and the operating assumptions should 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.

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. With energy modeling, project teams can assess conventional energy design goals with zero energy strategies, and the energy impact when multiple strategies are combined. It's important to use these tools to help guide the decision making process. Modeling should be leveraged to inform energy efficiency and cost-effectiveness throughout the design process.

Software advancements have given designers the capability to quickly 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 should include feedback throughout the process so that the energy impact of each design and construction decision can be evaluated. As part of this, the design team must provide accurate information concerning the components of the proposed design when they become available and, as the design process progresses, encourage the owner to generate accurate projections of how those components will be used. Examples of this information include daily and monthly operating and occupancy schedules, occupant densities, owner-provided equipment power and utilization, operation during unoccupied time periods, and operation during special or public events. The operating characteristics of the building will have a significant impact on the building energy usage in multifamily buildings.

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 define success. Lighting quality, thermal comfort, and indoor air quality (IAQ) provide non-energy benefits that should be considered, modeled, and assessed in conjunction with meeting the energy goals.

The recommendations presented in this Guide are the result of numerous building energy simulation analyses using a 4 story prototype multifamily 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.   Additional sensitivity analysis determined the energy impact of additional stories.

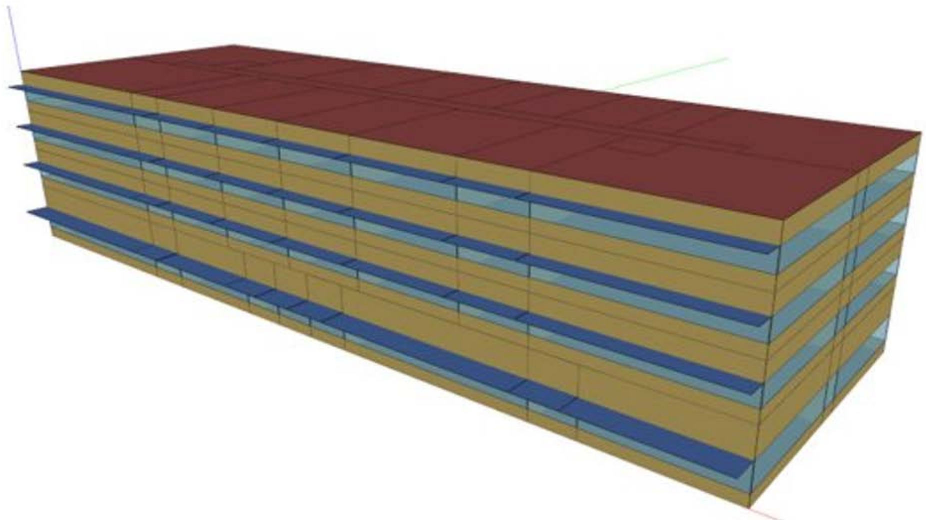
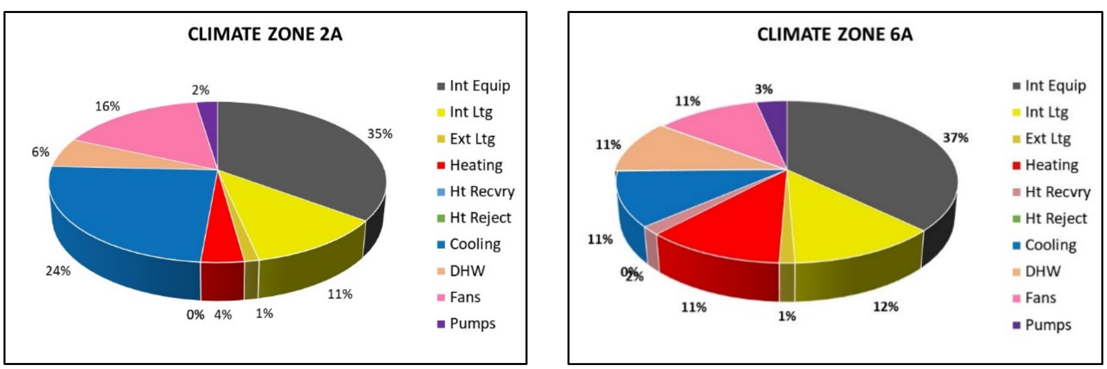


Figure 4-1 Multifamily Prototype Building

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 those major users. Figure 4.2 shows the energy end-use components of the 4-story prototype multifamily 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.



(a) Tampa, Florida **(b) Rochester, Minnesota**

Figure 4-2 Energy End-Use Components for Prototype Model using Typical Systems:

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).

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-ocumentation/getting_started/about_measures/
- Parametric Analysis Tool: http://nrel.github.io/OpenStudio-user-documentation/reference/parametric_analysis_tool_2/
- AEDG modeling information: www.zeroenergy.org

DESIGN PHASE STRATEGIES

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. 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
- Occupancy and user behavior
- Equipment schedules and loads, including smaller plug-in equipment
- Lighting
- Daylighting
- Mechanical ventilation
- Natural ventilation
- Infiltration
- Heating and cooling loads
- Domestic hot water plant and distribution
- Mechanical system comparisons
- Passive heating and cooling
- Renewable energy systems
- Thermal and battery storage

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 including location, use, and comfort goals. 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.

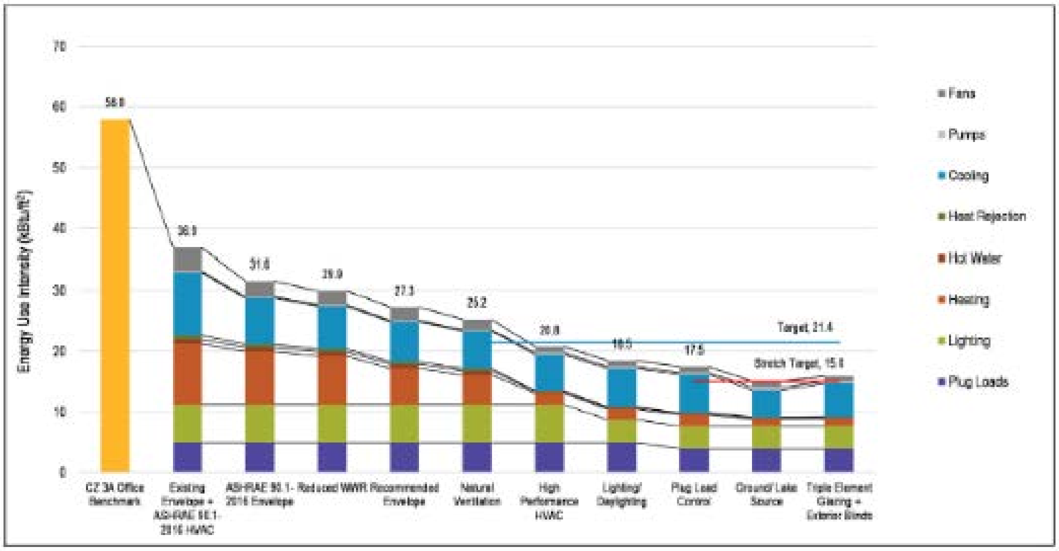


Figure 4-3 Incremental Impact of Energy-Saving Strategies Example

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
- 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. Post occupancy 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.

SPECIFIC ANALYSIS 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 and local weather including prevailing winds 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.

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.

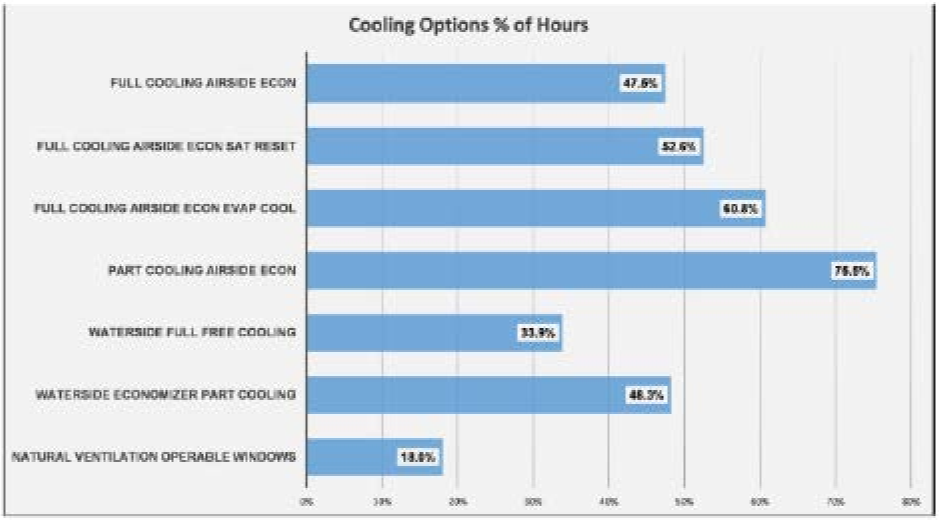


Figure 4-4 Climate Analysis of Free Cooling Availability Example Graph

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 this 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. Configuration options for multifamily buildings are further discussed in Chapter 5 (see BP4 and BP5).

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.

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 transmission). For additional information on WWRs, see 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.

Thermal bridging effects and associated design strategies are covered in the "Envelope" section of Chapter 5.

USER BEHAVIOR

Estimating user behavior is an attempt to understand how building occupants may react to their environment. The objective is to mimic occupant usage with operational schedules such that lights and HVAC are operated during "occupied" hours. Occupant density changes during the day and week and must be accounted for to properly model internal heat generated from the occupants, plug loads, lighting usage, and ventilation requirements. Surveys and other resources such as the Residential Energy Consumption Survey (EIA 2020) and Building America (DOE 2020) can be used to estimate building occupancy and schedules of use.

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 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, hard-wired vs.

plug-in lighting loads, daylight harvesting, controls options, and common/amenity spaces vs dwelling unit occupant schedules. For more information on these metrics, see the "Lighting" section of Chapter 5.

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

Due to the dominance of dwelling units in multifamily buildings daylighting should be only modeled in common/amenity spaces. To achieve a basic level of effectiveness a detailed climate-based 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 live and 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.

For more information on these metrics, see the "Lighting" section of 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 heat pumps, 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 modelling 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.

REFERENCES AND RESOURCES

AERC. 2017. *AERC 1: Procedures for determining energy performance properties of fenestration attachments*. NY: Attachments Energy Rating Council. https://arpa-e.energy.gov/sites/default/files/AERC.pdf.

ASHRAE. 2017a. ANSI/ASHRAE Standard 55-2017, *Thermal environmental conditions for human occupancy*. Atlanta: ASHRAE.

ASHRAE. 2017b. *Standard 90.1 user's manual*: *Based on ANSI/ASHRAE/IES Standard 90.1-2016, Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASHRAE. 2018. ANSI/ASHRAE Standard 209-2018, *Energy simulation aided design for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASE. 2019. OpenStudio® 2.8.0. United States: Alliance for Sustainable Energy, LLC. https://www.openstudio.net/.

EIA. 2020. https://www.eia.gov/consumption/residential/

DeKay, M., and G.Z. Brown. *Sun, wind and light: Architectural design strategies*, 3rd ed. NY: John Wiley and Sons.

DOE. 2019. EnergyPlus, ver. 9.1.0. Washington, DC: U.S. Department of Energy, Building Technologies Office. https://energyplus.net/.

DOE. 2020. https://www.energy.gov/eere/buildings/building-america

NREL. 2014. System Advisor Model (SAM). Golden, CO: National Renewable Energy Laboratory. https://sam.nrel.gov/.

NREL. 2019. PVWatts® Calculator. Golden, CO: National Renewable Energy Laboratory. http://pvwatts.nrel.gov/.

Olgyay, V. 2016. *Design with climate: Bioclimatic approach to architectural regionalism*, New and expanded edition. Princeton, NJ: Princeton UP

Chapter 5 How-to Strategies

Pathways to achieve a zero energy building are becoming more available as new technologies are developed, as existing technologies improve, and as renewable energy technologies rapidly advance. This chapter outlines strategies to move a multifamily 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 on-site 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 building sizes, heights, construction classifications, climate sensitivities, and regional practices make it impossible to address all the conditions that may be encountered in a typical project. The how-to information in this chapter is intended to provide guidance on strategies and good practices for achieving a zero energy 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).

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 (GA)
- Energy resilience (RS)
- Capital cost savings (CC)
- Building retrofit strategies (RT)

Table 5-1 Summary of Strategies and recommendations

	Component	How-to tips	✓	X
Building and Site Planning	Site Design Strategies	BP1-BP3		
	Building Massing	BP4-BP7		
	Building Orientation	BP8-BP9		
	Planning for Renewable Energy	BP9-BP17		
	PV Percent Area of Gross Floor Area	Table 5-3		
	Parking Considerations	BP18		

	Component	How-to tips	✓	✗
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	EN15-24		
	Fenestration and Doors Assembly Criteria	Table 5-6		
	SHGC Multipliers for Permanent Projections	Table 5-7		
	Air Leakage Control	EN25-EN29		
	Thermal bridging Control	EN30-EN40		
Lighting Design	General Guidance	LD1-LD2		
	Lighting Design Project Phase Tasks	LD3-LD7		
	Design Strategies	LD8-LD13		
	Interior Lighting Power Densities (LPDs)	Table 5-8		
	Lighting Control for Dwelling Units	Table 5-9		
	Lighting Control for Common Areas	Table 5-10		
	LED Specifications	Table 5-11		
	Space Specific Strategies	LD14		
	Average Space Distribution	Table 5-12		
	Residential Floor Sample Layouts	LD15-LD16		
	Common areas and Commercial Space Sample Layouts	LD17-LD26		
	Daylighting Design Considerations	LD27-LD33		
	Lighting Control Design Considerations	LD34-LD40		
	Exterior Lighting Design Considerations	LD41-42		
	Exterior Lighting Power Allowances	Table 5-15		
Plug Loads	General Guidance	PL1-PL2		
	Dwelling Units and Residential Spaces	PL3-PL7		
	ENERGY STAR Criteria for Dishwashers	Table 5-16		
	ENERGY STAR Criteria for Clothes Washers	Table 5-17		
	Recommended Energy Efficiency of Refrigerators	Table 5-18		
	Common Areas and Commercial Spaces	PL8-PL11		
	Building Process Loads	PL12		
	Power Distribution Systems	PL13		
SWH	System Descriptions	WH1-WH2		
	Design Strategies	WH3-WH8		
	ENERGY STAR Criteria for Faucets and Sprayers	Table 5-15		
	Calculation Procedure for Estimating Domestic Water Heating Size	Table 5-16		
	Gas Water Heater Performance	Table 5-18		
	Indoor Air-source Water to Water Heat Pump Performance	Table 5-19		
	Outdoor Air-source Water to Water Heat Pump Performance	Table 5-20		
	Water to Water Heat Pump Performance	Table 5-21		
	Parameters for Recirculation Pump Loss Calculation	Table 5-21		
HVAC Systems	Overview	HV1		
	System Descriptions	HV2-HV3		
	Minimum Efficiency Recommendations by System Type	Table 5-20		
	System A – Air Source Heat Pump Multisplit	HV4-HV7		
	Recommendations for System A	Table 5-21		

	Component	How-to tips	✓	✗
	System B – Water Source Heat Pump with Boiler/Closed Circuit Cooler and Water Source VRF	HV8-HV12		
	Recommendations for System B	Table 5-22		
	System C – Four Pipe Hydronic Systems	HV13-HV19		
	Recommendations for Hydronic Fancoils or Radiant Panels	Table 5-23		
	Dedicated Outdoor Air Systems	HV20-HV29		
	Recommendations for DOAS	Table 5-26		
	HVAC Tips for All System Types	HV30-HV39		
	Thermal Mass	HV40-HV41		
RE	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. Even the choice of location for a multi-family building has impact on building energy use and impacts on related energy uses such as transportation, infrastructure, etc. For example, a multi-family building located in a dense urban core may experience adverse solar shading, making it difficult to produce power on site. However, by locating within existing robust transportation networks and existing infrastructure, the project will likely have lower environmental impact compared to a suburban development on a greenfield site.

Urban multifamily developments typically have far less site optimization strategies at their disposal. Instead, projects are typically limited by the existing site footprint and a need to maximize the unit count on the site, within the zoning and height restrictions. This can eliminate some of the following strategies for consideration. However, suburban developments and rural multifamily developments may still be able to take advantage of site-responsive strategies.

SITE DESIGN STRATEGIES

BP1 Select Appropriate Building Sites (RS)
There are many factors that affect the selection of potential building sites. Some site aspects directly affect building energy use or renewable energy production, and 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 could be used to select a site for a zero energy multi-family project. Again, many urban infill sites will not offer the same site flexibility as suburban developments.

Property configuration and zoning

- Orientation for passive design and low energy
- Integration of renewable energy systems

Sunlight and shade

- Renewable energy (solar electric and solar thermal, building and ground mounted)
- Passive solar heating (climate dependent)
- Control heat gain and glare
- Shaded outdoor amenity spaces

Wind and breezes

- Natural ventilation (more challenging in double loaded corridor projects)
- Wind protection for outdoor amenity spaces, especially rooftop terraces.

Topography, ecology, geology and hydrology (More applicable to suburban sites)

- 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 ground-source heat pump systems
- Below-grade Parking garage earth coupling for cooling tower air pre cooling

BP2 Optimize Building Siting Combined with Landscaping and Site Features (RS)

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 building. Despite urban infill sites offering many constraints, landscape elements can be incorporated into the design to enhance performance regardless whether the project is located in a tight urban site or more suburban, less constrained site. 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, effective typically for the first three stories.
- Use trees and landscaping to funnel desirable breezes toward a building for cooling or ventilation. Especially at grade level common outdoor spaces.
- 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.
- Note the effect of landforms and plant forms on wind speed and wind quality relative to natural ventilation.
- 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. (Applicable for suburban sites.)
- Note the effect of landforms and plant forms on solar access and daylighting.

- Reduce the amount of paved surface (particularly dark, solar-absorbing colors) to reduce local heat island effect. Consider garage parking partially below grade or a ground level to reduce site impact.
- Recognize the beneficial effects of plant-based evapotranspiration on thermal comfort.
- Consider the beneficial effects of earth-coupling on reduced cooling loads.
- Consider green roofs and other planted spaces on roof terraces to reduce heat island effect in urban projects

BP3 Infill strategies

Many urban sites provide significant site design constraints. However, selecting sites that use those constraints to provide energy benefits can significantly reduce annual building energy. The following list summarizes infill site strategies that can improve energy efficiency.

- Select sites where zero lot line facades provide protection from adverse solar heat gain or can help buffer a project from adverse winter winds.
- Select sites where adjacent buildings, or buildings located across streets provide beneficial shading, reducing cooling loads in hot climates and risk for over-heating.
- In cooler climates, select sites where adjacent buildings do not over shade your site; reducing passive heating opportunities.
- Along long continuous building blocks provide massing breaks to allow natural ventilation between large masses; protect from overly strong breezes caused by venturi effect.
- Take advantage of zero lot line walls adjacent to existing buildings to provide additional thermal insulation, effectively creating adiabatic walls (i.e., a boundary the separates two parts of a system and does not allow heat or matter to be transferred across it).

BUILDING MASSING

BP4 Optimize Surface Area to Volume Ratio (CC)

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). Although unit layout typically plays a strong role in driving building massing, the arrangement of units and layout efficiency can have a significant impact on building performance.

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 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. In addition, a highly articulated massing, although beneficial visually by breaking up a massing, provides increased complexity, heat loss paths and higher risk for introducing air-infiltration. 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.

Although a more compact form factor will result in less heat loss/gain through conductive paths, it can also be beneficial to consider novel three-dimensional shapes, which can be designed so that the building is self-shading. This is especially true in multifamily buildings, as the variation in building massing including step outs and overhangs can provide beneficial shading of openings; contributing to reduce cooling loads. However, the bump outs would need to be substantial enough to actually cast a shadow of the majority of a window below during summer hours for it to be effective at reducing cooling loads. In addition, poor detailing will result in increased infiltration and increased risk of water intrusion, so care must be taken to properly design and detail heavily articulated facades, and these increases surface area must be weighed against the benefits from shading.

The envelope is also the interface for passive strategies such as natural ventilation and daylighting. 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. Multi-family buildings tend to lend themselves to long bar shapes driven by typical apartment unit depth and double loaded corridor configurations. When these area to volume ratios are analyzed for performance, A/V ratios of 0.7 and higher tend to be the most efficient.

BP5 Climate-Responsive Building Shapes (GA) (RS)

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, allowing access to daylight and views from all units within a relatively tight footprint. Typically, multifamily buildings are optimized by unit depth and access to light and air. These unit depths can be as low as 25 ft or as high as 35 ft. When doubled up on both sides of a corridor, the total floor depth typically lands around 65-75 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 5-3.

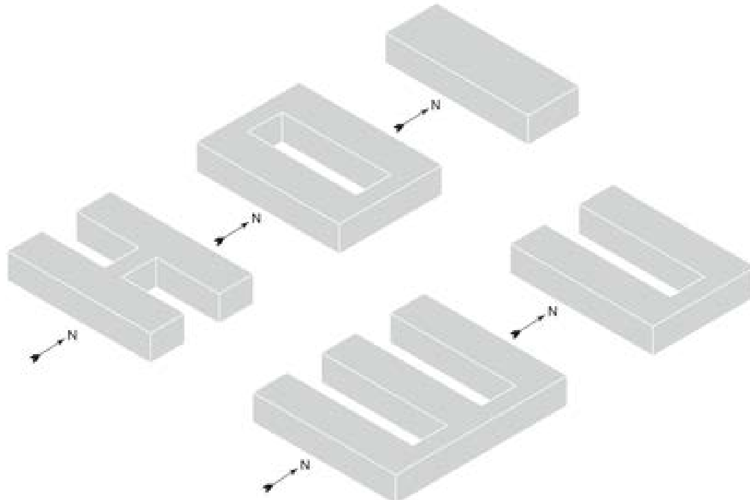


Figure 5-3 (BP5) Letter Building Shapes

BP6 Minimize and Shade Surfaces Receiving Direct Solar Radiation for Cooling (GA) (RS) (CC)

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. This is especially important for south and southwest facing units, where over heating is of particular concern, especially in power outages, where active cooling may not be available. 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 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 skylights that allow excessive solar gains 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.

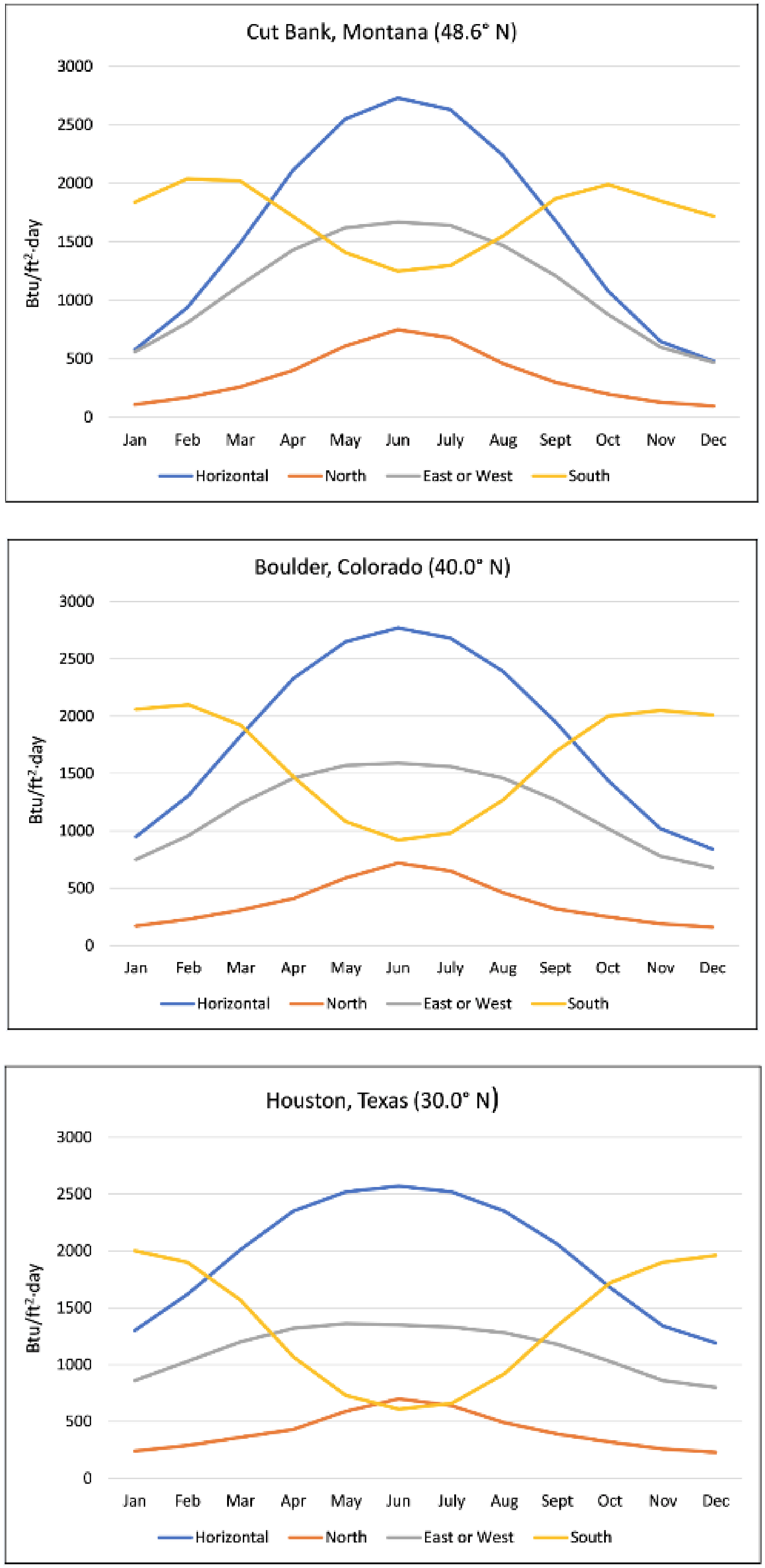


Figure 5-4 (BP6) Daily Average Incident Solar Radiation by Orientation for Diverse Locations

There are a variety of ways to provide shading for glazing and other envelope components including overhangs, shade structures, screens, 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 5-5.

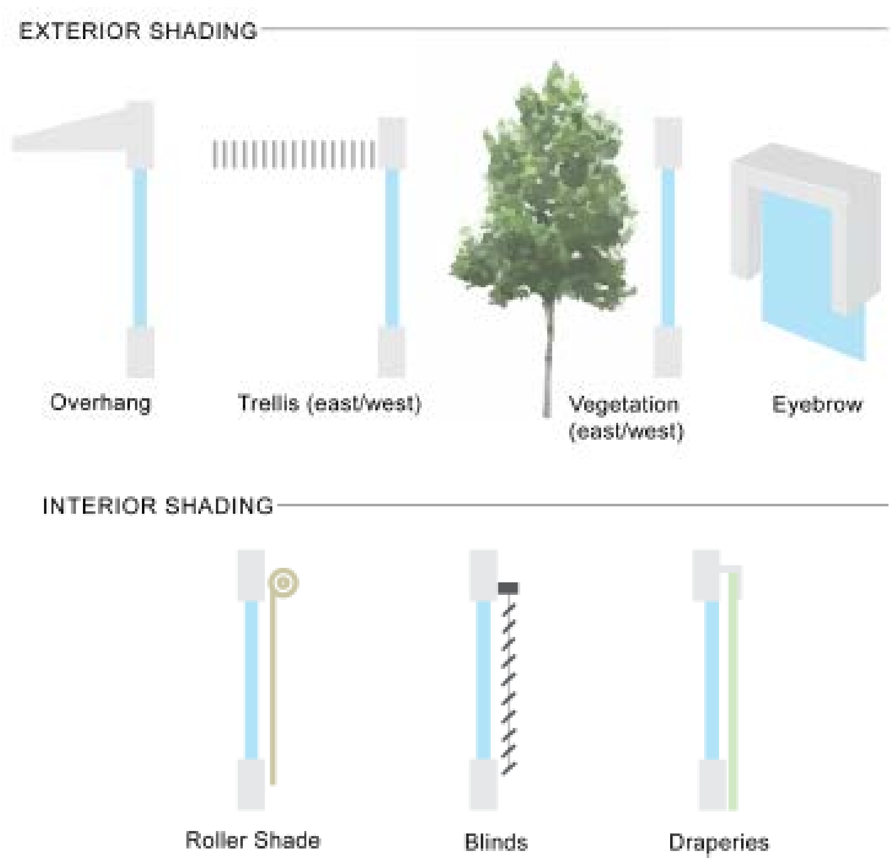


Figure 5-5 (BP6) Fenestration Shading Examples

BP7 Optimize Building for Natural Ventilation (RS)

It is important to consider a multifamily building's program and site when evaluating shape factor, especially related to passive design potential. Many multifamily buildings have an enclosed double-loaded corridor which makes natural ventilation difficult, as most units (except for corner units) do not typically have access on two sides for operable windows. Single sided openings are challenging for passive cooling, but can still provide the benefits of natural ventilation, as openings can be provided high and low to allow modest stack effect cooling. casement style windows can help capture winds that aren't blowing directly at a building. Corner apartments are often best suited to take advantage of cross ventilation wherever available.

Designers should review designs for compliance around fall protection for openings as well as egress windows with height limits. Additional challenges with passive cooling for multifamily buildings are related to issues around safety on the ground and 2nd floors. Window limiters may provide sufficient ventilation so long as they meet local codes for emergency egress.

Caution: Considerations need to be made for security, ambient exterior noise levels, outdoor air quality as per EPA National Ambient Air Quality Standards (NAAQS) (EPA 2015), outdoor air temperatures, humidity, operable window air leakage, pests, and allergens.

Some urban centers can have outdoor air quality below EPA recommendations (EPA 2015), where natural ventilation may not be a beneficial design consideration. In some more rural agricultural areas, dust and allergens may also prevent effective use of natural ventilation.

BUILDING ORIENTATION

BP8 Optimize Orientation (RS)

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 strategies are most applicable to suburban and rural sites. 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. Design is iterative, and while it is traditionally driven by unit layouts and building floor plate efficiencies, siting and orientation are also critical design parameters. Building energy use, resident comfort and the building's own passive survivability 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. This may include the use of outdoor balconies to provide shading to units below.

Figure 5-6 illustrates the effect of solar path and prevailing breezes on a building.

Multifamily image will be added

Figure 5-6 (BP8) Building Orientation with Solar Path and Prevailing Breezes

PLANNING FOR RENEWABLE ENERGY

BP9 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. However, if site parking is included, solar canopies can provide the dual benefits of energy production and decreasing residents' car temperatures. Planning for an array must begin with project conceptualization to ensure that an adequate roof area is reserved for renewable energy generation. This is especially challenging in multifamily design, as PV's are competing for roof space with HVAC equipment, amenity spaces including occupied roof decks, and green roofs.

BP10 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 5-7) 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.

PV systems may also be installed as a canopy, passing over rooftop equipment and still allowing for occupiable roof terraces. However, designers should always consult with local agencies, including fire officials to verify requirements for fire access and the impacts on canopies from local zoning restrictions. For projects where solar isn't installed right away, consider designing in the ballast weight into the initial design, or providing the racking stantions preinstalled.

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

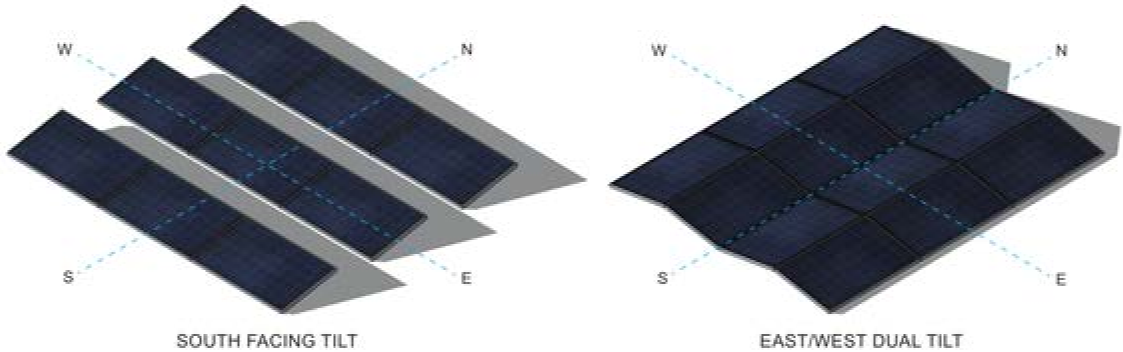


Figure 5-7 (BP10) Solar Panel Layout Options

BP11 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.

The required PV area for zero energy operation is both a factor of climate zone and also number of stories. Table 5-3 indicates the required area for a modeled prototype 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 a factor of 1.25 to account for spacing, aisles, and other installation requirements found on a typical project. The table demonstrates that in many climate zones, for multifamily buildings 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, 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 (BP11) PV Percent Area of Gross Floor Area

Climate Zone	Target EUI (kBtu/ft^2·yr)	PV Area as % of Floor Area
0A	27.5	38.2%
0B	28.9	26.1%
1A	26.0	24.9%
1B	27.1	30%
2A	25.5	26%
2B	23.3	21%
3A	23.3	26%
3B	22.2	20%
3C	19.8	20%
4A	22.6	28%
4B	21.4	20%
4C	21.0	31%
5A	22.0	29%
5B	21.6	22%
5C	19.9	28%
6A	23.7	30%
6B	22.4	28%
7	23.9	32%
8	25.3	47%

Note: Table percentages are for the PV 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 10º 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 multifamily building in climate zone 5B are as follows:

Gross floor area = 100,000 ft^2

Gross roof area = gross floor area / stories = 100,000 / 2 = 50,000 ft^2

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

Upgrade factor = 1.25

Roof area required for PVs = 100,000 ft2 × 0.187 × 1.25 = 23,375 ft^2

Percentage of roof area needed = 23,375 ft2 / 50,000 ft2 = 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.
- 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 in Chapter 5 for additional information on PV systems.

BP12 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. 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 5-9.

Picture of MF building roof array to be added

Figure 5-9 (BP12) Roof Mounted PV System

Consider the following strategies for maximizing available roof area:

- Limit or avoid skylights, which, in addition to the reducing continue roofing area for PV's, also increase cooling loads and only provide a daylighting benefit to top floor units.
- Require rooftop coordination drawings and shop drawings from the design and construction teams, 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 parking garages. 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.
- Gang plumbing vents where possible at the top floor ceiling or attic space to minimize vents interfering with panel layouts.

BP13 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 and roof superstructure the project goals can support. To host a solar PV system, a roof must be able to support the weight of PV equipment and ballast.

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/ft2.
- ***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.

BP14 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/or offer fall protection and will thus sacrifice roof area that could be otherwise used for solar electric generation. Additional clearances may also need to be provide for window washing equipment supports.

BP16 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.

B17 Alternatives to Roof-Mounted PV

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 or also be an urban infill location lacking site area for a ground mounted array. 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 (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 BP12 cannot be used.

PARKING CONSIDERATIONS

BP18 Parking Garages

The configuration and quantity of parking in multifamily projects is highly variable and primarily driven by local planning and building codes. Where the designer has a choice, the amount of parking should be minimized in areas where higher prevailing densities and good transit access will minimize the need for parking. Providing more parking than needed wastes energy in the supply chain for construction (concrete is very energy intensive, for example) and in encouraging more car ownership thus leading to more gasoline usage. It can reasonably be anticipated that for most multifamily projects in urban centers, car ownership will decline over the years and be replaced by car sharing and ridesharing.

For projects of significant scale that may include a central plant with cooling towers, especially in hot climates, consider locating the cooling towers in the below grade garage. The cooling towers can provide a portion of the garage exhaust, while also taking advantage of the earth-coupled precooling of the cooling tower inlet air. This can increase the water-side economizer hours and significantly depress the wet-bulb temperature of the inlet air, allowing the cooling tower to be more efficient and reduce the load or operating time on the chillers. Careful consideration must be paid to the cooling discharge area to maintain required clearances to occupied areas and operable windows. Although, special attention to cooling tower fouling will need to be paid, especially if a significant number of older, more polluting cars are parked there.

Parking garages can also be a useful space to locate energy storage systems. With increases in electric vehicle charging and the associated increase in electrical infrastructure in parking garages, there can be an economy of scale by providing space and installing battery storage systems. Garages are also a convenient location to include thermal energy storage tanks, if located close enough to central plant equipment. High-rise multifamily projects often already include water storage tanks in these locations to serve fire-water storage requirements. Consider using fire water storage as thermal storage if allowed under the local jurisdiction. This can allow heat pump based central plants to optimize performance without significant increase to cost. The garage is also an ideal location for large centralized heat pump water heating systems. (See DWx.)

REFERENCES

EPA. 2015. National Ambient Air Quality Standards Table. Washington, D.C.: U.S. Department of Energy. https://www.epa.gov/criteria-air-pollutants/naaqs-table.

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 5-11 presents heating and cooling loads by climate zone. This information can be quite useful as an intuitive 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 Envelope 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 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.

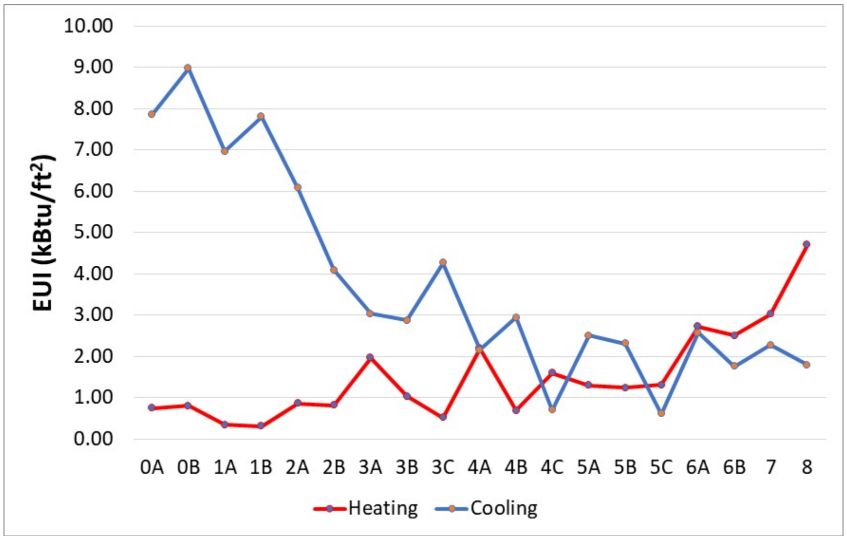


Figure 5-11 (EN) Heating and Cooling Loads by Climate Zone

THERMAL PERFORMANCE OF OPAQUE ASSEMBLIES

EN1 Building Insulation General Guidance (RS) (CC)

There are numerous insulation products available, and there are multiple criteria used to evaluate insulation, including R-value, moisture resistance, recycled content, recyclability, combustibility, health impacts of flame retardants, global warming potential of expanding agents and embodied carbon. 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 may save energy; however, this benefit may be minimal. Over insulation can also increase cooling energy use. 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.

Table 5-4 (EN1) Envelope Construction Factors

	Recommendations by Climate Zone														
Component	**0A**	**0B**	**1A, 1B**	**2A, 2B**	**3A, 3B**	**3C**	**4A**	**4B, 4C**	**5A**	**5B**	**5C**	**6A**	**6B**	**7**	**8**
Roof U-factor	0.038	0.038	0.038	0.036	0.032	0.038	0.022	0.026	0.018	0.023	0.032	0.017	0.022	0.017	0.017
Frame walls above grade U-factor	0.040	0.040	0.040	0.053	0.048	0.091	0.025	0.038	0.022	0.032	0.050	0.018	0.029	0.017	0.017
Mass walls above grade U-factor	0.040	0.040	0.040	0.053	0.048	0.091	0.025	0.038	0.022	0.032	0.050	0.018	0.029	0.017	0.017
Slab F-factor	0.730	0.730	0.730	0.730	0.540	0.540	0.494	0.494	0.494	0.494	0.494	0.450	0.450	0.400	0.400

Units for U-Factor is Btu/h·ft^2·°F.

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 by completing extensive multi-variable parametric energy modeling. Appendix A presents alternative constructions that have equal to or even better U-factors or F-factors for the appropriate climate zone.

Table 5-5 outlines common commercial insulation material applications for the envelope components discussed in this Guide (refer to EN2 through EN8); however, attention must be paid to the global warming potential and embodied carbon of each of the materials.

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	X	X	X
	Fiberglass	X				X		
Spray-in-place	Polyurethane	X	X	X				
Loose Fill	Fiberglass			X				
	Cellulose			X				
Batts	Fiberglass			X			X	
	Mineral Wool			X		X	X	

EN2 Insulation of Roofs (RT)

Insulation entirely above the structural deck is recommended; although must be balanced by attachment requirements for PV systems. 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).

An inverted membrane roof system is also common in many climate zones for low-sloped roofs, where the insulation provides a protective layer over the roofing membrane. This can extend the life of the membrane and protect it from UV exposure.

To minimize thermal losses and infiltration, board insulation should be installed in at least two layers staggering the joints. Refer to Table x-x 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. In addition, insulated curbs are often used to allow loads to be transferred while maintaining thermal integrity.

EN3 Insulation of Mass Walls—Concrete and Masonry (GA) (RS)

For mass walls, continuous exterior insulation is preferred over interior insulation as it can aid the thermal mass (when exposed to the interior) for energy efficiency, load shifting and passive resilience. 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-EN11, and HV55-HV57.

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 hygro-thermal modeling in compliance with ASHRAE Standard 160 demonstrates that vapor will not cause a condensation or mold risk problem. 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 such as XPS 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 such as a parking garage) 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. Thermal bridge modeling can be used to show how far the insulation should be turned down for maximum benefit. For columns extending to below-grade parking, insulation should be turned down to the extent possible without presenting a durability issue with vehicles. Insulation material should meet local building codes in terms of non-combustibility requirements in parking garages. 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 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 or in contact with the ground., 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 including gypsum board, 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. Also refer to HV54, HV55 and HV56 for additional information on utilizing thermal mass.

EN10 Internal Thermal Mass (GA)

Exposed internal thermal mass within multifamily units tends to mitigate temperature swings that might result from a mismatch between occupancy, 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, or to better align with daily PV production or electrical grid stability. 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. In multifamily projects, this exercising of thermal mass is typically dependent on action by the resident in opening windows at night and “locking down” the apartment during the day. Some residents will resist allowing the nighttime temperature to drop below the comfort range, so building mechanical systems must still be sized for a peak load not dependent on active thermal mass optimization.

Night mass cooling is the strategy of opening windows at night to cool thermal mass (drywall) and closing windows during the day to keep spaces cool. During the heating season, super insulation, air barriers, and solar heat gain keep spaces warm. Required elements of the strategy include:

- Climate in which night outside temperatures reliably drop to 65°F or lower.
- Internal Thermal Mass. Given the limited exterior wall area of a MF unit; the 0.5 inch drywall on ceiling and walls provides adequate thermal mass.
- Operable Windows sized for necessary free cooling.
- Well-insulated envelope with good air sealing.
- Windows and shading systems for good winter heat gain and minimal summer heat gain.
- Air-movement fans for extending the thermal comfort range in the summer.
- HVAC space temperature setpoints of 65F heating and 80F cooling.

The following is a concept level control strategy:

- Open windows on summer evenings when OSA temp drops below space temp. Experience tells you how much to open windows.
- Close windows if space temp approaches 65°F. You’ll wake up if it gets too cold.
- Close windows when OSA temp exceeds space temp or when you leave for work.
- Allow daytime space temps to rise to near 80°F in the winter to heat drywall for upcoming night.
- Operate air movement fans to extend cool comfort range.
- Increase Clo values to extend heat comfort range. (Note: Clo value is used as a measure of clothing thermal insulation.)
- HVAC will maintain space temps in the 65°F to 80°F range.

Thermally massive elements in a space will dampen variation in the space mean radiant temperature, improving comfort even with significant changes in the 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 and requires an increased ramp rate to compensate for the reduction in solar generation on the grid. 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 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.

Active thermal mass, i.e. radiantly heated/cooled thermal mass can often provide even more load shifting capabilities, allowing the cooling and/or heating energy to be delivered into the slab with considerable time flexibility, in many cases being up to 12 hours offset from the actual space peak load. Additional strategies for tuning thermal mass setpoints include the use of phase change materials. Depending on the chemistry of the phase change material, they can be used to release energy or absorb energy as certain setpoints, allowing room temperatures to avoid peak gains for a few more hours than those buildings without.

Figure 5-12 shows an example of exposed thermal mass at … [new text to be added to go with photo]

Photo to be added of Condo/Apartment
with exposed thermal mass… can be concrete, brick, etc.
Typical of "Loft" look buildings

Figure 5-12 (EN10) Exposed Thermal Mass in Multifamily Building

EN11 External Thermal Mass (GA) (RS)

In climates with a high diurnal temperature swing, weternal 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, 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. This strategy does not typically provide any benefit in cold climates, as the mass never has a chance to heat up during the diurnal cycle. In nearly all climate zones, the external thermal mass must be paired with internal insulation to achieve the required total u-value for the wall assembly.

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 multifamily building's top floor 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 BP14 for strategies on designing a long-lasting roof.

EN13 Cool Roofs and Warm Roofs (RS) (CC)

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. However, coolroofs can have benefits in climate zones 5-6, especially in Urban settings, where they can assist in resiliency and ability to shelter in place during power outages in summer time. 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 and potential improvement to rooftop amenity spaces. These advantages include improved storm-water management, sound insulation, improved air quality, biodiversity, biophilia, aesthetics, and additional life for the roofing membrane. For all systems, climate appropriate plantings should be selected to avoid excessive irrigation demand.

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.

The best way to achieve low-cost daylighting, views, and natural ventilation is to integrate fenestration concepts 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 including WRR (EN16), U-factor (EN18), solar heat gain coefficient (EN19), and visible transmittance (EN20). 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 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 (GA) (CC)

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.

In multifamily buildings, the WWR is often set as a function of the price point for the unit rental or sale value; however, all unit types deserve access to daylight and views. Regardless of the price point of the project, the WWR is a significant driver in project cost and energy performance.

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. In addition, window head height plays the largest role in daylight penetration into a space, so approporately locating windows for daylighting performance is especially important.

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 by completing extensive multi-variable parametric energy modeling. Fenestration products are available that exceed the minimum requirements in Table 5-6 and should be considered for zero energy multifamily 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														
Component	**0A**	**0B**	**1A, 1B**	**2A, 2B**	**3A, 3B**	**3C**	**4A**	**4B, 4C**	**5A**	**5B**	**5C**	**6A**	**6B**	**7**	**8**
Maximum U-Factor (Fixed)	0.48	0.49	0.49	0.38	0.31	0.42	0.23	0.27	0.17	0.23	0.23	0.17	0.23	0.14	0.12
Maximum U-Factor (Operable)	0.48	0.57	0.57	0.43	0.35	0.54	0.23	0.30	0.17	0.26	0.26	0.17	0.25	0.14	0.12
Maximum SHGC (Fixed)	0.21	0.21	0.22	0.24	0.24	0.25	0.34	0.34	0.36	0.36	0.36	0.36	0.36	0.38	0.38
Maximum SHGC (Operable)	0.19	0.19	0.20	0.22	0.22	0.23	0.31	0.31	0.31	0.31	0.31	0.32	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	1.10	1.10	1.10	1.10	1.10	1.10
Swinging Doors U-factor	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Note that the values in Table 5-6 represent values for the overall fenestration assembly, not just the glazing. This is particularly important for the U-factor (EN18). Units for U-Factor is $Btu/h \cdot ft^2 \cdot °F$.

EN18 Window U-Factor (RT)

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 (i.e., climate zones 6, 7, and 8), 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, although long term performance is still being evaluated. Additional research is currently underway into “Thin-Triples”, triple element windows which fit into existing dual-pane frames.

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. 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.

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 and accounted for in an energy modeling. For complicated connections, three-dimensional thermal bridging modeling software can be used to help minimize heat loss. In addition, stainless steel has a much lower conductivity than that of black steel and aluminum, allowing thermal bridges that can’t be avoided to have a minimized impact.

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.

Figure 5-11 (EN18) Thermally Broken Aluminum Frames
Double pour-and-debridge (left) and wide thermal struts (right)
Photos courtesy of Azon (left) and Technoform (right)

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.

A high performance U-value is also dependent on the use of appropriate low-e coatings. Many contemporary high performance windows include multiple spectrally selective low-e coatings preventing wintertime heat loss, mitigating excessive solar heat gain while maintaining a high visible light transmittance.

EN19 Solar Heat Gain Coefficient (RT)
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 heat gain. As a starting point, the SHGC of fenestrations should comply with the SHGC delineated in Table 5-7. SHGC is ideally tuned to each facade orientation, with the lowest value typically for west-facing glass and the highest value typically for north-facing glass.

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 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. Special attention should be paid to East and West facades, as projection factors should not be used in those orientations to increase the SHGC values.

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

Projection Factor	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

Bug screens also reduce solar heat gain coefficients. Some bug screens have been designed with a 3-dimensionsal weave which provides additional shading of sun altitude angles higher than 60 degrees.

EN20 Visible Transmittance

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 Acoustics and Impact on Energy

Multifamily projects can have stringent acoustical requirements for glazing systems, especially in urban settings or project sites adjacent to road or railways. Typically, the window systems needed to meet these rigid acoustical requirements can be designed in a way to also provide increased thermal performance. This includes triple element windows with varied thickness glass panes, laminated glass layers and double window systems

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 challenging 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. Due to the complex hygro-thermal behavior of each specialized spandrel assembly, a envelope specialist should be consulted.

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.

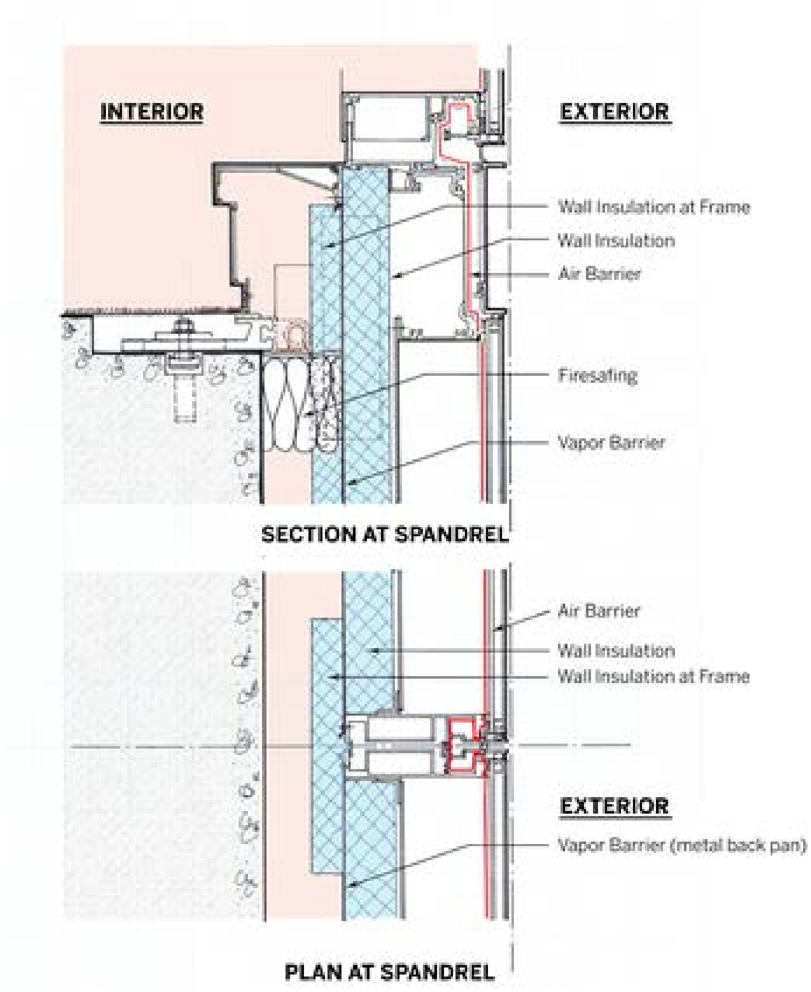


Figure 5-13 (EN22) Spandrel Insulation Continuity

Figure Created by Keith Boswell, FAIA

EN23 Operable Fenestration (RS)

Operable fenestration offers personal comfort control and connections to the environment, as well as egress and fire ladder access. 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 HV39 for information on integration of natural ventilation with HVAC systems, especially with the use of window interlocks used to reset space cooling and heating setpoints.

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. In addition, operable windows tend to become points for infiltration over time as seals fail.

EN24 Glazed Entrance Doors

Metal-framed glazed entranced doors should have a U-factor of less than xxx Btu/h·ft2·°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 not heated, or a semi-heated space and not mechanically heated to above 45°F. The space should not be mechanically cooled.

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

EN25 Air Leakage Control General Guidance (CC) (RT)

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 infiltration is the largest source of moisture within the envelope assembly one you exclude bulk water leaks. 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 transient dew-point temperature (and possible condensation or moisture accumulation) 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 over varied weather conditions, occupancy patterns and envelope design options.

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.

EN26 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, NFRC 400, or ASTM E283) 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.

EN27 Whole Building Air-Sealing

New methods of air-sealing have recently appeared on the market, including aerosol based whole building air sealing. These systems work in conjunction with a blower door test. While the unit, entire floor, or whole building (dependent on building size and massing) is pressurized, an air sealing agent is released in an aerosolized form. The material naturally finds the air leakages paths and self-seals them, much like a duct sealing system. The result is an excellent air seal in a very short amount of time

EN28 Establish a Maximum Air Leakage Rate Target

The recommended target air leakage rate is 0.35 cfm/ft2 (or less) of total envelope surface area at 75 Pa for all climate zones. 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 and several others.
- 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).

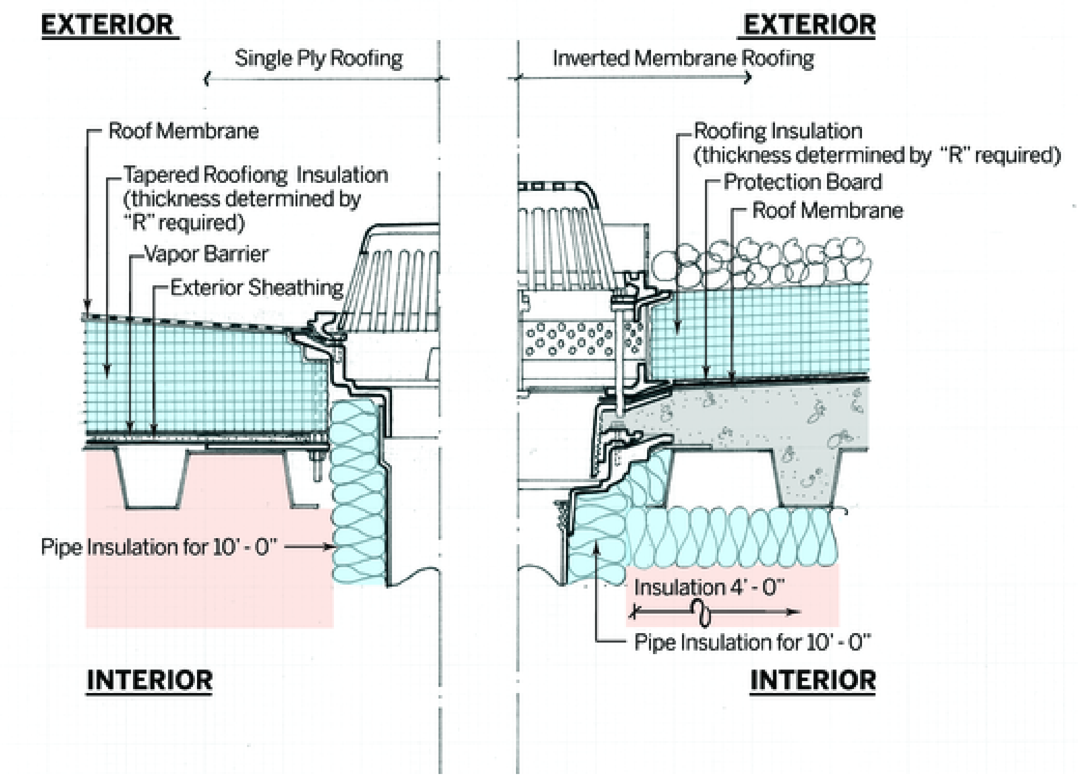


Figure 5-14 (EN31) Roof drain insulation.

Figure Created by Keith Boswell, FAIA

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.

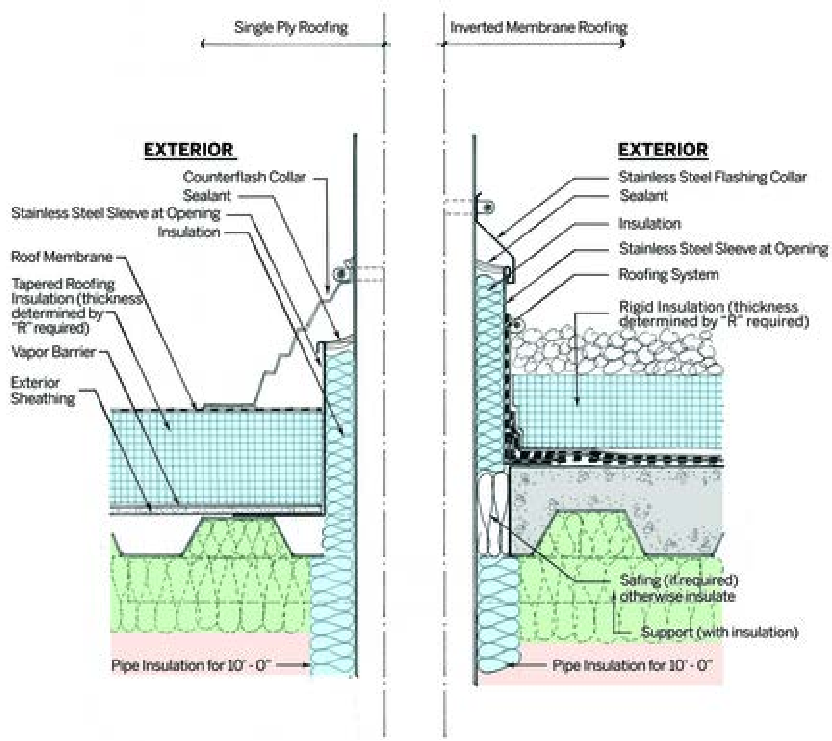


Figure 5-15 (EN31) Plumbing vent insulation.
Figure Created by Keith Boswell, FAIA

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 Photovoltaic (PV) Supports

Photovoltaic panels need structural supports. It is important that these supports be designed so that they do not compromise the thermal integrity of the envelope. On flat roofs, PV panels can be installed without structural penetrations with ballasted systems. On standing seam roofs, PV systems can be attached without penetrations with clips designed for this application. (See also RE5 for more information on mounting options.)

EN33 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.
- 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.

EN34 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.

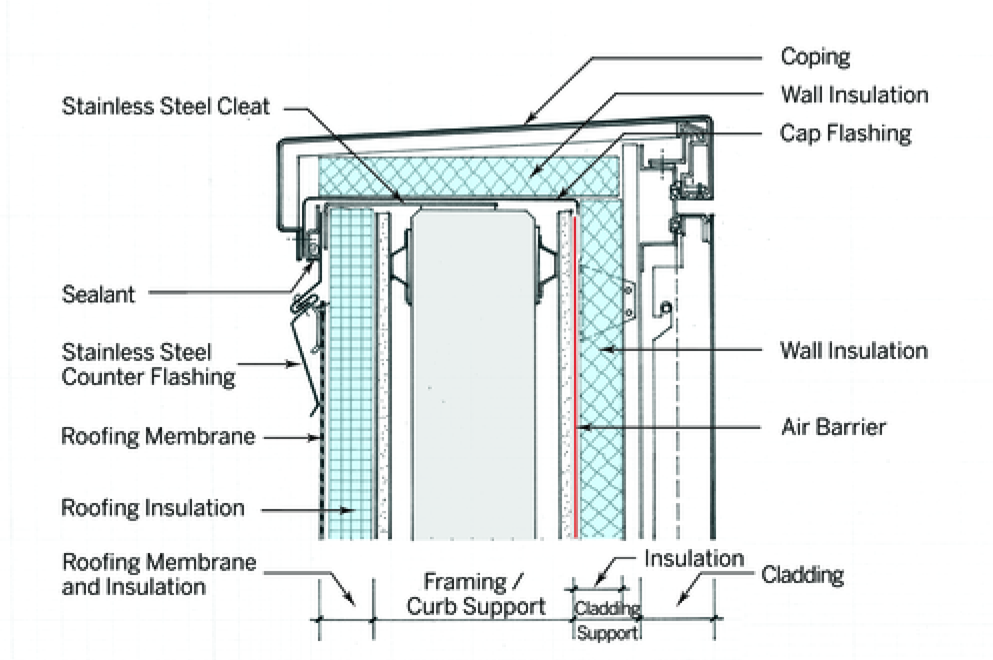


Figure 5-16 (EN34) Parapet insulation.

Figure Created by Keith Boswell, FAIA

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.

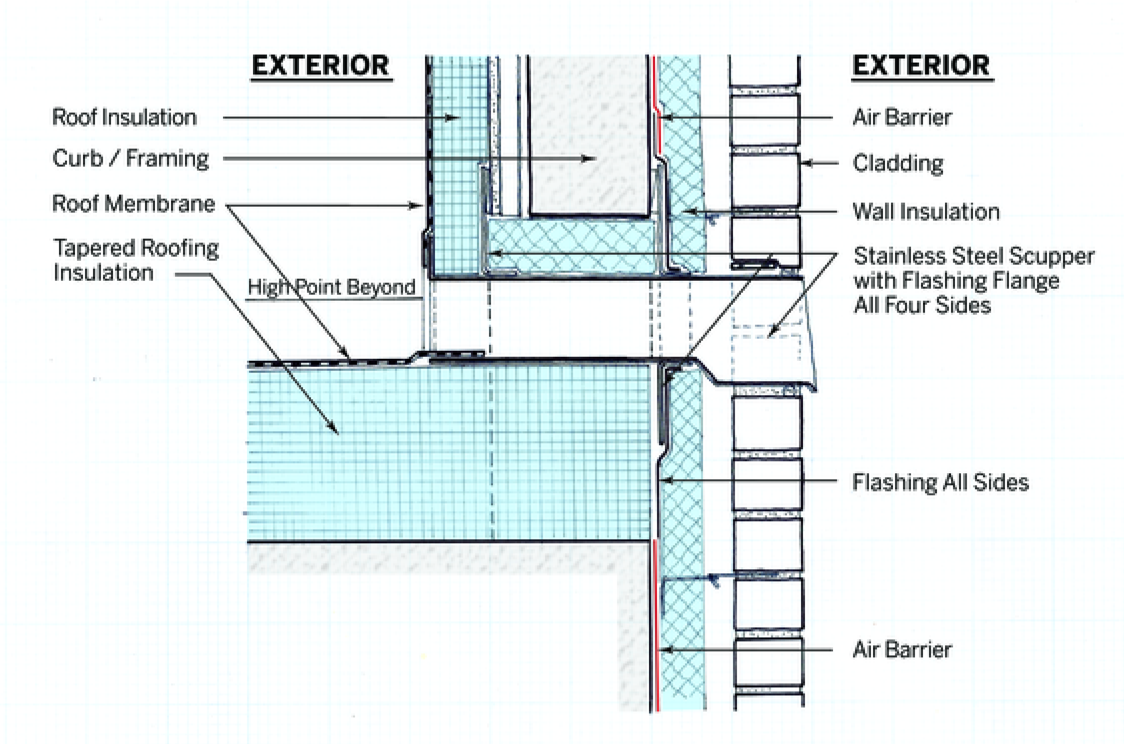


Figure 5-17 (EN34) Through-wall scupper insulation.

Figure Created by Keith Boswell, FAIA

EN35 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.

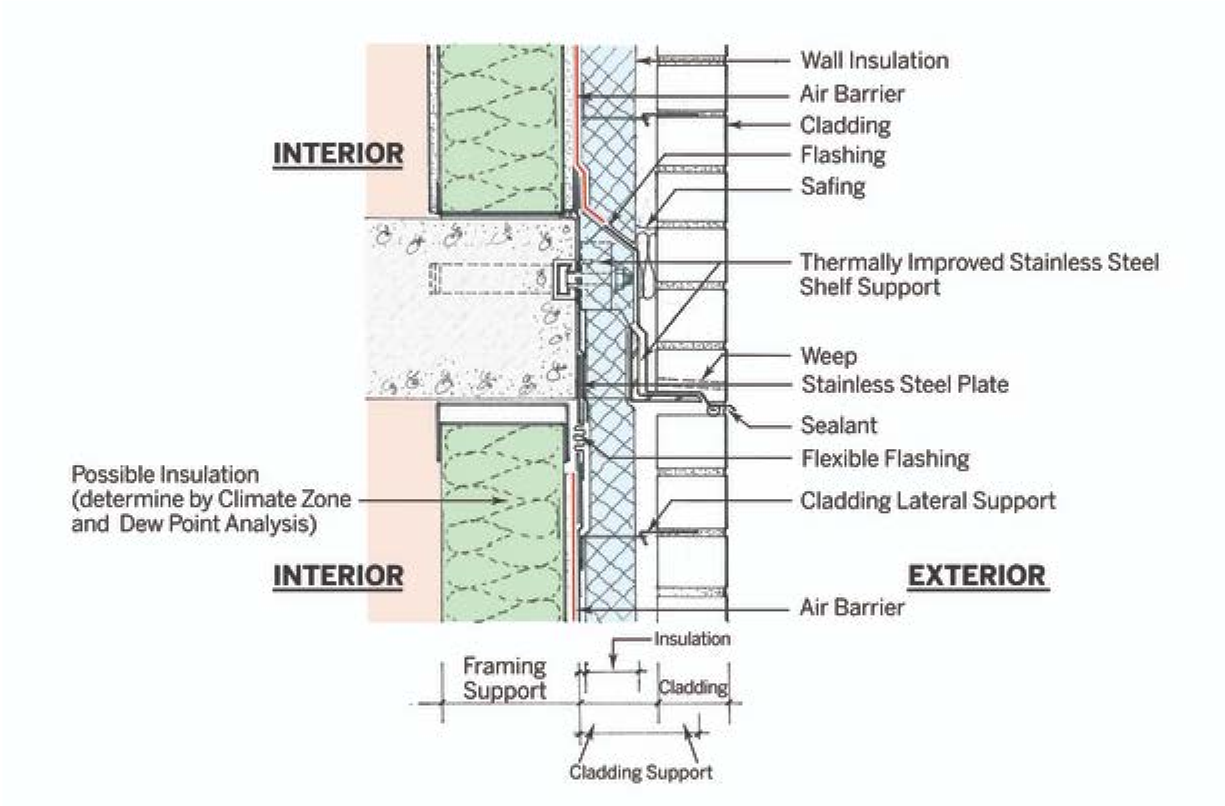


Figure 5-18 (EN35) Shelf angle installation at floor edge.

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.

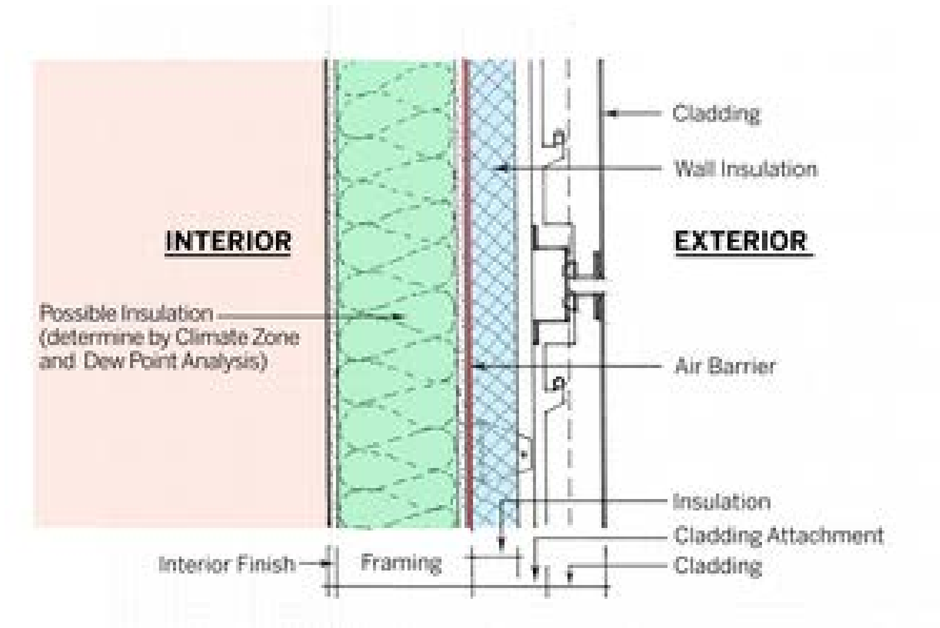


Figure 5-19 (EN35) Wall cladding attachment

Figure Created by Keith Boswell, FAIA

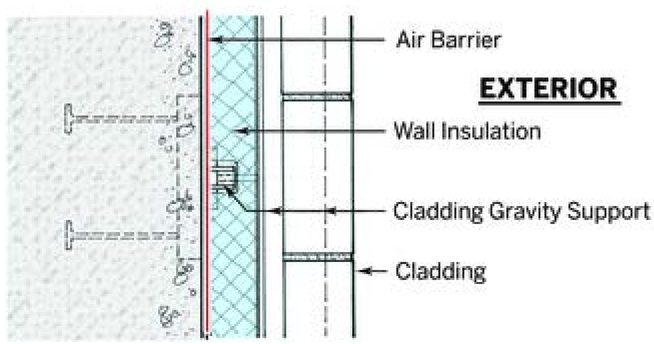


Figure 5-20 (EN35) Wall Masonry Attachment – Cladding Gravity Support

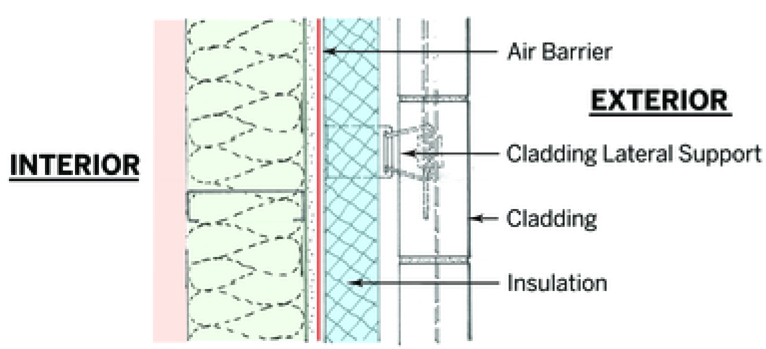


Figure 5-21 (EN35) Wall masonry attachment – Cladding Lateral Support

Figure Created by Keith Boswell, FAIA

EN36 Thermal Broken Attachments

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.

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).

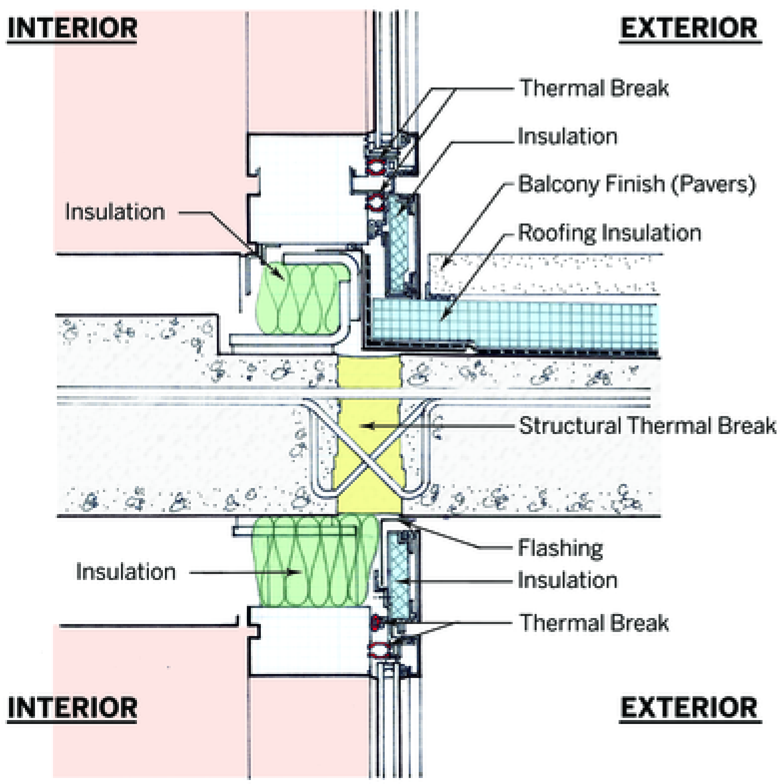


Figure 5-22 (EN36) Wall to balcony.
Figure Created by Keith Boswell, FAIA

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**.**

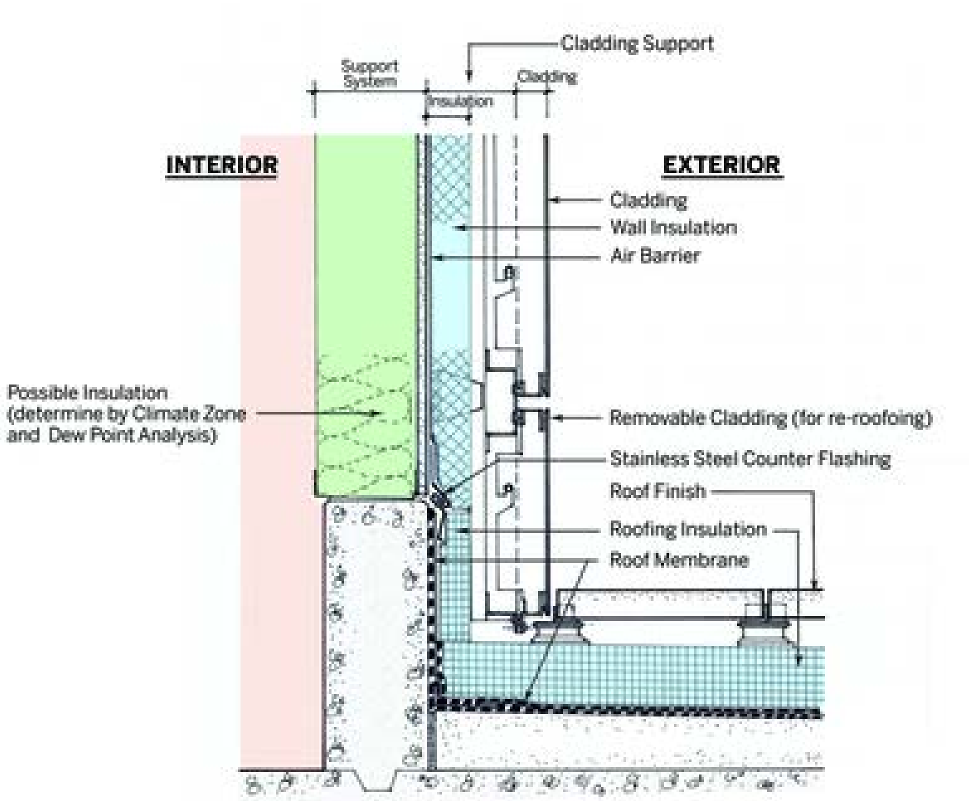
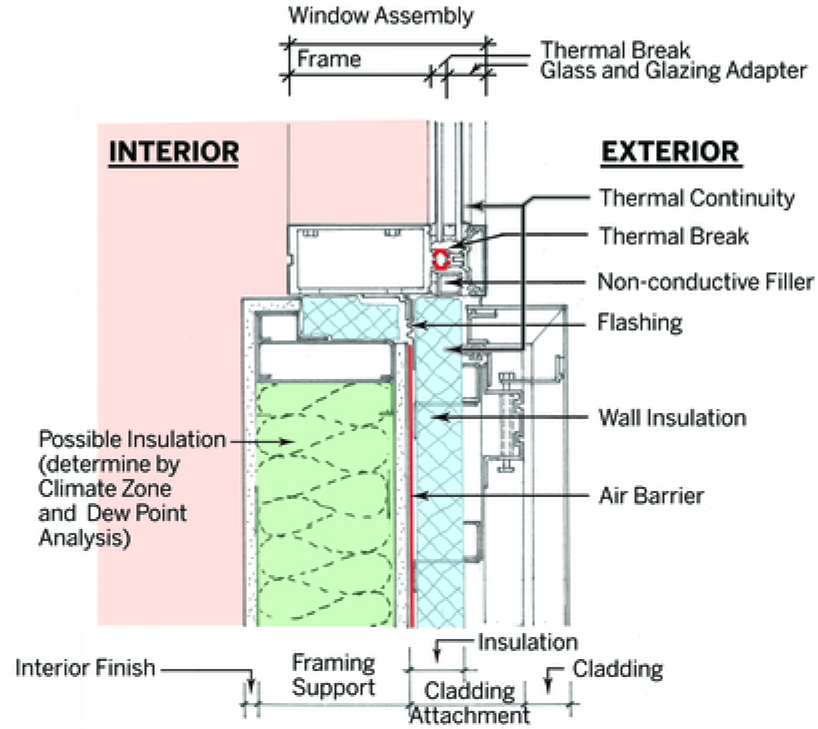


Figure 5-23 (EN35) Exterior Wall Above Roof.

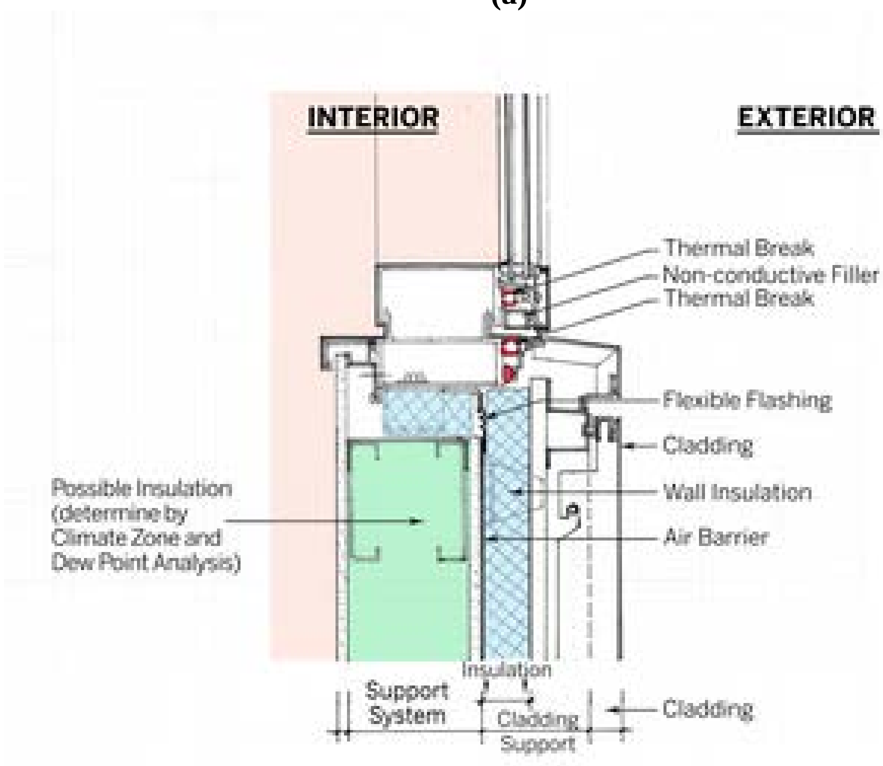
Figure Created by Keith Boswell, FAIA

EN37 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.



(a)



(b)

Figure 5-24 (EN37) Window System to Opaque Wall Connection:
a) Plan @ Jamb and b) Section @ Sill.
Figure Created by Keith Boswell, FAIA

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

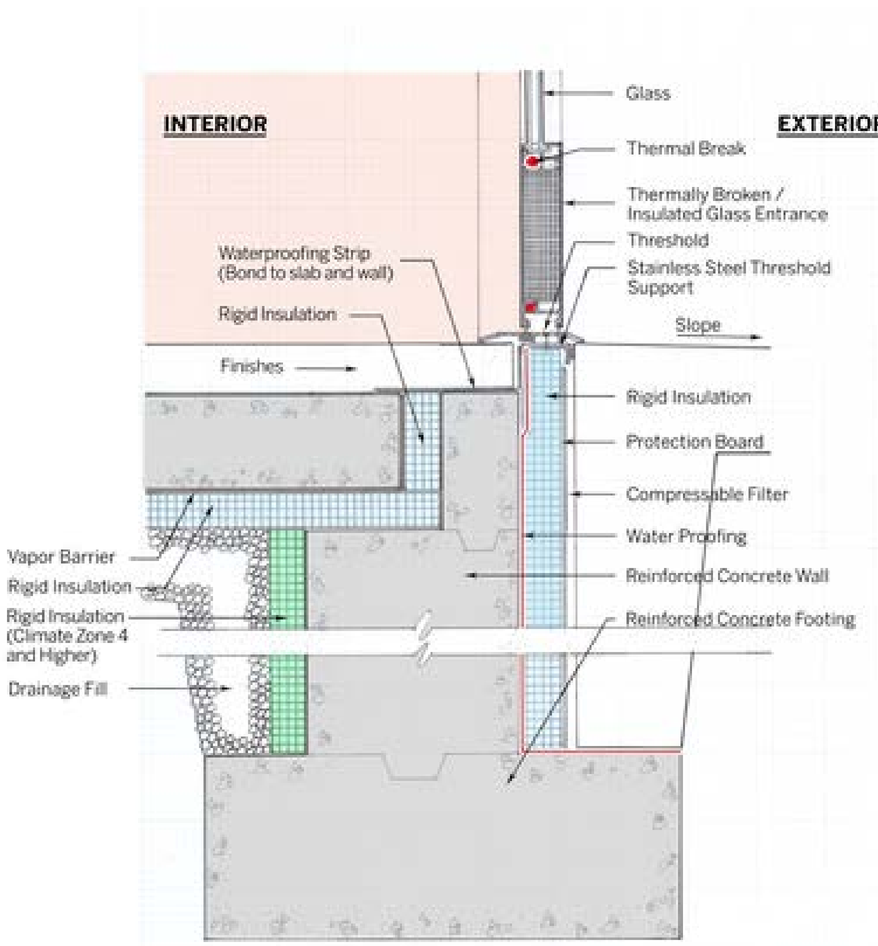


Figure 5-25 (EN37) Exterior door insulation installation.

Figure Created by Keith Boswell, FAIA

EN38 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 members). 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.

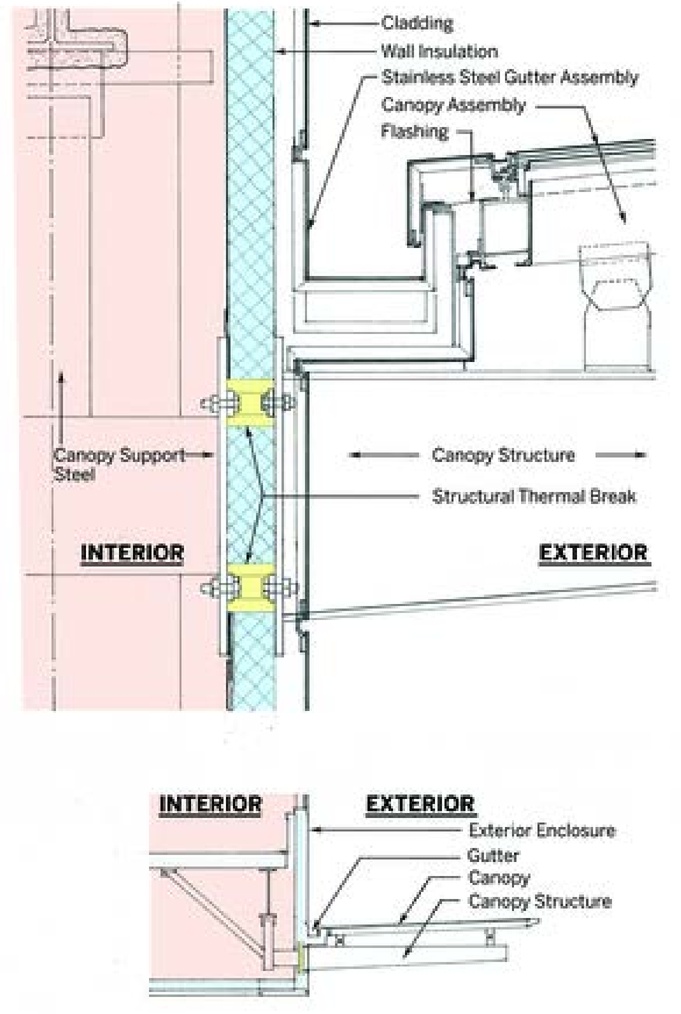


Figure 5-26 (EN38) Canopy Support.
Figure Created by Keith Boswell, FAIA

Vertical and horizontal shade supports and other similar structural penetrations may be common in zero energy buildings 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 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).

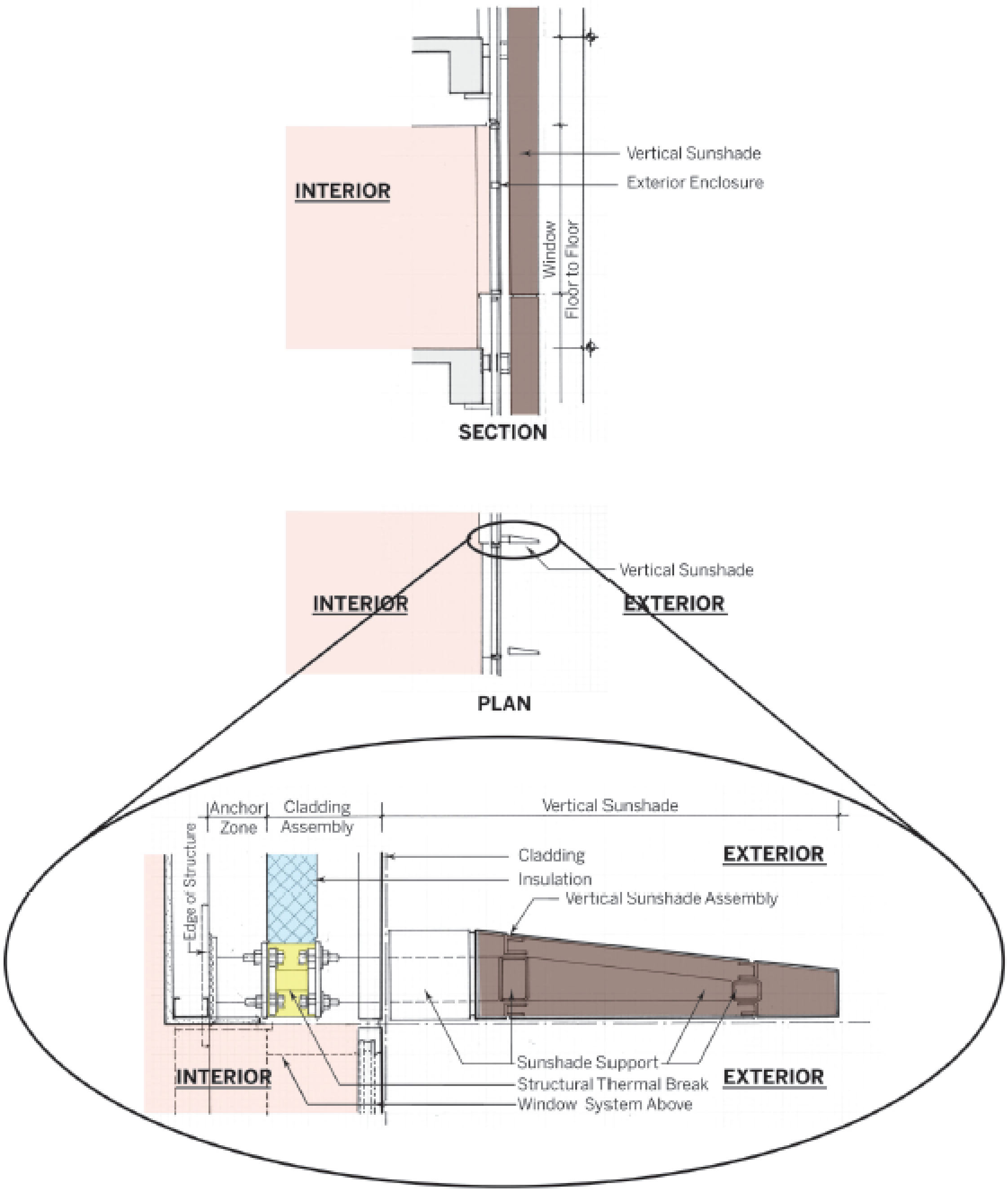


Figure 5-27 (EN38) Vertical Sunshade Support.

Figure Created by Keith Boswell, FAIA

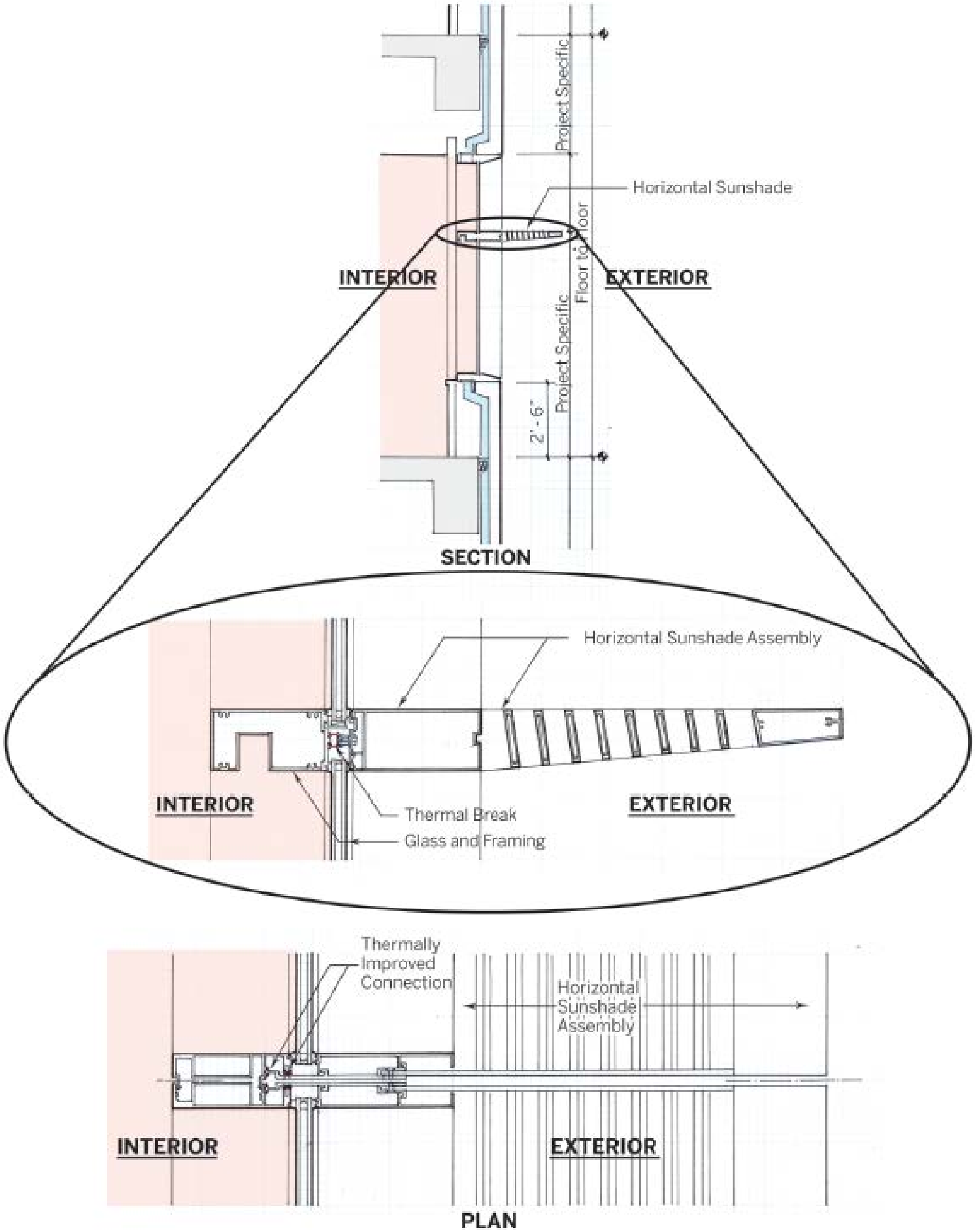


Figure 5-28 (EN38) Horizontal Sunshade Support.

Figure Created by Keith Boswell, FAIA

EN39 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**.**

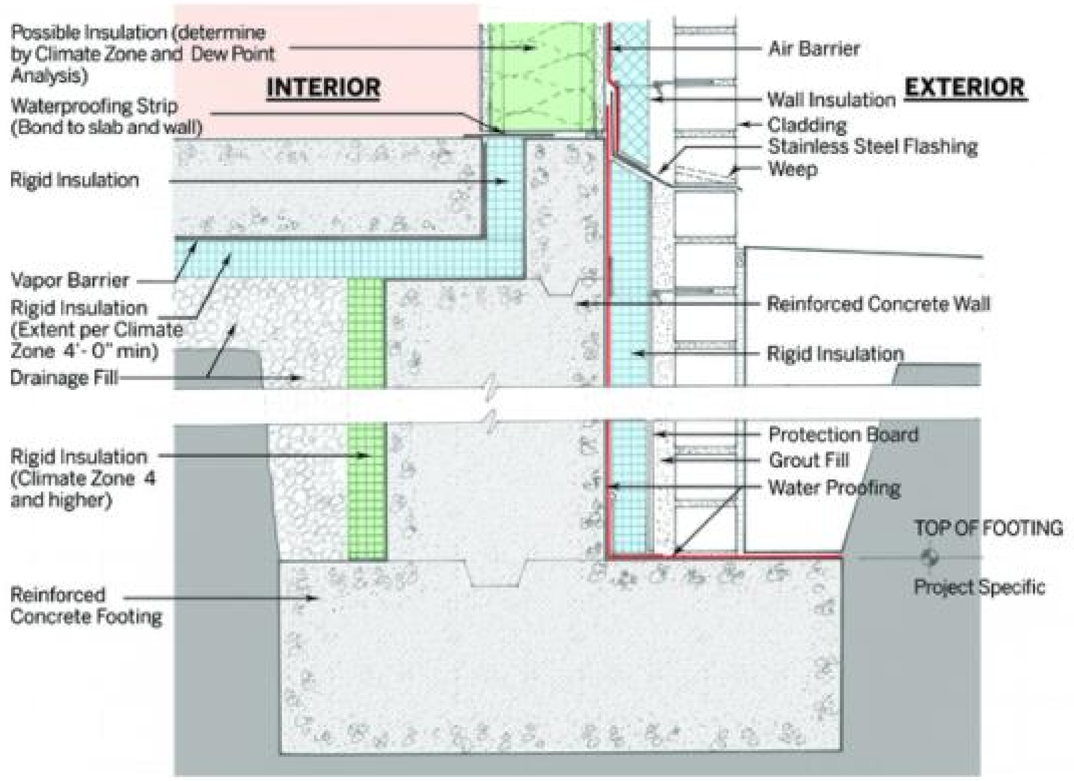


Figure 5-29 (EN340) Wall transition with insulation continuous to foundation.

Figure Created by Keith Boswell, FAIA

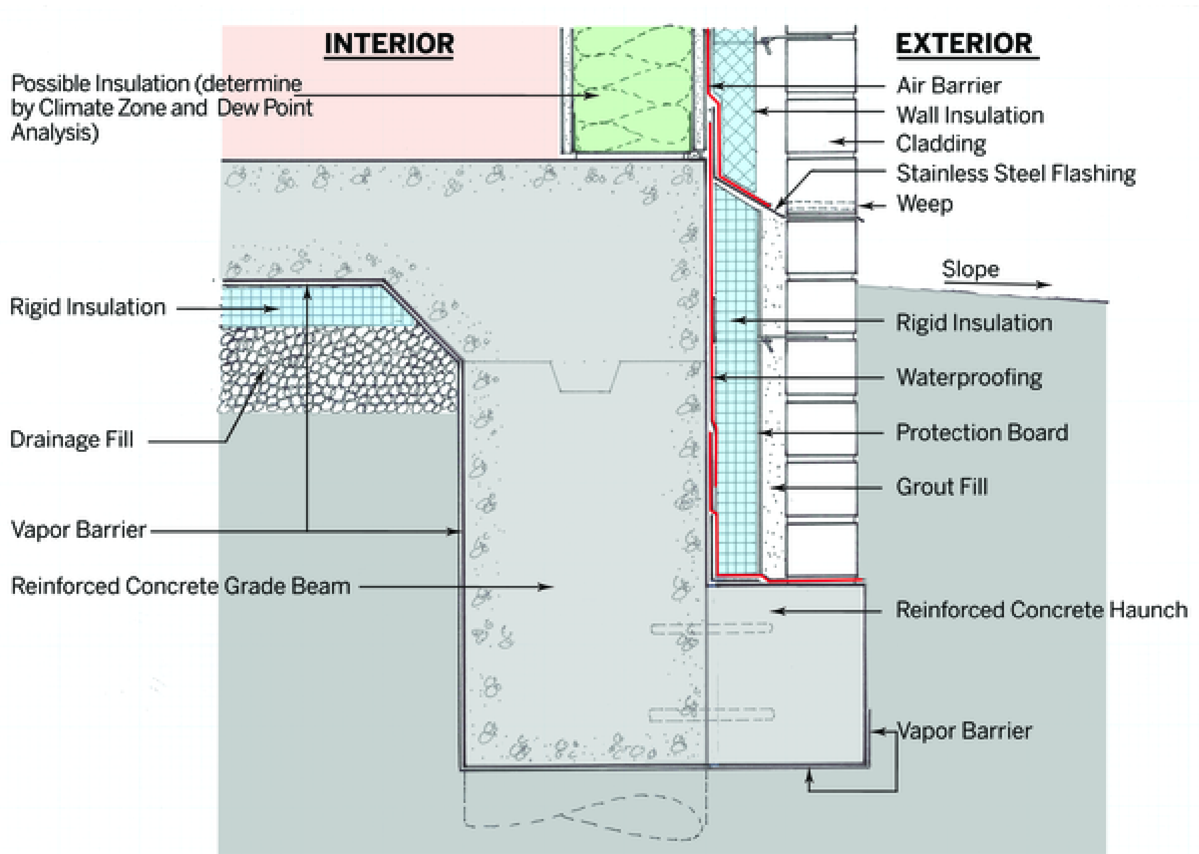


Figure 5-30 (EN40) Wall transition with insulation.
Figure Created by Keith Boswell, FAIA

REFERENCES AND RESOURCES

ASHRAE. 2016. ANSI/ASHRAE/IES Standard 90.1-2016, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta: ASHRAE.

ASHRAE. 2017. ASHRAE Handbook—Fundamentals. Chapter 24. Chapter 26, Heat, Air, and Moisture Control In Building Assemblies—Material Properties. Table 1, Building and Insulating Materials: Design Values. Atlanta: ASHRAE.

ASTM. 2003. ASTM E2178-03, *Standard Test Method for Air Permeance of Building Materials*. West Conshohocken, PA: ASTM International.

ASTM. 2011. ASTM E1980-11, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces*. West Conshohocken, PA: ASTM International.

BSC. n.d. *Builder's Guide* series. Joseph Lstiburek, ed. Building Science Corporation. https://buildingscience.com/book-categories/builders-guides. Westford, MA: Building Science Corporation.

Cool Roof Rating Council. http://coolroofs.org/.

D'Annunzio, J. 2016. Thermal and dew point transfer: How to avoid issues related to steel- deck fasteners. Troy, MI: Building Enclosure. www.buildingenclosureonline.com/articles/85717-thermal-and-dew-point-transfer.

DOE. 2010. *Guidelines for selecting cool roofs.* Oak Ridge, TN: Oak Ridge National Laboratory. https://heatisland.lbl.gov/sites/all/files/coolroofguide_0.pdf.

Nordbye, T. 2011a. Air sealing. Journal of Light Construction, January. Nordbye, T. 2011b. Passive house. *Journal of Light Construction*, April.
Nordbye, T. 2013. Air sealing without foam. *Journal of Light Construction*, May.
Pallin, S., M. Kehrer, and A. Desjarlais. 2014. The energy penalty associated with the use of mechanically attached roofing systems. Presented at the Symposium on Building Envelope Technology. pp. 93–102. http://rci-online.org/wp-content/uploads/2014-BES-pallin-keh rer-desjarlais.pdf.
PHIUS. 2017. Software resources. Chicago: Passive House Institute U.S. www.phius.org/soft ware-resources
DOE. 2013. Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Climates, January 2013 Jan Kosny, Nitin Shukla, and Ali Fallahi

LIGHTING DESIGN

***[Question for reviewers**: The LIGHTING section is organized somewhat differently in this AEDG than has been done in previous AEDGs and also in previous reviews for this specific AEDG. Does the information make sense organized in this way?]*

OVERVIEW

Lighting design can be broken down into; daylighting – how is the building envelope is used to bring daylight into the building and provides occupants a connection with the outdoors, electric lighting – lighting that allows the space to be used both day and night, and controls – manual or automatic switching / dimming of the electric lights due to occupant intervention, occupant sensing or daylight entering the space. The successful integration of these three elements provides a pathway to achieve a successful zero energy design.

The 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.

Successful integration of daylighting, electric lighting and controls 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 lighting outcomes by generating design ideas and validating expected outcomes throughout the process.

At the end of the lighting section there is a further discussion on daylighting, controls and electric lighting.

GENERAL GUIDANCE

LD1 Daylighting Design Principles

Daylighting is an occupant well-being, building resiliency, and energy-efficiency design measure. Daylighting provides occupants 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. Daylighting also offers a layer to the lighting system that can be used to support demand-response load reductions and wayfinding during peak energy usage times.

In the context of zero energy multifamily building, daylighting as an energy reduction tool will be most effective in tenant support, common areas and amenity spaces. In tenant "owned" spaces (the dwelling units) daylighting's primary role will be to provide views and well-being.

Due to the dominance of dwelling units in multifamily buildings, daylighting reveals itself as a lower priority energy reduction measure. Additionally, the recent increase in lighting system efficacy in the use of LED light sources and the embedding of controls within the lights makes it important to weigh the cost of more daylighting versus the energy that can be saved from the electric lights. Over glazing 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 energy use should decrease with the daylight availability as one of the many steps needed to reach zero energy.

LD2 Electric Lighting Design Principles

Electric lighting first and foremost is an energy-efficiency design measure providing the correct amount of illumination at the least possible energy use. Electric lighting also provides occupant comfort, wayfinding and security. Whenever possible electric lights should be automatically controlled to respond to both occupancy and daylighting.

In the pursuit of zero energy, an additional focus must be placed on providing electric lighting only at the time and quantity needed to meet occupant needs. Controls contribute to occupant comfort and productivity by providing 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. Controls support energy and capital-cost-saving by providing data about occupancy patterns and equipment performance to building information and control systems. In multifamily buildings, automatic controls should be used throughout common areas and amenity spaces. In the dwelling units hardwired automatic controls have minimal applications, but connected lighting scheduled and controlled by the occupant can provide flexibility and energy savings.

LIGHTING DESIGN PROJECT PHASE TASKS

LD3 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 orienting fenestration in a predominantly north- and south-facing direction. Maximize the amount of space that has access to windows and minimize the distance from the building core to the perimeter. A frequent challenge with existing buildings is their depth of floor plate, which prevents easy retrofits for daylighting, views, and natural ventilation.

LD4 Schematic design

During the schematic design phase, focus on spatial considerations such as ceiling height as well as on space layouts including occupants' primary usage and optimal orientation. In the dwelling units plan for an open concept to allow daylight deep into the unit. 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.

LD5 Design development

During the design development phase, focus on envelope design to optimize quantity and quality of daylight while minimizing solar gains.

In dwelling units, sunlight is highly desirable, so static building elements should not block occupants view and connection to the outdoors. Permanently installed electric lighting should be designed into each space so supplemental plug-in lighting can be minimized.

In common areas, 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 2019) 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.

LD6 Construction documents

In common areas 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 transmittance (VT) for each façade and window type.

LD7 Construction administration

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 spaces.

DESIGN STRATEGIES

LD8 Lighting Power Allowances

The overall lighting power density (LPD) target for the electric lighting is 0.19 W/ft^2 for the residential floors and 0.4 W/ft^2 for the first floor (and amenity spaces if located on upper floors). Individual spaces may have higher power allowances as shown in Table 5-12 if they are offset by lower power allowances in other areas. The sample designs at the end of the lighting section (L13 to L24) offer a way, but not the only way, that these lighting power allowances can be met.

Table 5-8 (LD8) Interior Lighting Power Densities (LPDs)

Interior Spaces	AEDG LPA (W/ft^2)	ASHRAE Standard 90.1-2019	Daylight Priority
Residential Floors			
Dwelling Units (average for studio,1-bed, 2-bed, and 3-bed units)	0.166	NA	1
Corridor	0.4	0.41	2
Elevator Lobby	0.4	0.84	1
Stairway	0.4	0.49	2
First Floor, Commercial Areas, and Common Spaces			
Retail	0.5	1.05	1
Community room	0.3	0.97	1
Fitness Room	0.3	0.50	1
Lobby	0.4	0.84	1
Private Office	0.3	0.74	2
Corridor	0.4	0.41	2
Stairway	0.4	0.49	2
Mail/Shipping room	0.3	0.68	3
Garbage	0.3	0.38	3
Restroom	0.4	0.63	3
For Other Spaces	0.03	NA	
Exterior Areas			
Parking Garage	0.10	0.15	
Parking Lots	0.04	0.04	
Walkways and Plazas	0.08	0.10	

LD9 Lighting Controls

Lighting controls range from manual wall switches to advanced controls (networked occupancy and daylight sensors) integrated into luminaires. Tables 5-9 and 5-10 provides a basic description of typical controls and their energy-saving potential for both dwelling units (Table 5-9) and for common areas in the building (Table 5-10).

Table 5-9 (LD9) Lighting Controls for Dwelling Units

CONTROL	BASICS	ENERGY SAVING POTENTIAL
Manual Switching	A basic wall mounted control that allows the user to turn lights on /off.	Residents 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. Be sure to specify LED capable dimmers.	Residents are empowered to dim the lights to improve their comfort in the space. Combined with manual switch the dimmer will create a single preset which will provide persistency in savings.

CONTROL	BASICS	ENERGY SAVING POTENTIAL
Scene/Preset control	A grouping of manual switching and dimming into a single control station to allow the user to select different lighting scene for different tasks from a single button.	User acceptance and energy savings will be based on the setup of the scenes and the initial grouping of the lights in the space.
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.
Spectral Tuning	Changing the color temperature of the light to match the mood of the space/user.	Spectral Tuning by itself does not save energy but may provide higher user satisfaction.
Voice Control (connected lighting)	An internet based control allowing the user to speak to a smart speaker to turn lights on/off, dim or schedule the lights	Savings may be minimal but residents are empowered to control the lights to improve their comfort in the space.

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.

> ***Caution:*** Consider spectral tuning carefully. Common areas should only have preprogramed color-changing sequences based on time of day. Areas under the control of a single occupant or group may have manual control, but all lights should be controlled together so as to not create a rainbow effect of colors emanating from the lights.

Table 5-10 (LD9) Lighting Controls for Common Areas

CONTROL	BASICS	ENERGY SAVING POTENTIAL
Occupancy Sensor	An automatic control that turns the lights on when the user(s) enters the space and off after all user(s) have left the space.	Provides persistence in energy savings due to automatic off. Placement of sensor is critical that it sees the entire space and the user is not 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. Manual operated blinds will reduce savings.

CONTROL	BASICS	ENERGY SAVING POTENTIAL
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 will be dependent on the tuning level but can be as high as 25%.
Time Scheduling	Using a time switch to automatically turn the lights on / off at predetermined times.	Saving is generally zero as time scheduling is often the minimum code required control.
NLC (Networked Lighting Controls)	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 as 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.
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 or LLLC but uses Ethernet cabling for power and control signal.	Savings can be high as 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.
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.	Saving is similar to exterior photo control. Employ time switch capabilities to turn lights off/on during astronomic on period to save additional energy. Time scheduling is often the minimum code required control.
Exterior Photo Control	A daylight sensor that turns the light on around dawn and off around dusk.	Photo control is often the minimum code required control.

4174

LD10 Light-Colored Interior Finishes in Common and Amenity Spaces

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

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. Note that a light-colored walkway 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.

LD11 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 (L13 through L24), LED luminaires were used for all general, decorative, task, and accent lighting. LED specifications are shown in Table 5-11.

Table 5-11 (LD11) LED Specifications

Metric	Recommendation (min)
Efficacy	125 LPW
End of Life	L70 50,000+ hours
CRI	80+
Fidelity & Gamut	Rf above 85, Rg 90-110
Warranty	5+ years
Dimmable	Specify Dimming Driver

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 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.

L12 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 the *Advanced Energy Design Guide for K-12 School Buildings: Achieving Zero Energy* (ASHRAE 2018).

LD13 Connected Lighting

Connected lighting is the combination of wirelessly controlled light fixtures, lamps and smart plugs through a phone app or voice control with a smart speaker. Tenants likely will have a smart speaker and may want to control their lights and plugs through it. Many fixture manufacturers have controllable trim kits for standard 4/5/6 inch diameter downlights and lamp manufacturers have controllable screw-in lamps for cans and table lamps. These lamps and fixtures operate like standard lights when not connected to an app or smart speaker. When connected to an app or smart speaker the lights can be remotely turned ON/OFF, dimmed, scheduled to turn ON/OFF, and some have color adjustability.

As a tenant amenity install connected light fixtures whenever possible in all hard wired fixtures in the dwelling units. Note, because connected lighting can be controlled by an app or smart speaker the need to install LED capable wall dimmers is eliminated potentially offsetting the cost of the connected lighting.

SPACE SPECIFIC STRATEGIES

LD14 General Guidance

The overall target for the electric lighting is 0.19 W/ft^2 for the residential floors and 0.4 W/ft^2 for the first floor common/commercial areas. Individual spaces may have higher power allowances as shown in Table 5-8 if they are offset by lower power allowances in other areas. The example designs described in the following how-to strategies offer a way, but not the only way, that this watts-per-square-foot limit can be met.

The examples in L15 through L26 are based on national average building space distributions. These averages are shown in Table 5-12. No building is average, and each building will have a different space allocation. When using the recommendations in the following how-to strategies, adjust the standard space allocation to match the specific building's space allocation.

Table 5-12 (LD14) Average Space Distribution

Commercial Spaces		**Residential Floors**	
Space Type	% of floor area	Space Type	% of floor area (per floor)
Retail	35%	Corridor	6%
Coffee shop	12%	Elevator	2%
Mail/shipping	3%	Stairs	5%
Lobby	5%	Studio	20%
Bathroom	2%	1 Bed	40%
Elevator	2%	2 Bed	30%

Commercial Spaces	
Space Type	% of floor area
Stair	5%
Garbage	3%
Office	6%
Corridor	8%
Fitness	8%
Community Room	12%

Residential Floors	
Space Type	% of floor area (per floor)
3 Bed	10%

RESIDENTIAL FLOOR SAMPLE LAYOUTS

LD15 Typical Dwelling Unit

The average LPD target for the dwelling units is 0.166 W/ft^2. Hard-wired light fixtures will be found in the entry, kitchen and bathroom spaces. Additional hard-wired fixtures may be used in the bedrooms and should be placed adjacent to the closets to light clothing and also provide general light for the bedroom. Higher LPD's will be found in the studio and one bedroom units than the two and three bedroom unit as the bedrooms have fewer hard-wired fixtures. Figure 5-31 shows a sample design for a typical dwelling unit.

Illumination level. The target lighting in the dwelling unit ranges from 3 footcandles in the living room, to 5 footcandles in the bedroom and shower/tub, to 30 footcandles at the bath vanity, and up to 50 footcandles on the kitchen counters.

Existing building opportunity. In existing buildings all recessed lights with screw based lamps can be retrofitted with LED trims or screw based LED lamps. All incandescent or screw based CFL lamps in plug-in fixtures should be replaced with LED screw based lamps. If linear fluorescent fixtures are used in the kitchen or laundry these can be retrofitted with LED kits or replaced with new LED fixtures.

Electric Lighting. LED lighting fixtures can either be integral LED, hard-wired LED fixtures or screw-in LED lamps installed in standard screw base fixtures. Integral LED fixtures will have a higher efficacy, but maintenance will be easier with screw-in LED lamps or LED trims. Typical wattages for LED lamps and fixtures should be 10 watts or less.

- Kitchen lighting needs to light the countertops, sink and into the upper cabinets. This can be accomplished by installing recessed can lights or shallow surface mounted lights located approximately 12 inches away from the counter edge to light into the upper cabinets and the counter without creating shadows. Install a pendant mounted fixture over the adjacent table.
- Living room lighting needs to provide flexible lighting and typically uses plugin lamps. Use Connected LED bulbs in these fixtures. If these light fixtures are user provided the owner should provide LED bulbs to further the zero energy mission.
- Bedroom lighting needs to provide flexible lighting for both relaxing and clothing selection. Typically, they have both hard-wired ceiling fixtures and screw based table fixtures. Install the ceiling fixture centered in front of the closet so the lighting does

double duty of lighting the bedroom and lighting into the closet. Use Connected LED bulbs or hard-wired Connected trims in these fixtures. For user provided table lights the owner should provide LED bulbs to further the zero energy mission.

- Bathroom lighting needs to provide vertical illumination at the mirror over the vanity, and general lighting for the shower/bath/toilet areas. For the mirror lighting the best lighting is vertical lights on both sides of the mirror as it reduces shadowing on the face. Horizontal lighting directly above the mirror is acceptable.
- Hallways and other general lighting is typically recessed can lights or shallow surface mounted lights.

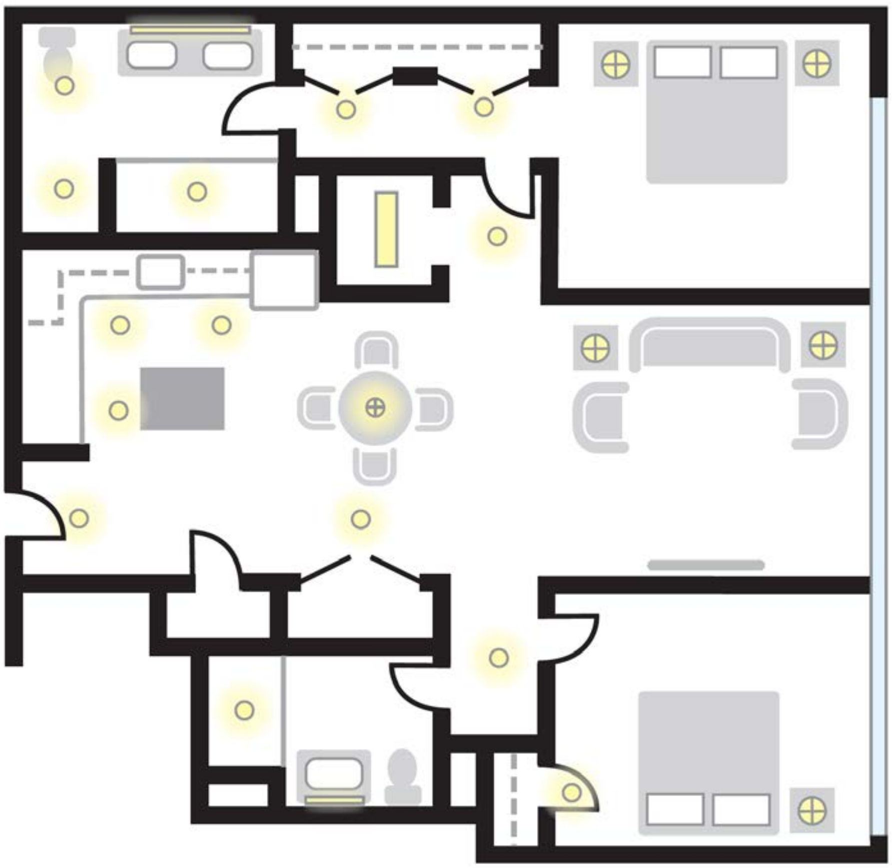


Figure 5-31 (LD15) Typical Dwelling Unit Sample Design

Daylighting. Daylighting in the dwelling units provides occupants 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. Opportunities for daylighting from an automatic energy savings standpoint is limited in most spaces, but occupants should be encouraged to turn lights off when daylight provides adequate illumination.

Control. As a tenant amenity, install connected light fixtures whenever possible in all hard wired fixtures. Note, because connected lighting can be controlled by an app or smart speaker the need to install LED capable wall dimmers is eliminated potentially offsetting the cost of the connected lighting.

LD16 Typical Residential Floor Corridor and Elevator Lobby and Stairway

A sample design for typical corridor, elevator lobby, and stairway spaces on residential floors is shown in Figure 5-32.

Illumination level. The target lighting in tenant corridors is 5–10 average maintained footcandles. Wall surface reflectance will have a major impact on the light level and energy efficiency and should be 70% or higher above 3 feet.

Existing building opportunity. Existing buildings can replace or retrofit in place the existing fluorescent or incandescent fixtures with new LED fixtures or LED retrofit kits. Use full LED retrofit trim kits instead just replacing the existing incandescent or CFL fixtures with retrofit LED lamps as the full trim kit will provide better lighting distribution and energy efficiency.

Electric Lighting. Corridors, stairs and the elevator lobby account for approximately 12% of the floor area and are designed to 0.4 W/ft^2, which is equivalent to about one 20 W LED luminaire for every 50 ft^2. Electric lighting should be designed to light as much of the wall surface as possible to make the corridors, lobby and stairs feel bright. Avoid using downlights that just light the floor as it is the least reflective surface and will make the spaces feel dark, a better option is to use a wall wash fixture so the wall is also lighted. Decorative ceiling fixtures in the elevator lobby can provide a visual style connection to the main building lobby.

Residential floors may also have small janitorial closet and garbage/recycling rooms. Install linear LED fixtures and occupancy sensors in these spaces. Average the connected load in these spaces to 0.3 W/ft^2, which is equivalent to about one 15 W LED luminaire for every 50 ft^2.

Daylighting. Corridors, stairs and the elevator lobby provide a minimal opportunity for daylighting as there is typically few windows. If windows are present, lights within 10 feet can be dimmed in response to daylight.

Control. In typical corridors and elevator lobby use ceiling-mounted occupancy sensors. Lights should be set to reduce lighting to 50% or lower when no occupants are present during normal hours. In stairs use fixtures with integrated occupancy sensors that allow for a low light level when no occupants are present.

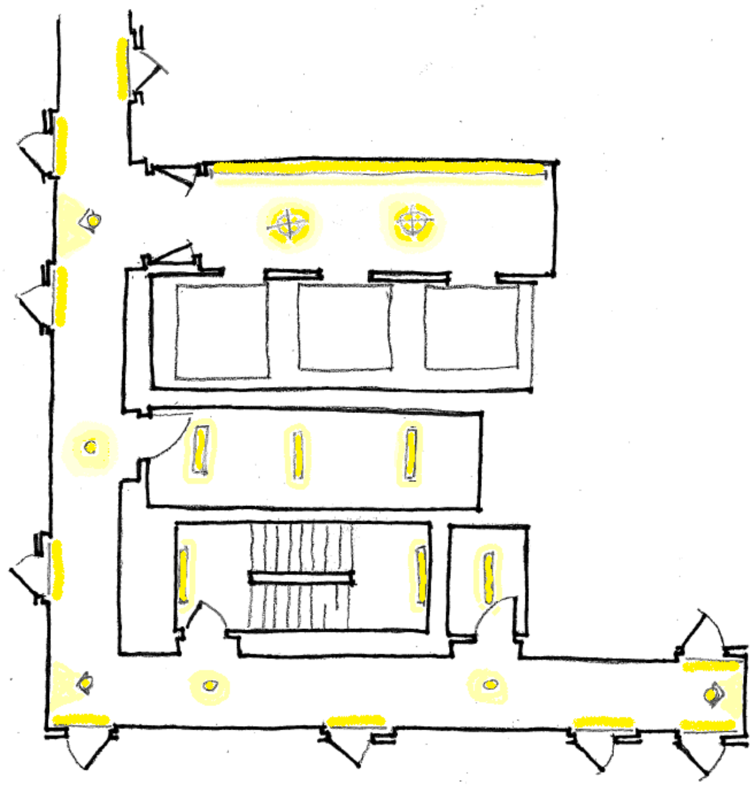


Figure 5-32 (LD 16) Typical Residential Floor Corridor, Elevator Lobby, and Stairway Sample Design

COMMON AREAS AND COMMERCIAL SPACE SAMPLE LAYOUTS

LD17 Main Lobby

A sample design for a typical main lobby space is shown in Figure 5-33.

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 can replace or retrofit in place the existing fluorescent or incandescent fixtures with new LED fixtures or LED retrofit kits. Use full LED retrofit trim kits instead just replacing the existing incandescent or CFL fixtures with retrofit LED lamps as the full trim kit will provide better lighting distribution and energy efficiency.

Electric Lighting. Lobbies account for approximately 4% of the floor area and are designed to 0.4 W/ft^2. Lobbies provide the first impression to visitors, so provide pendant or decorative ceiling lights over the seating areas. Highlight the feature wall behind the reception desk with LED wall washers or accent lights. Vertical surface lighting can enhance the perception of spaciousness; however, adjacent surfaces should be kept to a maximum of 20:1 luminance ratio relative to the daylight glazing to maintain visual comfort. If plug-in lighting is used only use LED integrated fixtures or screw base LED lamps.

Lobbies may also have adjacent spaces such as the mail or storage rooms. Install linear LED fixtures and occupancy sensors in these spaces. Average the connected load in these spaces to 0.3 W/ft^2, which is equivalent to about one 15 W LED luminaire for every 50 ft^2.

Daylighting. Lobbies provide an excellent opportunity for daylighting. Dim lights within 10 feet of windows response to daylight. For glare control use passive shading and filtering strategies first, then consider automatic devices in spaces for which passive shading cannot mitigate glare or for climates where passive shading blocks valuable daylight for much of the year.

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 and after dark for night adaptation.

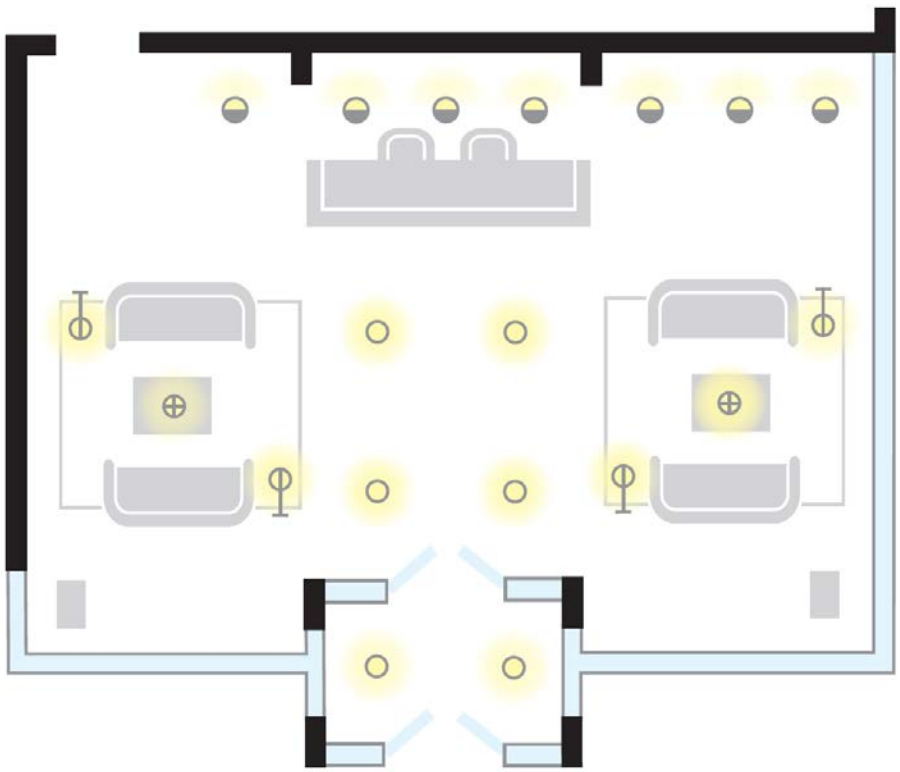


Figure 5-33 (LD17) Main Lobby Sample Design

LD18 Office(s)

A sample design for typical office spaces on the main floor is shown in Figure 5-34.

Illumination level. The target lighting in private offices and conference room 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 non-daylight 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.

Space planning. Locate private offices and conference room 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.

Electric Lighting. Private offices and conference room account for approximately 6% of the floor area and are designed to 0.3 W/ft^2 including plug-in task lighting wattage.

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.

Daylighting. 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.

For occupant comfort orientate the computer monitor perpendicular to the windows. Monitors facing the windows will have reflected exterior brightness causing glare at the monitor.

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. Option – set sensor to turn lights to 50% on initial trigger as occupants may find lower light level acceptable. Electric lighting supports daylighting through lighting that is controlled, manual-ON by occupants when needed, allowing flexibility for various occupant preferences and tasks.

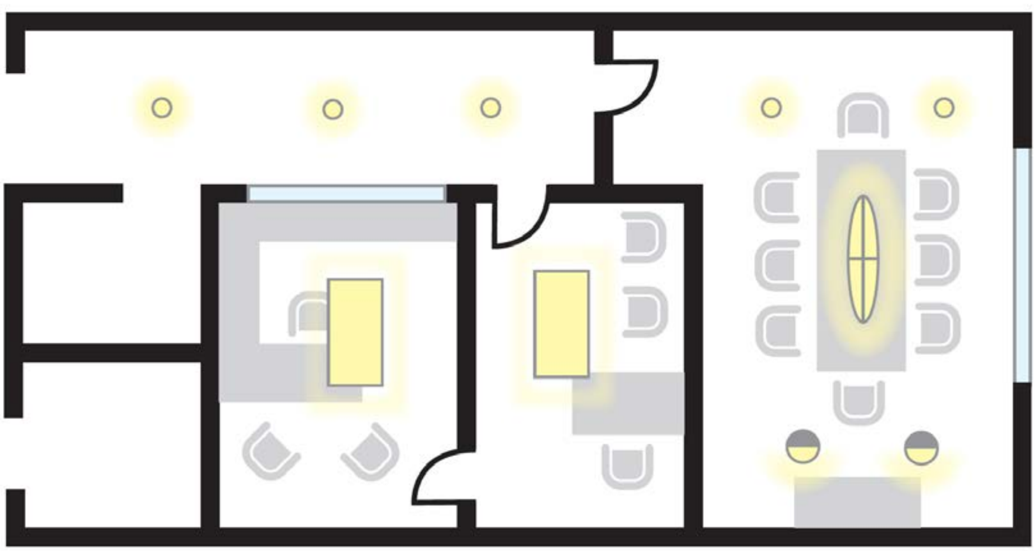


Figure 5-34 (LD18) Office Sample Design

LD19 Retail Spaces

The Retail lighting design may not be under the direct control of the apartment owner/developer; however, the lease should stipulate that the maximum LPD not exceed 0.5 W/ft^2. Light levels in retail spaces vary dramatically dependent on the type of retail. A convenience store will have higher general light levels compared to a boutique clothing store, but the level of accent lighting will be the opposite. In general, the light levels should be in the 30 to 50 footcandle range.

Existing buildings can replace or retrofit in place the existing fluorescent or incandescent fixtures with new LED fixtures or LED retrofit kits. Use full LED retrofit trim kits instead just replacing the existing incandescent or CFL fixtures with retrofit LED lamps as the full trim kit will provide better lighting distribution and energy efficiency. For incandescent / CFL track lights replace the lamps with LED lamps.

A sample design for a typical boutique clothing store is shown in Figure 5-35. The general lighting is relatively low with a few LED downlights, track lights highlight the clothing and wall displays and pendants are at the register drawing focus to this area. Daylighting should be evaluated carefully as if the lights are dimmed in response to daylight the store can look closed. Occupancy sensors controlling the general lighting can be set to only operate after store closing and accent lighting should be scheduled to turn off after store closing.

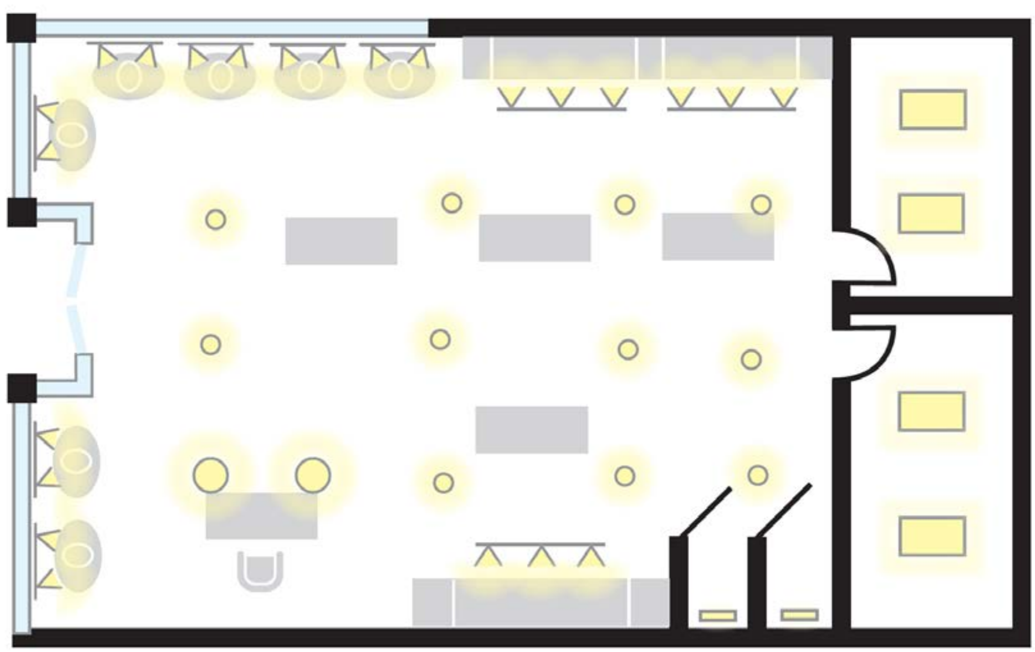


Figure 5-35 (LD19) Boutique Clothing Retail Sample Design

A sample design for a typical coffee shop is shown in Figure 5-36. The general lighting is relatively low with a few LED downlights, track lights highlight the menu boards and pendants are at the window seating and over the bar / barista station to draw focus and signal that the shop is open. Daylighting should be evaluated carefully as if the lights are dimmed in response to daylight the shop can look closed. Occupancy sensors controlling the general lighting can be set to only operate after store closing and accent and pendant lighting should be scheduled to turn off after shop closing.

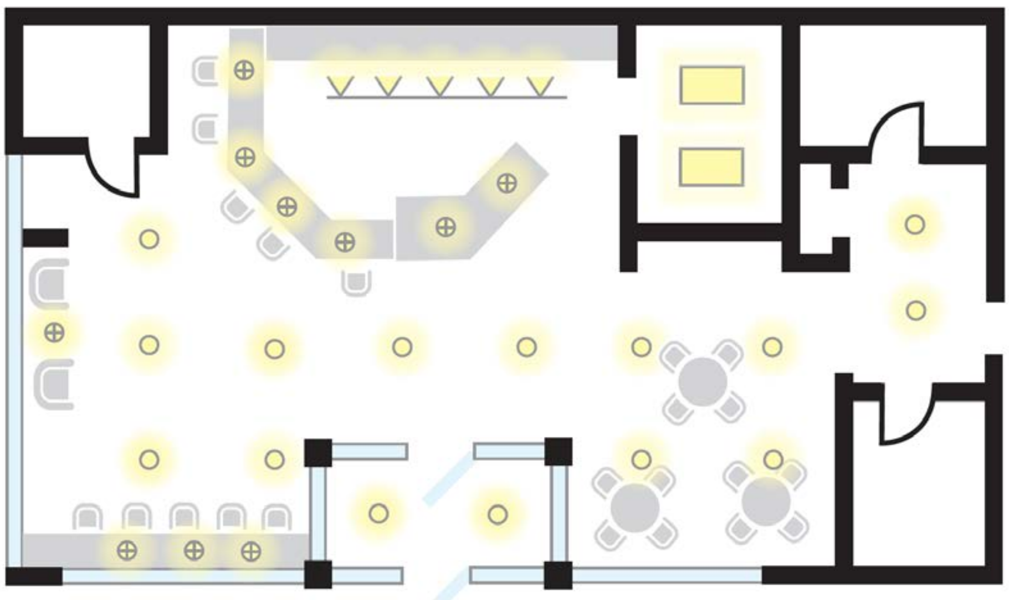


Figure 5-36 (LD19) Coffee Shop Sample Design

LD20 Fitness Room

A sample design for a typical fitness or workout room is shown in Figure 5-37.

Illumination level. The target lighting in fitness rooms is 15 average maintained footcandles for ambient lighting. The lighting should be even throughout the space as fitness equipment may move or change.

Existing building opportunity. Existing buildings can replace or retrofit in place the existing fluorescent or incandescent fixtures with new LED fixtures or LED retrofit kits. Use full LED retrofit trim kits instead just replacing the existing incandescent or CFL fixtures with retrofit LED lamps as the full trim kit will provide better lighting distribution and energy efficiency.

Electric Lighting. Fitness areas account for approximately 8% of the floor area and are designed to 0.3 W/ft^2. Lighting in fitness areas should be even and low glare as fitness equipment may change or move and users may be on their back looking up into the lights. The desired lighting and energy target can be achieved by using one 24 W, 125 LPW luminaire for every 80 ft^2 (8ft by 8ft spacing center to center), or one 30 W, 125 LPW luminaire for every 100 ft^2 (10ft by 10ft spacing center to center).

Daylighting. Fitness areas provide an excellent opportunity for daylighting, however privacy for the users should also be considered for first floor fitness areas that face the street. For first floor street facing fitness areas use daylight windows above 7ft. Dim lights within 10 feet of windows response to daylight. For glare control use passive shading and filtering strategies first, then consider automatic devices in spaces for which passive shading cannot mitigate glare or for climates where passive shading blocks valuable daylight for much of the year.

Control. Dim lights within 10 feet of windows response to daylight. Control all lights with manual ON automatic OFF vacancy sensors. In large workout room use at least 2 ceiling mounted sensors set to 20 minute time out.

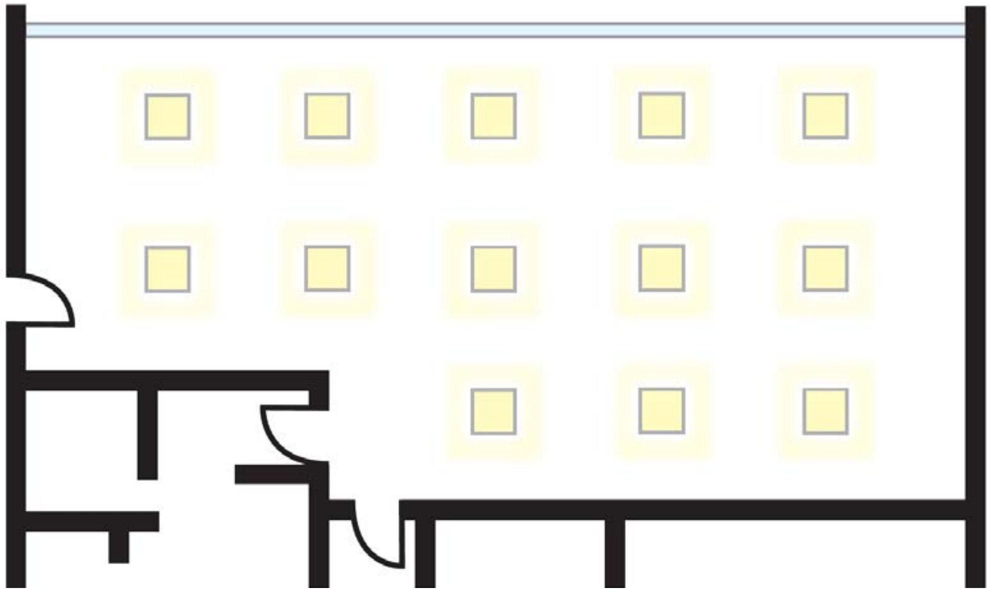


Figure 5-37 (LD20) Fitness Room Sample Design

LD21 Community room

A sample design for typical community room spaces is shown in Figure 5-38.

Illumination level. Community rooms typically consist of a number of rooms; theater, private dining kitchenette, bar and social area. The target lighting in the community rooms is 10-15 average maintained footcandles for ambient lighting. *Existing building opportunity*. Existing buildings should replace or retrofit in place the existing fluorescent or incandescent fixtures with new LED fixtures or LED retrofit kits. Use full LED retrofit trim kits instead just replacing the existing incandescent or CFL fixtures with retrofit LED lamps as the full trim kit will provide better lighting distribution and energy efficiency. For incandescent / CFL track lights replace the lamps with LED lamps.

Lighting and Control. Community rooms account for approximately 12% of the floor area and are designed to 0.3 W/ft^2.

- Lighting in the theater area should be subdued and should not light the walls or produce glare on the screen from themselves or from light on the walls. Use one 7.5 W fixture for every 25 ft^2. Daylight should be excluded from the theater space. Control lights on a LED compatible dimmer and an occupancy sensor. Control the lights near the screen separate for the lighting over the seating.
- Lighting in the private dining area should be layered with decorative lighting over the table, separate general lighting, art accent lighting. Use one 10 W fixture for every 36 ft^2. Daylight should control the general lighting in the space. Control lights with LED compatible dimmers and an occupancy sensor.
- Lighting at the bar and in the social area should provide a high end living room feel with pendants over the bar and possibility over tables, with a general lighting level throughout. Table lamps can be provided at seating areas. Use one 10 W fixture for

every 36ft^2. Daylight should control the general lighting in the space. Control lights on LED compatible dimmers and an occupancy sensor.

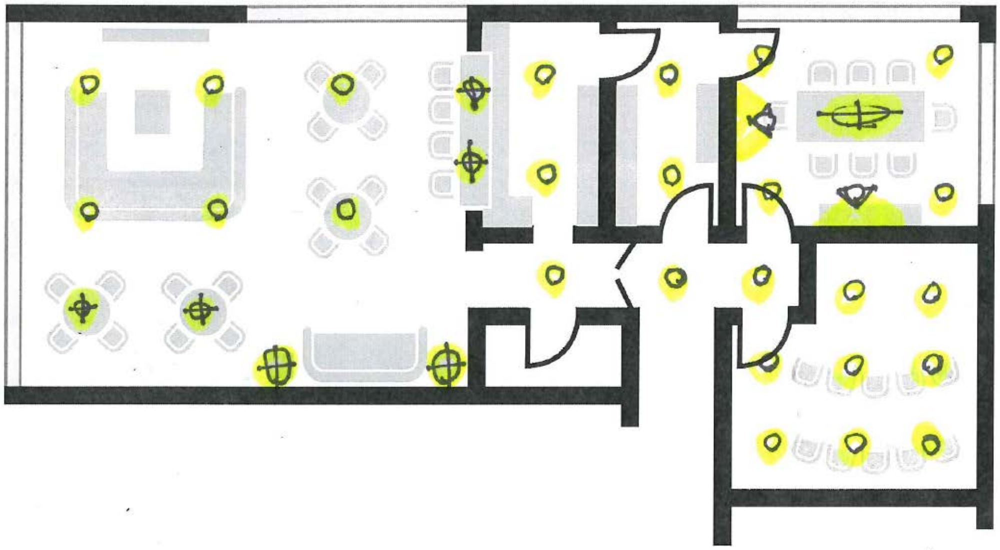


Figure 5-38 (LD21) Community Room Sample Design

LD22 Other Spaces

Other space types include restrooms, break rooms, electrical/mechanical rooms, stairways, garbage/recycling rooms, 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 0.3 W/ft^2, which is equivalent to about one 25 W LED luminaire for every 80 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. Electric lighting supports daylighting through lighting that is controlled, manual-ON by occupants when needed, allowing flexibility for various occupant preferences and tasks. In stairs use fixtures with integrated occupancy sensors that allow for a low light level when no occupants are present.

LD23 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 of that area to 10% of the LPA for that space.

LD24 Parking Garage

A sample design for parking garages is shown in Figure 5-39.

Illumination level. The target lighting in the parking garage is a minimum of 1 footcandle on the floor, and 0.5 vertical footcandles on the walls. Wall lighting is extremely important for a safe feeling environment so reflectance value of the walls should be 70 or higher. Additionally the first 50 feet of the vehicular entry/exit should be lighted to 50 footcandles during the daytime to help with eye adaptation.

Existing building opportunity. Typically parking garage lighting in existing buildings will be either HID or fluorescent. In either case the existing lighting can be replaced by LED fixtures that use one third to one half of the existing wattage. In the case of the HID to LED replacement, the LED will not only provide similar if not better illumination, but the LED will provide a dramatically better color quality for the space.

Often the existing lighting is left on 24/7 and controlled at a central location. With new lights they can easily be integrated with occupancy sensors to be controlled individually or wirelessly controlled to act in groups and to be dimmed to respond to daylight.

Electric Lighting. To meet the vertical footcandle requirement the lighting should be split and mounted at the edge of the driving lane instead of the traditional placement in the center of the driving lane. Average the connected load in these spaces to 0.1 W/ft^2, which is equivalent to about one 50 W LED luminaire for every two parking stalls. In the 50 entry/exit adaptation zone dimmable higher wattage fixtures can be used as long as they are controlled to reduce in output during nighttime hours.

Daylighting. If the parking garage is above ground and has openings to let in daylight the lighting can respond to dim the lighting when daylight is present.

Control. 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 in elevator lobby should be grouped together with the adjacent lights in the parking area 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. In stairs use fixtures with integrated occupancy sensors that allow for a low light level when no occupants are present.

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 above ground garages and at all times in underground garages.

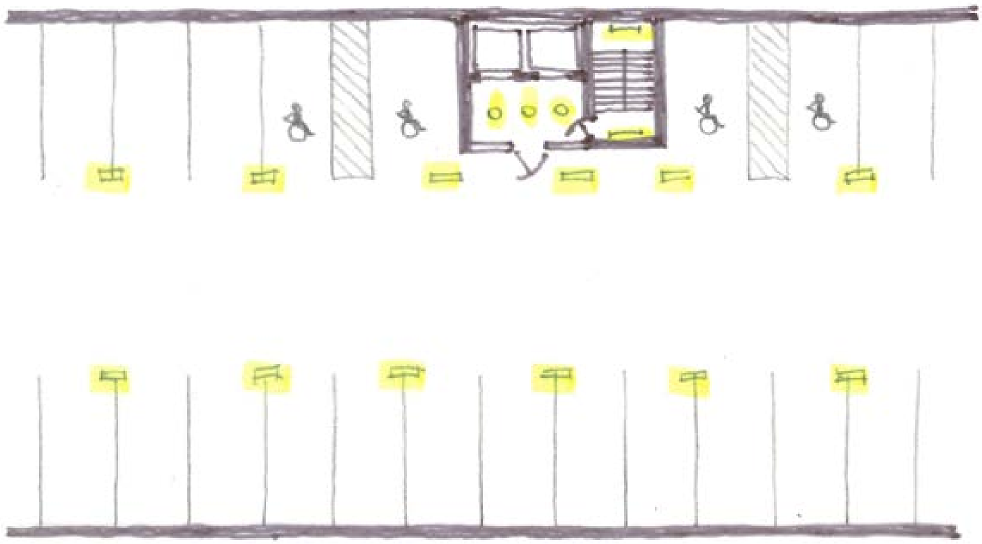


Figure 5-39 (LD24) Parking Garage Sample Design

LD25 Exterior—Parking Lots and Drives

For parking lots and drive 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.

Illumination level. The target lighting in parking lots is a minimum of 1 footcandle for concrete surfaces, and 0.5 footcandles for asphalt surfaces. Higher footcandle levels are recommended with concrete surfaces due to contrast ratios with wheel stops and columns.

Existing building opportunity. Existing buildings should replace the existing fixtures with LED fixtures. Use a rule of thumb of a 140 W fixture for every 3600 ft^2. With existing buildings, the uniformity of the lighting should also be evaluated looking for overly bright or dim areas. In overly bright areas do not exceed the 140 W for every 3600 ft^2 by lowering the wattage instead of removing light fixtures as removing light fixtures may create a new under lighting area. In under lighted areas consider increasing the wattage but if the under lighted area is more than 3 times the height of the poles away from the nearest pole a new pole should be added to serve that area.

Electric Lighting. The parking and drive areas are designed to 0.04 W/ft^2 which is equivalent to one 140 W fixture for every 3600 ft^2.

Control. 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 and drive lighting by at least 75% when no activity is detected for not longer than 10 minutes by using individual fixture mounted occupancy sensors. Lights at the transition of the street and the parking lot entry should maintain 100% power for visual wayfinding. Lights at the transition of the main building entry and the parking lot entry should maintain 50% power for visual wayfinding.

L23 Exterior—Walkways, Stairs and Entries

Illumination level. The target lighting on walkways should be designed to an average of 0.5 footcandles horizontal on the ground, and 0.2 footcandles vertical 5-feet above grade. Exterior stairs and entries and exits to the building should be lighted to 5 minimum footcandles horizontal and 2.5 footcandles vertical.

Existing building opportunity. Existing buildings should replace the existing fixtures with LED fixtures. Use a rule of thumb of replacing HID lighting with LED lighting of 1/3rd the wattage and incandescent with 1/10th the wattage. The uniformity of the lighting should also be evaluated at any entry and stair area to keep the uniformity of the lighting in a 2:1 ratio.

Electric Lighting. The walkway, stairs and entries are designed to 0.08 W/ft^2. Locate pole lights at stair landings for even illumination on the stair. On walkways light intersections and stairs first then infill with one 20 watt fixture every 40 linear feet. Avoid using bollard light fixtures as they do a poor job of providing the recommended vertical footcandles.

Control. Reduce the power of all walkway, pathway and feature 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. 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.

L26 Exterior—Decorative Façade Lighting

Decorative façade lighting is lighting that highlights the building architecture and is used sparingly if at all in Zero Energy multifamily buildings.

Control. If used, reduce the power of all facade lighting by at least 75% of the design level between 9:00 p.m. and 6:00 a.m.

DAYLIGHTING DESIGN CONSIDERATIONS

LD27 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.

LD28 Space Programming

In concert with the building orientation, identify the spaces that benefit most from daylighting (high occupant density amenity spaces) and locate those spaces on the perimeter of the building. Transition spaces such as corridors, stairs and elevator lobbies also benefit from daylighting but due to the use patterns should be considered only after the high occupant density amenity spaces are located at the perimeter.

LD29 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 approximately 7 ft (bottom is above typical eye height), extends as high as possible and maintains a high VT of 60% or higher. View windows should be located at eye level and should have a VT of 30% to 60% depending on the brightness of the scene being viewed (e.g., dense vegetation versus light concrete buildings). 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.

A WWR of 25% to 35% will enable sufficient daylighting and views in most 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 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.

Nonvisual Benefits of Daylighting and Electric Lighting

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 important 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. Melatonin suppression is not the only measure of light’s effect on the human circadian system, but empirical data are available to evolve the understanding of the nonvisual impacts of light exposure (Rea and Figueiro 2018).

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 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.
- Eliminate façade lighting that can enter apartment units.
- Provide room darkening/blackout window treatments.

LD30 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 illuminance for a depth of about one times the head height of the window into the space. Partial 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, 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 climates and east and west orientations can benefit from sunlight redirection.

Optical louvers, shown in Figure 5-40, 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.

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.

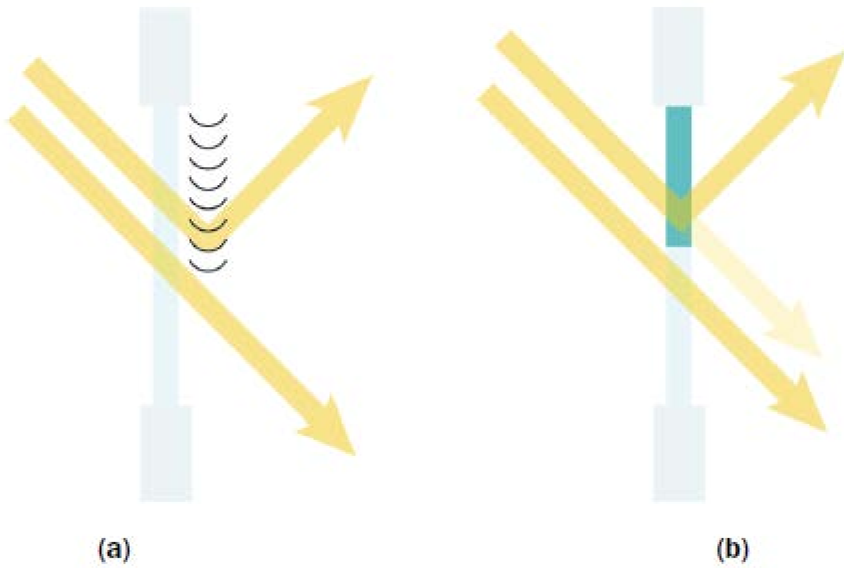


Figure 5-40 (LD30) (a) Optical Louvers and (b) Microstructure Applied Film

LD31 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 bringing daylighting into the space.
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 daylighting 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. 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.

LD32 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 EN15 through EN21 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 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 near walls allowing daylight to wash the ceiling and wall, which will in turn reflect more light onto the space, 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.

LD33 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 30 footcandles (fc) for at least 50% of the operating hours. This illumination is then supplemented as needed by electric lighting.

Annual Metric Descriptions

Point-in-time daylighting calculations (for example, illuminance in a area 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.

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.

A well-daylighted 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.

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).

LIGHTING CONTROL DESIGN CONSIDERATIONS

LD34 Separately Control Electric Light Distribution, Intensity, and Spectrum

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.

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). In non-residential spaces these two daylight zones must dim in response to daylight separately from each other and separately from the non-daylight zone. Occupancy zones, especially in common areas, are harder to define but are a source of significant savings. Corridors on residential floors are good examples of an occupancy zone that is controlled together and can respond to daylight and occupancy patterns.

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, task tuning and response to occupant patterns, so take time to consider the control signal versus power curve of the specified driver.

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.

LD35 Use an Occupant-Engaged Control Strategy

As a default strategy for all zero energy buildings, employ an "opt-in" or "occupant-engaged" lighting control strategy, which is characterized by manual-ON settings for controls. 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 (generally 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.

LD36 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 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.

LD37 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.

LD38 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 task lights are installed (see EL??) they need to be automatically controlled to turn off when the workstation is unoccupied for plug load control options (see PL??).

LD39 Measure and Verify Expected Lighting Power Profiles

The lighting power profile for a zero energy building typically looks like that shown in Figure 5-42. The base load should be very low at night (see LD??), 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 periods 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.

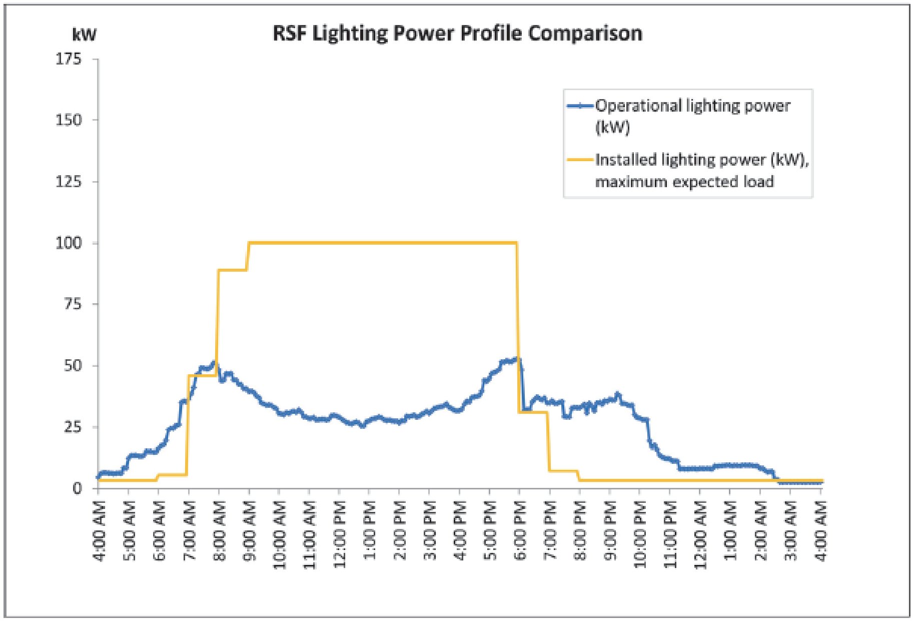


Figure 5-42 (LD39)) Example Zero Energy Daily Lighting Load Profile

LD40 Task Lighting (plug in table lamps)

If the space-planning recommendations in L?? through L?? are followed by locating amenity and common 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. Connect all task lights to vacancy sensors (see L??) 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.

EXTERIOR LIGHTING DESIGN CONSIDERATIONS

LD41 Lighting Zones

Exterior lighting is an important factor in meeting the goal of a zero energy building. The total exterior LPD is created from the individual area allowances shown in Table 5-8. Exterior LPDs are classified into lighting zones (LZs). For this Guide it is assumed that most 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. For areas that are intended to be lighted, design with a maximum-to-minimum ratio of illuminance no greater than 30 to 1. Therefore, if the minimum light level is 0.1 fc, then the maximum level in that area should be no greater than 3 fc.

LD42 Luminaire 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

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. 2019. ANSI/ASHRAE/IES Standard 90.1-2019, 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.

Guglielmetti, R., J. Scheib, S.D. Pless, P.A. Torcellini, and R. Petro. 2011. Energy use intensity and its influence on the integrated daylighting design of a large net zero energy office building. *ASHRAE Transactions* 117(1):610–20.

ICC. 2017. *2018 International energy conservation code*. Washington, DC: International Code Council.

IES. 2011. The lighting handbook, 10th ed. NY: Illuminating Engineering Society.

IES. 2013. *Approved method: IES spatial daylight autonomy (sDA) and annual sunlight exposure (ASE)*. IES LM-83-12. NY: Illuminating Engineering Society.

IES. 2017. ANSI/IES TM-23-17, *Lighting control protocols*. NY: Illuminating Engineering Society.

IWBI™. 2019. Certification links. WELL Building Standard™ v1. NY: International WELL Building Institute™. https://www.wellcertified.com/certification/v1/standard.

Rea, M.S., and M.G. Figueiro. 2018. Light as a circadian stimulus for architectural lighting. *Lighting Research and Technology* 50:497–510

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. Heat generated from plug loads is removed by the HVAC system, adding to the energy impact.

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.

Successful implementation of energy reduction across PPLs is the responsibility of the owner developer, the design team, and building occupants. During design, the design team should identify all equipment that is specified as part of the project that will be plugged in. The design team should work with the building owner to identify equipment that will meet occupant requirements and reduce plug loads.

GENERAL GUIDANCE

PL1 Energy Efficient Equipment (GA) (RT)

Select 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). 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).

If the building 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.

Look for efficient equipment even if not rated by ENERGY STAR. Remember that once any energy-efficient equipment is installed, the energy reduction settings must be enabled.

PL2 Plug Load Controls (RT)

Plug equipment typically runs at normal operating power when in use and may have the capability to partially power down when not in use. Studies show that many types of plug load equipment remain on at full or reduced power even when not in use (Hart et al. 2004; Sanchez et al. 2007). 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.

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
- Floor to Floor competitions
- Engagement of building occupants
- Removal of equipment not approved for use
- Removal of obsolete equipment that is energized but not being used

DWELLING UNITS AND RESIDENTIAL SPACES

PL3 Control Strategies

Many consumer devices and electronics continue to use small amounts of power even when they are turned off. These small loads, know as vampire or parasitic loads, can be reduced by providing advanced power strips (APS) within the dwelling units so that equipment is completely turned off when not in use.   Advanced Power Strips (APS) are designed to reduce the amount of energy used by electronics plugged into the strip. A number of different types of APS exist all of which operate by cutting power to devices when not in use. Residential applications for APSs include home entertainment systems and home office equipment.   The type of power strip used will depend on the level on control and convenience desired (NREL 2013.). The types of APS available include:

- *Time power strips* turn off power based on a programmed schedule which is set via a digital or dial timer on the power strip.
- *Activity monitor power strips* sense motion in a room via a motion sensor or infrared eye and turn off power when no movement is detected.
- *Remote switch power strips* allow the power to be turned off via a tethered or remote switch.
- *Master controlled power strips* have one outlet labeled as the "master" outlet so that when a master device (such as a computer or television) is manually turned off, the power strip turns off power to the remaining, controlled outlets where peripheral devices (such as printers or game consoles) are connected.
- *Masterless power strips* have no master outlet, so when the connected devices are turned off, the power strip turns off power to those outlets via automatic switching or power detection.

PL4 Cooking Appliances

The basic strategy for cooking appliances in a zero energy residence is to select appliances that are very effective in putting heat into the food without putting heat into the room, and then to use those appliances to minimize heat gain to the room while executing the required cooking task. Reducing the total amount of heat required to accomplish a specific heating task not only has the benefit of reducing the amount of energy used for cooking, but it also reduces the amount of heat gain to the dwelling unit. The energy efficiency of all cooktop cooking processes is increased by cooking food in a covered pot. Certainly, many recipes don't lend themselves to covered pot cooking, but this measure should be pursued whenever the recipe allows. In warm climates, reducing heat gain to the dwelling unit reduces air conditioning cooling load. In cold climates, the additional heat gain from cooking might reduce the amount of space heating for cooking, but that heat could likely be provided more efficiently the space heating system. Reducing the amount of heat delivered by a cooktop, specifically by concentrating heat gain to the food itself, may allow a reduction in the exhaust capacity of the kitchen hood that removes both the excess heat and the emissions from the cooking process. Reduction in exhaust airflow through the hood reduces the amount of make-up air required and reduces the energy required to condition the make-up air.

Electric Resistance Cooktops

Traditional electric cooktops rely on either an electric resistance coil or infrared element within the cooktop to heat cooking containers directly. While more efficient at delivering heat directly to the cooking container than a natural gas burner, these types of systems have a worse reaction time, temperature uniformity and shutoff response time than natural gas. Furthermore, minimization of heat gain to the room requires selection of a cooking container that is sized for the specific cooking task and utilization of the cooking element on the cooktop that is most consistent with the size of that container. So, when cooking a single hamburger, use a small skillet on the smallest cooking element of the cooktop.

Induction Cooktops

Induction cooktops combine both the efficiency of a traditional electric cooktop with the beneficial performance and response time of natural gas, while also increasing temperature uniformity within the cooking container. Furthermore, the size of the cooking container and the required temperature in the container are the sole determinants of the total amount of heat delivered by the cooktop, so that the user does not have to select the appropriate cooktop element to insure efficient cooking.

Induction cooktops function by creating an electro-magnetic field within close proximity to the cooktop surface. The cooktop surface is typically a ceramic glass and is not heated directly by the induction field. Instead, the electro-magnetic field excites ferrous molecules within the cooking container (i.e. pots and pans) directly, effectively turning the actual container into the heat source. This process is illustrated in Figure 5-49. Most induction systems include sensing technology to narrow the field to match the container size and will shutoff automatically anytime a pan is removed. Because the system is not heating the cooktop directly, it remains relatively cool, only picking up residual heat coming off the cooking container. This can be of great benefit in projects with tenants at more risk for unintended burns, such as the elderly and young children.

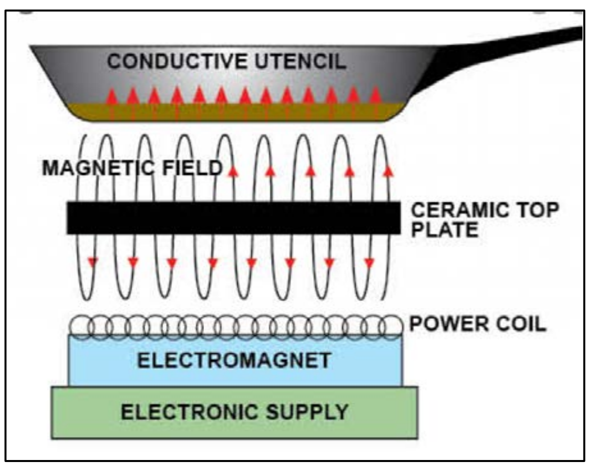


Figure 5-49 (PL4) Induction Cooktop process

Induction cooktops and ranges also include more flexibility in terms of control. Many manufactures include “boost” functions, which provide a temporary boost of power to a single zone on the cooktop. These systems can boil water faster than traditional gas or electric cooktops and can instantaneously change heating input for faster response time as well.

> ***Caution:*** The one challenge with induction cooktops, is that they require ferrous content in the cooking container. Cast iron, stainless steel and hybrid pans including a ferrous layer will work. Many cookware manufactures now include “induction ready” labeling on pan sets to indicate to consumers if their pans will work on induction cooktops. One

way to overcome this challenge with tenants is to provide a starter set of cookware with each dwelling unit to ensure that all tenants are able to use the cooktop upon occupancy. Also, the user should have access to cooking containers of various sizes, so that they can select the correct size for each cooking task, maximizing the fraction of delivered heat that goes into the food.

Convection Ovens

Convection ovens are more energy efficient than standard ovens because the heated air is continuously circulated around the food being cooked. As a result, the air temperature within the oven is more uniform and because of the velocity of the air across the surface of the food, the thermal resistance of the boundary layer between the food mass and the air is reduce, increasing heat transfer into the food. As a result, the cooking time for any given dish is significantly reduced with a convection oven, resulting in less energy consumption for any given cooking task. According to the US Department of Energy, cooking with a convection oven provides an energy savings of approximately 20% compared with performing the same cooking task with a conventional oven. (DOE 2014).

Microwave Ovens

Microwave ovens effectively concentrate the electric energy used for heating into the body of the food to be cooked. However, they are better suited for some cooking tasks and not others. For example, microwave ovens are less efficient at boiling water for tea or coffee than are electric cooktops (Scientific American, 2009). Microwaves are much more efficient than ovens because they cook faster and deliver heat directly to the interior of the mass of the food, rather than heating the exterior of the food mass and relying upon thermal conduction to complete the cooking of the interior of the mass. The appeal of certain foods, however, such as a standing rib roast, rely upon different degrees of cooking between the surface of the food mass and the interior. Microwave ovens also are relatively ineffective at creating a charred surface, another important component of some dishes. For general heating, especially of solid or viscous liquids, microwave ovens are more energy efficient than cooktops or conventional ovens. According to US EPA Energy Star, Microwave ovens should comply with USDOE Standard 10CFR 430.2 which requires that "microwave-only ovens and countertop convection microwave ovens manufactured on or after June 17, 2016 shall have an average standby power not more than 1.0 watt. Built-in and over-the-range convection microwave ovens manufactured on or after June 17, 2016 shall have an average standby power not more than 2.2 watts."

Electric Kettles and Coffeemakers

Insulated electric kettles are by far the most efficient means for heating water for preparation of coffee or tea, because almost all of the electric energy is absorbed by the water within the vessel. By extension, electric coffee makers are much more efficient for making coffee than heating the water separately in a vessel on the cooktop. Electric kettles are more efficient than cooktops, because the electric element is within the insulated body or the vessel, rather than exposed to room air around its periphery.

Electric Pressure Cookers and Slow Cookers

The primary difference between an electric pressure cooker and a slow cooker is the temperatures generated in the device. The temperatures that the slow cooker can created are limited to the boiling point of water, because the cooking chamber is open to the atmosphere. The electric pressure cooker can generate higher temperatures, because it is sealed and the boiling temperature of water increases as the pressure in the pot increases. As a result, the electric pressure cooker can finish the required cooking task in a shorter period of time, if the dish to be prepared can tolerate the higher temperature. The electric pressure cooker, furthermore, conveys less heat to the room, because it allows no hot steam to escape. Both appliances, however, are much more efficient than ovens, or electric cooktops for isolating the heat generated to the food resulting in minimized heat gain to the room.

PL5 Dish Washers and Clothes Washers

Dishwashers should meet the ENERGY STAR criteria as shown in Table 5-16. When hot water usage has been minimized the efficiency of the systems and equipment that provide the hot water can be addressed.

Table 5-16 (PL5) ENERGY STAR Criteria for Dishwashers

Equipment	Corresponding Base Specification	High Temperature Efficiency Requirements***		High Temperature Efficiency Requirements**	
		Idle Energy Use*	Water Consumption	Idle Energy Use*	Water Consumption
Under Counter	ENERGY STAR	<= 0.90 kW	<= 1.00 gal/rack	<= 0.50 kW	<= 1.70 gal/rack

**Idle energy rate as measured with door closed and rounded to 2 significant digits*
***Machines designed to be interchangeable in the field from high temp to low temp, and vice versa, must meet both the high temp and low temp requirements to qualify*
**** CEE 2008.*

The only clothes washers eligible for ENERGY certification are front and top-loading clothes washers with capacities greater than 1.6 ft^3 and less than 8.0 ft^3 and which are not defined as Combination All-In One Washer-Dryers, Residential Clothes Washers with Heated Drying Functionality, or top-loading commercial clothes washers. Below is a discussion of the performance factors considered for EnergyStar clothes washers.

- *Modified Energy Factor* (MEF_{J2}) is the energy performance metric for ENERGY STAR certified commercial clothes washers as of February 5, 2018. MEF_{J2} is the quotient of the capacity of the clothes container (C), divided by the total clothes washer energy consumption per cycle, with such energy consumption expressed as the sum of the machine electrical energy consumption (M), the hot water energy consumption (E), and the energy required for removal of the remaining moisture in the wash load (D). The higher the value, the more efficient the clothes washer is. The equation is shown below(units are ft3/kWh/cycle):

  $$MEF_{J2} = C / (M+E+D)$$

- *Integrated Modified Energy Factor* (IMEF) is the energy performance metric for ENERGY STAR certified residential clothes washers as of March 7, 2015. IMEF is the quotient of the capacity of the clothes container (C) divided by the total clothes washer energy consumption per cycle, with such energy consumption expressed as the sum of the machine electrical energy consumption (M), the hot water energy consumption (E), the energy required for removal of the remaining moisture in the wash load (D), and the combined low-power mode energy consumption (L). The higher the value, the more efficient the clothes washer is. The equation is shown below(units are ft3/kWh/cycle):

IMEF = C / (M+E+D+L)

Note that the IMEF can be improved by reducing the amount of energy the clothes dryer must consume by more effective removal of water from the washed clothing. Some commercial clothes washers are equipped with more powerful drive motors and stronger tubs to allow a higher rotational speed during the spin cycle to generate greater force for water removal. Energy required for clothes drying can be reduced by 40% with a ultra-high speed spin cycle compared with a standard speed spin cycle. (Korn and Dimetrosky 2010)

- *Integrated Water Factor* (IWF) is the water performance metric for ENERGY STAR certified residential clothes washers as of March 7, 2015 and ENERGY STAR certified commercial clothes washers as of February 5, 2018. It allows the comparison of clothes washer water consumption independent of clothes washer capacity. Manufacturers must submit their water consumption factors with their ENERGY STAR certified residential clothes washers. IWF is the quotient of the total weighted per-cycle water consumption for all wash cycles (QA) divided by the capacity of the clothes washer (C). The lower the value, the more water efficient the clothes washer is. The equation is shown below:

  IWF = QA/C

The federal EnergyGuide label on residential clothes washers shows annual energy consumption and cost. These figures use the IMEF/MEFJ2, average cycles per year, and the average cost of energy to make the energy and cost estimates. The Integrated Modified Energy Factor, or Integrated Water Factor may not appear on the EnergyGuide label. ENERGY STAR criteria for clothes washers are shown in Table 5-17.

Table 5-17 (PL5) ENERGY STAR Criteria for Clothes Washers

Product Type	EPA Criteria Levels (as of 2/5/2018)	CEE Highest Tier (As of 9/1/2019)
ENERGY STAR Residential Clothes Washers, Front-loading (> 2.5 cu-ft)	IMEF ≥ 2.76 IWF ≤ 3.2	IMEF ≥ 3.1 IWF ≤ 3.0
ENERGY STAR Residential Clothes Washers (≤ 2.5 cu-ft)	IMEF ≥ 2.07 IWF ≤ 4.2	IMEF ≥ 2.2 IWF ≤ 3.7
ENERGY STAR Commercial Clothes Washers, Front-loading	$MEF_{J2} \geq 2.20$ IWF ≤ 4.0	$MEF_{J2} \geq 2.4$ IWF ≤ 4.0

PL6 Heat Pump Dryers and Dryer Alternatives

The annual energy use for laundry is relative to the location and convenience of the laundry facilities. In unit laundry results in more frequent laundry use by occupants which increases the annual energy use associated with it. The total energy use varies in relationship to the number of household members, with more energy use associated with larger households. Centralized laundry on a floor-by-floor basis results in less frequent laundry use and fuller loads per wash cycle, which results in reduced energy use per year. Further decreases in use and annual energy use are seen in facilities that have only a single centralized laundry facility located on the ground floor or basement due to the reduced convenience of the service. However, availability of in-unit laundry is often an amenity required to attract tenants and is not typically decided by its impact on energy use alone.

Of the total energy consumed for washing and drying of laundry, including heating of the wash water, drying represents about 80% of the total energy consumption, while water heating represents 13%, and the clothes washer motor represents only 6% (Korn and Dimetrosky 2010). Strategies for reducing energy consumption for the whole washing process, therefore should focus on reducing the evaporation load on the dryer and improving its efficiency at removing water.

Energy efficient laundry equipment, such as ENERGY STAR rated appliances, should always be selected. Energy use associated with dryer use can be further minimized through the use of heat pump dryers. There are two main types of heat pump dryers on the market currently, each of which offer benefits:

- *Heatpump-only ventless models* are the most efficient and offer the lowest energy use per load of laundry. They operate by heating the air up with the condenser coil of a closed loop heat pump. The hot air passes into the drum, where it picks up moisture evaporating off the clothes. The hot-moist air returns to the heat pump, where it passes over the evaporator coil, which is the cold side of the heat pump. The moisture contained in the air stream condenses on the coil, where it is collected and drained. The air, which is also cooled down in this process is then passed over the evaporator coil again, where it is reheated and the cycle repeats. These systems are closed loop, meaning no air is pulled from the room, nor vented to the outdoors. Figure 5-48 illustrates the process.

  As no air is pulled from the room, these systems are ideal for very tight construction and passive design strategies. They also do not dramatically change the apartment ventilation balance. However, dry times are typically 20% longer than a traditional electric vented or gas dryer, especially if occupants overload the dryer. If they are located in a closet, the closet should have adequate air circulation with the rest of the dwelling unit as the dryers do produce heat, which can build up in a small closet. Note that ducting to the outdoors is not necessary.

  Lint build up on the coils of the heat pump can dramatically reduce the efficiency and also increase the dry time beyond acceptable limits. Different manufacturers have different systems built into the units to clean the coils from lint. Building owners should train occupants in the proper lent cleaning procedures needed to maintain optimum performance or risk occupant dissatisfaction with their performance.

Figure 5-48 (PL6) Heat Pump Dryer Technology Schematic

- *Hybrid heat pump dryers* combine the heat pump system described above with a traditional electric resistance coil, which allows elevated temperatures similar to a traditional dryer. However, these dryers are typically still vented to the outdoors and consume more energy than a heatpump-only dryer. Because the dryers are vented to the outdoors, pathways for the exhaust ductwork must be planned. Special attention must be paid to the maximum length and number of turns allowed by the manufacturer for the exhaust ductwork, as dryer performance and risk of fire from lint buildup increases beyond those limitations. In addition, adequate makeup air must be designed into the ventilation system to eliminate depressurization of the apartment.

PL7 Refrigerators

Purchase appropriately sized refrigerators with an ENERGY STAR rating. The size of the refrigerated volume significantly affects the total energy consumption, so that refrigerators should be selected at the smallest size consistent with the expected use. Refrigerators with a top-mounted freezer tend to use less energy than side by side or bottom-mounted freezers. The guidelines in Table 5-18 are useful for selecting energy efficient refrigerators, based upon rated energy usage per year divided by refrigerated volume

Table 5-18 (PL7) Recommended Energy Efficiency of Refrigerators

Refrigerated Volume	kWh per year/ft^3 Volume
< 10.0 ft^3	< 30.0
10.0< <12.5	< 27.5
12.5< <15.0	< 25.0
15.0< <20.0	< 21.0
20.0<	<19.0

The following guidelines for refrigerator installation and operation will insure improved energy efficiency performance.

- Set the refrigerator thermostat at 35 to 38 degrees Fahrenheit.
- Locate the refrigerator in a cool place away from heat sources such as an ovens, cooktops, dishwashers, or direct sunlight from a window.
- Allow air circulation behind the fridge by leaving a few inches between the wall and the refrigerator.
- Keep the condenser coils clean. Read the user's manual to learn how to safely clean coils. Coil cleaning brushes can be purchased at most hardware stores.
- Periodically check the door seals for airtightness. If they are leaky, replace them.
- Minimize the amount of time the refrigerator door is open.

COMMON AREAS AND COMMERCIAL SPACES

PL8 Control Strategies

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).

Use timer switches for central equipment that is unused during unoccupied periods but that should be available throughout occupied periods.

Occupancy controls should be considered in addition to plug load controls to reduce energy consumption when equipment is not in use. Options include occupancy-sensor-controlled power strips and room-based occupancy sensors. 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.

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, 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).

PL9 Office Equipment (RS) (CC)

Select laptops, docking stations, and monitors with ENERGY STAR ratings. 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. An added benefit of laptops is that uninterruptible power supplies, which are very inefficient, are not needed and can be eliminated from workstations.

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 and 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.

Consolidate printing services to minimize the number of required devices and use multifunction devices that provide printing, copying, and faxing capabilities.

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.

PL10 Audio/Visual Equipment

To ensure that equipment in community and/or conference rooms is not drawing power when the rooms are vacant, 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).

PL11 Security and Fire Systems

Use low-voltage security systems. Security cameras have improved significantly in recent years so that additional lighting is no longer necessary for quality images.

BUILDING PROCESS LOADS

PL12 Elevators

Incorporating elevators with energy savings features can cut elevator energy consumption by up to half. (Kroll n.d.). The biggest impact on energy use is the type of elevator system used, the travel speed, and the number of elevators. In reviewing travel speeds, evaluate the total travel time from door opening to door opening. Many times, the door action, control selection, and acceleration/deacceleration dominate the time and the actual specified speed is small. 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.

A typical design rule of thumb is one elevator per 100 dwelling units. However, the project team should work with the elevator vendor to test different scenarios to achieve the required handling criteria. Factors to consider include building height, number of floors, dwelling units/floor, estimated occupants/unit, and the desired response times.

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 include sensors that shut down the lights, music, signage, and ventilation when the elevator sits idle for a preset period of time. Because of the need to know the weight of the elevator cab for motor control, the elevator "knows" when it is or is not occupied. More sophisticated control technologies include sequencing, batching, and staging of elevator cars. (Sniderman 2012, Kroll n.d., Penney 2013)

Minimizing elevator use is the most effective way to save energy. Incorporate active design principals, such as appealing, centrally located, and easily accessible stairwells.

Electric Vehicle Charging Stations

While still a small portion of the overall vehicle sales, electric vehicles (EVs) are penetrating the automobile market. Tenants are asking for places to charge vehicles at their residence as well as asking their employers to install them at the workplace. While a few charging stations will not impact the building electrical infrastructure, large numbers can have a significant impact. According to the Zero Energy Building Definition, EVs are considered an export from the building and are therefore subtracted from the building energy total. (The exception is if the EV is used within the building and part of the building or site internal transport.) If there are limits on the export of energy from the site, EVs can provide an additional mechanism for exporting power from the building.

EV Charging Station

EVs are connected to the building via a charging station. Charging stations are designated as level 1, level 2, or level 3. Level 1 and Level 2 chargers are most applicable for multifamily as EVs can be parked for longer periods of time. Level 3 are also called “DC Fast Chargers” and are typically used for areas where users have a limited timeframe such as highway rest areas or restaurants. Level 3 charges are not recommended for multifamily dwellings unless the mixed-use part of the building can justify them.

Level 1 are typically attached to a 120V electrical circuit and can charge the vehicle at a power rate of 1 kW to 1 kWh per hour. Some level 1 chargers will go to 1.5 kW. An apartment owner who doesn’t install EV charging stations may find tenants connecting vehicles through windows and doors to 120V outlets.

Level 2 chargers are most common in commercial properties. These chargers typically have capacities of 3.5 kW to 7.2 kW; however, SAE J1772 standard allows for charging capacities of up to 19.2 kW. These units are typically hardwired to 208V or 240V electrical circuits and require electrical breakers of 30 Amps to over 80 Amps. This can quickly change the needs of an electrical panel.

Many of these charging stations can demand limit the current based on load on other stations. This can help match EV charging to minimize electrical demand costs or align with resources, such as on-site PV. They can also be specified to accept payment. Ideally, EV charging would align with excess on-site generation which can be difficult as most residential chargers are used at nighttime.

POWER DISTRIBUTION SYSTEMS

PL13 Rightsizing Power Distribution Systems (RS) (RT)

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).

Most small and medium buildings are anticipated to use 120/208 V power distribution systems; however, power distribution should be designed with future (or present) electrification of heating, water heating, and automobiles in mind. It is relatively inexpensive to put in enough amperage when the building is constructed, but it is relatively expensive to retrofit. 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 buildings, 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 building. 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 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. Figure 5-50 illustrates a typical building power distribution system.

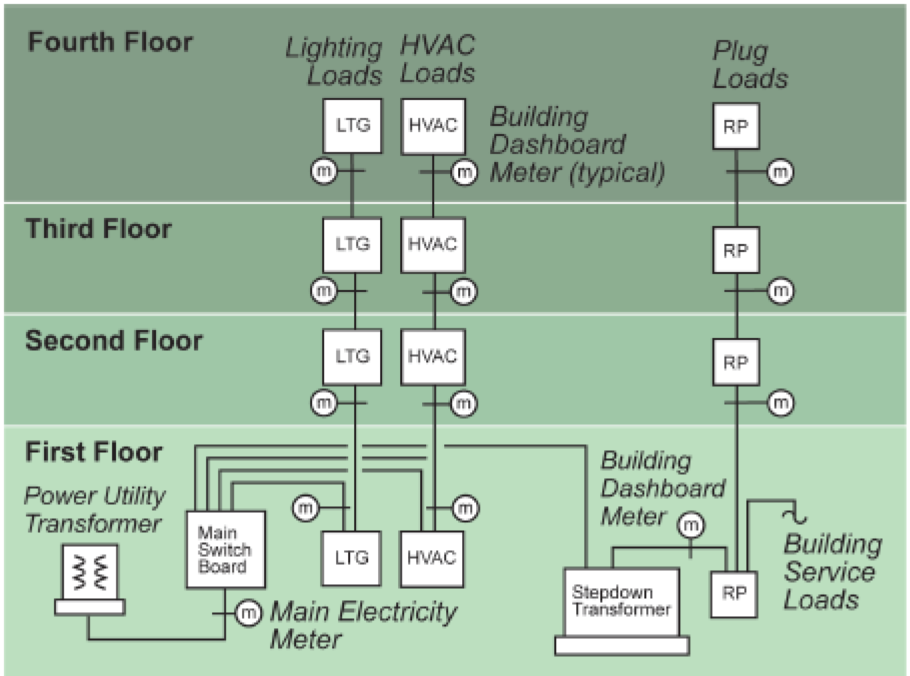


Figure 5-50 (PL18) Typical Power Distribution

REFERENCES AND RESOURCES

ASHRAE. 2010. ANSI/ASHRAE/IES Standard 90.1-2010, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASHRAE. 2013. ANSI/ASHRAE/IES Standard 90.1-2013, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASHRAE. 2016. ANSI/ASHRAE/IES Standard 90.1-2016, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

CBSC. 2016. *2016 California building standards code*. California Code of Regulations, Title 24. Sacramento, CA: California Building Standards Commission. https://www.energy.ca.gov/title24/2016standards/.

DOE. n.d. Distribution transformers. Appliance and Equipment Standards Rulemakings and Notices. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office. https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=55&action=viewcurrent.

DOE. 2014. *Cooking Up Some Energy Saving Tips*. Energy Saver website. Washington, DC: U.S. Department of Energy. July 9, 2014. https://www.energy.gov/energysaver/articles/cooking-some-energy-saving-tips

DOE. 2019. Plug & process loads. Better Buildings website. Washington, DC: U.S. Department of Energy. https://betterbuildingssolutioncenter.energy.gov/alliance/technologysolution/plug-process-loads.

EPA. 2018. ENERGY STAR product finder. Washington, DC: U.S. Environmental Protection Agency. https://www.energystar.gov/productfinder.

EPA. 2019a. ENERGY STAR Most Efficient 2019. Washington, DC: U.S. Environmental Protection Agency. https://www.energystar.gov/products/most_efficient.

EPA. 2019b. ENERGY STAR overview. Washington, DC: U.S. Environmental Protection Agency. https://www.energystar.gov/about.

GPO. 2016. *Code of federal regulations*. 10 CFR Ch. II, §431.196. Washington, DC: U.S. Government Publishing Office. https://www.govinfo.gov/content/pkg/CFR-2010-title10-vol3/pdf/CFR-2010-title10-vol3-sec431-196.pdf.

Korn, David, Sscott. Dimestrosky. 2010. "Do the Savings Come Out in the Wash? A Large Scale Study of In-Situ Residential Laundry Systems", David Korn and Scott Dimetrosky, The Cadmus Group, Inc. ACEEE Summer Study Proceedings 2010.

Kroll, Karen. No date. *How to reduce Elevator Energy Use*. Facilitiesnet, Builidng Operations Management. https://www.facilitiesnet.com/elevators/article/How-To-Reduce-Elevators-Energy-Use--15510?source=previous

Lobato, C., S. Pless, M. Sheppy, and P. Torcellini. 2011. Reducing plug and process loads for a large-scale, low-energy office building: NREL's Research Support Facility. *ASHRAE Transactions* 117(1):330–39. https://www.nrel.gov/docs/fy11osti/49002.pdf.

NREL. 2013. *Saving Energy through Advanced Power Strips*. NREL/PO-5500-60461. October 2013. https://www.nrel.gov/docs/fy14osti/60461.pdf

NFPA. 2014. NFPA 70, *National electric code*. Quincy, MA: National Fire Protection Association.

NFPA. 2017. NFPA 70, *National electric code*. Quincy, MA: National Fire Protection Association.

Penney, Janelle. 2013. Taken Elevator Efficiency to the next level. Buildings.com. https://www.buildings.com/article-details/articleid/15882/title/take-elevator-efficiency-to-the-next-level/viewall/true

Sanchez, M.C., C.A. Webber, R. Brown, J. Busch, M. Pinckard, and J. Roberson. 2007. Space heaters, computers, cell phone chargers: How plugged in are commercial buildings? LBNL-62397. Presented at the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, August 13–18, Asilomar, CA. https://www.osti.gov/servlets/purl/913164.

Scientific American. 2009. "Stove vs. Microwave: Which Uses Less Energy to Make Tea", Scientific American, June 11, 2009
https://www.scientificamerican.com/article/stove-versus-microwave-energy-use/

Sheppy, M., C. Lobato, S. Pless, L. Gentile-Polese, and P. Torcellini. 2013. *Assessing and reducing plug and process loads in office buildings*. NREL/FS-5500-54175. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy13osti/54175.pdf.

Sniderman, Debbie. 2012. *Energy Efficient Elevator Technologies*. ASME website: https://www.asme.org/topics-resources/content/energy-efficient-elevator-technologies

DOMESTIC WATER HEATING

OVERVIEW

Domestic water heating is the second largest energy end-use component on average in small multifamily residential buildings behind space heating and the largest component in large multifamily buildings. See Figure 5-51. The physical mechanisms behind water heating are more straightforward than those of space heating, so, addressing energy conservation for water heating is much straightforward. Energy efficiency strategies should emphasize both the minimization of hot water usage, and the efficiency of generation of the hot water. Minimization of usage should include selection of both fixtures and appliances for both low water usage and minimization of required operating water temperature. Efficiency of generation should include both renewable energy sources, and heat recovery.

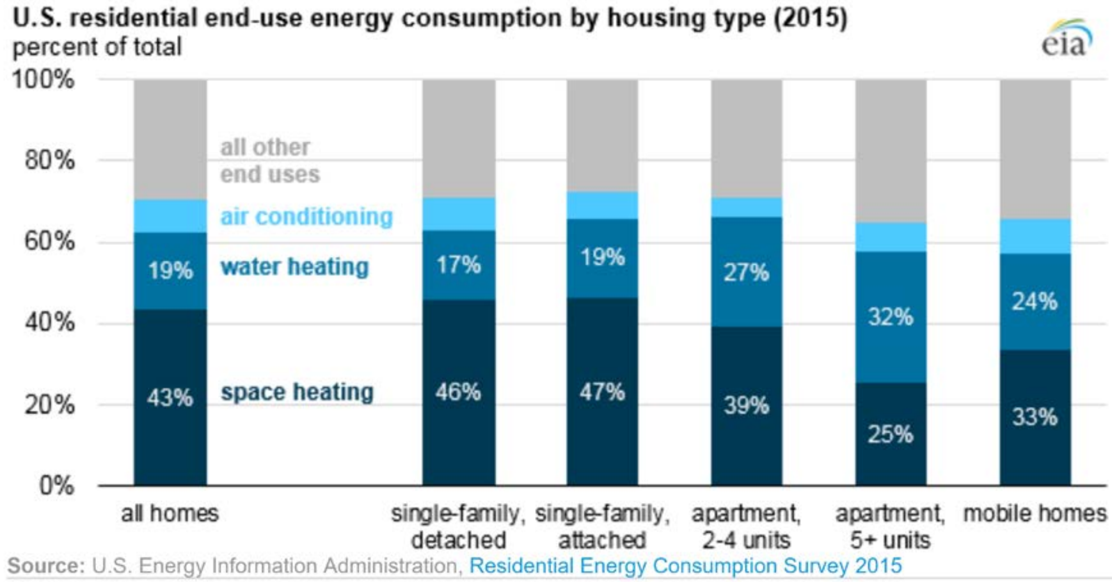


Figure 5-51 Energy End Use (EIA 2015)

SYSTEM TYPES

WH1 System Descriptions

Domestic water heating systems for residential buildings can be characterized as central, semi-distributed or individual. Central systems incorporate water heating and storage and a distribution system that serves multiple dwelling units. A central system could be as limited as a single floor or a building or could serve the entire building. Semi-distributed systems typically cluster 2-6 dwelling units on an individual shared tank. Individual systems incorporate a water heating source and hot water storage in every dwelling unit. Individual systems have the advantage of facilitating metering of hot water usage and cost on a unit by unit basis. Central systems have the advantage of more easily accommodating certain types of water heating sources, such as solar thermal, wastewater heat recovery, cogeneration, heat pump and fuel fired sources. While natural gas water heaters can be used on a unit by unit basis, in taller buildings, management of gas service, flue exit and combustion air can be more difficult for individual dwelling units in taller buildings.

WH2 Water Heating Sources

Water heating sources for residential buildings almost always include some form of hot water storage because provision of hot water for each load with tankless heaters would require individual heaters, each with capacity for the load served. Many of these loads are highly diverse, in that all showers, handwash sinks, dishwashers, and clothes washers never operate simultaneously or together for an extended duration. Hot water service for all fixtures in a dwelling unit can be provided by a heater with a reasonably sized tank (40 to 50 gallons per dwelling unit) and a heating capacity that is a small fraction of the sum of the instantaneous loads for the fixtures. Below are some water heating sources appropriate for zero energy residential buildings.

Indoor Air Source Heat pump electric water heater

This system consists of 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 domestic hot water. For this system, the source from which the heat pump draws heat is the internal air of the dwelling unit. For this reason, this system is very beneficial in cooling dominated climates (climate zones 1, 2, and 3), in that the water heater reduces the amount of cooling required annually for the unit. For heating dominated climates, however, the heat removed from the dwelling unit by the water heater, for the most part, must be replaced by the space heating system for the unit, resulting in additional energy consumption. The heating system for the unit must be sized to include not only the heat loss through the building envelope, but also the heat extracted from the unit to heat hot water. This system can be utilized only with an individual water heating system, as it requires access to the room air with a unit. Conceivably, some larger multi-family buildings might have server rooms, or electrical rooms that could serve as heat sources, but these rooms would likely provide sufficient heat only sufficient to serve a few of the dwelling units in the building.

Indoor air heat pump water heaters should exceed Energy Star criteria for residential heat pump water heaters.

> ***Caution:*** Careful attention must be paid to make sure the heat pump has adequate air-exchange with the surrounding dwelling units. Locating the ASHP in a small closet without appropriate air-exchange will result in the heat pump tripping into electric resistance mode and reducing the unit efficiency.

Outdoor Air Source Heat pump electric water heater

These systems are now available utilizing CO2 as a refrigerant which have demonstrated much higher COP's at low ambient temperatures than systems using more common refrigerants, making them suitable for outdoor use in cold climates (climates zones 4, 5, 6, and 7). Residential size versions of these products do not yet have an Energy Star rating as the official test procedures for the products have not yet been finalized. Products are available commercially that maintain 100% capacity down to 5°F ambient air temperature, with a COP of between 2.0 and 2.2 depending upon the supply temperature of the heater. Some systems are designed to store hot water at a higher temperature than the conventional 140°F with use of a thermostatic mixing valve to provide water to fixtures at a lower temperature, in order to reduce the size of the storage tank and to increase the effective capacity of the heater at the mixed water supply temperature. These systems may be used centrally or for individual dwelling units. When used as a part of a central system, consider oversizing the storage tank to enable more freedom to schedule operation of the heating unit. A larger storage tank will enable the heating unit to be freed from the immediate demands of hot water supply so that it can be operated during the middle of the day, when ambient air temperature is likely higher, increasing the COP of the unit and while the building photovoltaic system is providing local renewable energy, When implemented for individual units, outdoor area in close proximity to the indoor tank must be provided for the compressor unit. Currently products sized for individual unit installations are limited. Larger units are available from several manufacturers for central systems.

Locations for outdoor units for central heat pump domestic water heating systems can improve their performance. Locating the unit directly downstream from an exhaust system outlet will moderate the incoming air temperature to the evaporator coil of the system. Locating outdoor units at the exhaust outlet of an underground parking garage may also moderate the air temperature entering he evaporator coil.

Sewer heat recovery Heat pump electric water heater

For climate zones where design heating temperatures fall below the minimum ambient temperature for air-source heat pumps and for which ground coupled heat pumps are not usable because annual heating loads greatly exceed annual cooling loads (climate zones 7, and 8), heat recovery from sewer water generated within the residential building can be a viable heat source for water-to-water heat pumps. Logically, sewer outflow is greater than domestic water heating system supply flow, because the sewer flow will contain a significant portion of tap water flow that has not been heated. The unheated tap-water flow, furthermore, will have absorbed some heat from the dwelling unit environment. Water sitting in toilet bowls, likely will be discharged at a temperature near to that or the room in which the toilet sits. As a result, the sewer water flow provides more than sufficient heat for a water-to-water pump to supply domestic hot water needs for the residence. This system would most likely be implemented as a central system, because of the maintenance requirements and first cost economy of scale for implementation. These systems should be able to achieve a COP of between 2.8 and 3.2 depending upon wastewater temperature and desired domestic hot water supply temperature.

Condensing Gas-fired storage water heater

This system consists of a water heater with an integral water storage tank. A thermostat controls the delivery of gas to the heater's burner. The heat exchanger surfaces for the water heater are sized and configured to reduce the temperature of the combustion products leaving the flue to as temperature sufficiently low that much of the water produced by the process of combustion is condensed, and the recovered latent heat of vaporization of that condensed water is applied as additional heating of the hot water supply. .As a result, the efficiency of these heaters is typically as much as 15% higher than conventional non-condensing heaters. These heaters have fan forced air flow through the heater and do not rely on buoyancy driven flow to bring combustion air to the flame in the heater. With fan forced flow and significantly reduced flue gas temperature, the limitations on exit locations for the flue are greatly simplified. Often both flue gas and combustion are routed through polymeric pipes that may pursue circuitous routes from the heater connection to the outside.

Groundwater Source Heat pump electric water heater

Ground coupled water-to-water heat pumps for domestic water service can be beneficial in some climate zones (climate zones 3, 4, and 5), depending upon the need to maintain an annual thermal balance with the ground mass. For projects using ground-coupled heat pumps for space conditioning in climates that have excessive heat rejection into the ground, because annual cooling loads are greater than annual heating loads, using the ground as a source for heat pumps providing domestic hot water can help balance the annual load. Ground-coupled systems may not be appropriate for extremely cold climates where they would impose a significant heat extraction from the ground, causing a local ground temperature depression that would, after a period of time, render the system inefficient or inoperable. Ground-coupled source water-to-water heat pumps are suitable for either individual or central installations. These units should be selected for a COP of 2.1, assuming a heat source temperature of 30°F, and a water supply discharge temperature of 150°F.

Solar Thermal water heater

Solar thermal water heating in almost all circumstances must be supplemented by some other water heating source, because solar incidence is not sufficiently reliable to provide service throughout the year. Great care must be taken if interconnecting solar thermal systems with heat pump based water heating. Heat pump efficiency will drop if consistently operating with the elevated water temperatures produced by solar thermal systems. Design of solar water heaters is discussed in Section WH-6.

System Type Selection Criteria

As one can see in Figure 5-52, the domestic water system heating type has a small but detectable impact on building EUI, depending on climate zone. Energy modeling studies were performed on three types of heat pump water heaters, indoor single package heat pump systems, split system heat pumps with outdoor condensing units serving a single residential unit and central wastewater heat recovery heat pump systems. In climate zones 0, 1 and 2, the single package indoor units were beneficial, because their heat extraction from the residential unit decreased air conditioning load in the unit. In Climate Zone 3, single package indoor systems have a negative or negligible effect on the residential unit EUI. For Climate Zones 4 and above single package heat pump systems result in higher EUI's for the unit. Split system heat pumps dedicated to each residential unit have the best EUI in Climate Zones 4, 5 and 6, while central waste water heat recovery heat pumps have the best EUI in Climate Zones 7 and 8. While the central waste water heat recovery systems have a higher COP than the split systems, heat losses through the pumped recirculation distribution system offset that advantage. In Climate Zones 5 and 6, a central wastewater heat recovery heat pump system would outperform a central outdoor split system heat pump system that was also subject to distribution system losses.

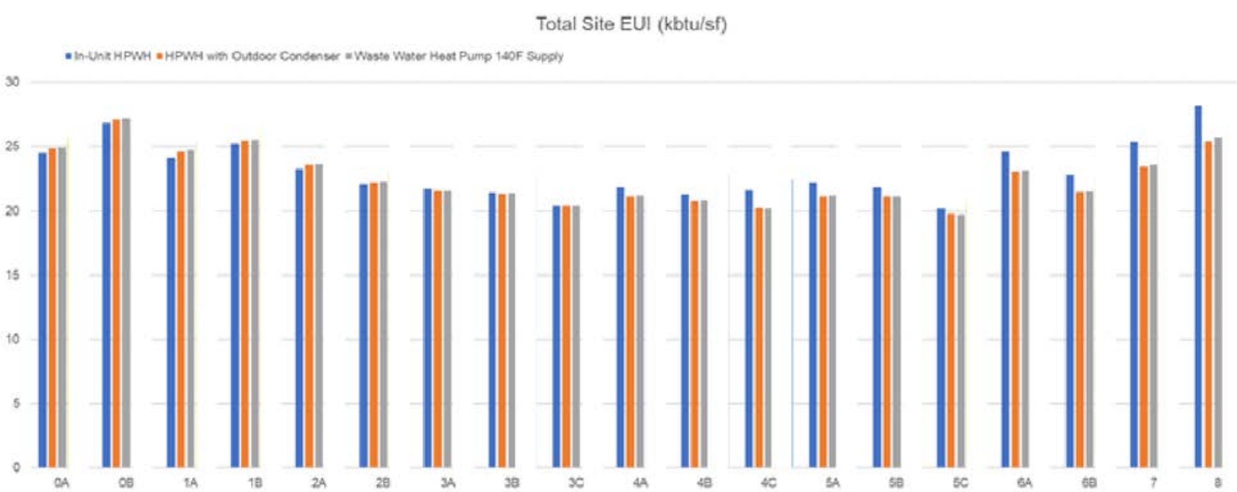


Figure 5-52 (WH-2) Building EUI for Various Domestic Water Heating Systems

DESIGN STRATEGIES

WH3 Cogeneration

Cogeneration can be applied to larger multi-family buildings, especially high rises. Typical applications utilize microturbines of 35 to 70 kW generating capacity. The heat exchanger on the exhaust of the microturbine becomes a separate heater for a large insulated hot water storage tank. When the temperature in the tank has fallen sufficiently to justify a turbine run time above its minimum, the turbine is energized to provide both hot water and electricity that is delivered to the house electrical distribution system. Because hot water delivery temperature does not significantly affect the efficiency of energy recovery from the microturbine, the storage temperature of the tank is often well above the 140°F temperature typical for standard water heaters, allowing a smaller tank to achieve the required storage. A thermostatic mixing valve discharges water from the tank at a safe temperature.

WH4 Reduce Overall Water Consumption (RS) (RT)

The four largest users of hot water in a residence are showerheads, kitchen sink spray washers, dishwashers and clothes washers.

Kitchen and Bathroom Fixtures. The first step to reducing the energy consumption of the service water heating system is to reduce the demand for hot water. The simplest step to achieving this end is to specify low flow sink faucets and showerheads. These fixtures should comply with the criteria in the EPA WaterSense™ program (EPA n.d.) as shown in Table 5-15; however, based on a review of available reviewed products, fixtures with lower flow rates are available and provide acceptable performance.

See the Plug Load section (PL5) for additional specific information on dishwashers and clothes washers.

Table 5-15 ENERGY STAR Criteria for Faucets and Sprayers (EPA n.d.)

Fixture Type	WaterSense Maximum Allowable Flow (gpm)	Recommended Maximum Allowable Flow (gpm)
Lavatory Faucet	1.5	0.5
Showerhead	2.0	1.5
Kitchen Sink Sprayer	1.0	1.0

WH5 Properly Size Equipment

The water heating system should be sized to meet the anticipated peak hot-water load. Calculate the demand for each water heater based the first hour rating. The required first hour flow can be calculated using a table similar to Table 5-16.

Table 5-16 Calculation Procedure for Estimating Domestic Water Heating Size

Use	Avg Gallons Hot Water per Usage		Times Used During 1 hour		Gallons Used in 1 hour
Shower	10	x		=	
Shaving (.05 gal/min)	2	x		=	
Hand dishwashing or food prep (2 gal/min)	4	x		=	
Automatic dishwasher	6	x		=	
Clothes Washer	7	x		=	
Total Peak Hour Demand				=	

Note: In the above worksheet, values for average gallons of hot water per usage are based on conventional fixtures. Values used in the sizing of water heating systems should use average values for the actual water-saving features used in the project.

Note that the average gallons of hot water usage for each end-use in the above table are based on standard fixtures. Water efficient fixtures, such as low flow shower heads, will have significantly reduced usage and rates for the exact fixtures used in the dwelling should be used to calculate the required water heater size.

Requirements for supply temperature at the fixtures with direct user contact vary by local and state code within the range of 100°F–120°F. If showers are included in the program, the temperature of hot water provided should be 100°F–110°F. Note the American Society of Plumbing Engineers Research (ASPE) 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 for a residential building, consider oversizing storage capacity to give flexibility in the operation of heat sources. This flexibility can be used to align operation of an electric heating source with renewable energy production both locally at the building level as well as grid-wide renewable production, or to enable outdoor air source heat pump systems to operate during warmer times of the day, when both the COP and capacity are increased, rather than in response to immediate hot water draw.

WH6 Equipment Efficiency (RT)

Water heating equipment fuel source and efficiency should recognize the impact of site/source energy multipliers, both regionally and nationally.

Efficiency levels are provided in this Guide for gas-fired storage 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.

Commercial tank-type water heaters for central domestic hot water delivery systems 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 Energy Star standby loss criteria is given by the following equation:

$$\text{Standby Loss (Btu/hr)} \leq 0.84 * (\text{Input Rate (Btu/hr)} / 800) + 110 * \sqrt{\text{Volume}}\ \text{(gal)}$$

The incorporation of condensing technology is recommended for all gas-fired water heaters to achieve a minimum E_t of 94%. Table 5-18 gives performance requirements for residential and commercial gas-fired water heaters of various capacities and sizes, derived from a variety of sources including the Consortium for Energy Efficiency (CEE 2008) Tier 2 requirements, ASHRAE Standard 90.1-2019 (ASHRAE 2019), ENERGY STAR (EPA 2019), and IgCC/189.1 (ICC 2018). Performance values are given for a “High Draw Pattern”.

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.

Table 5-18 (WH4) Gas Water Heater Performance

Storage Volume (gal)	Capacity, kBtu/h	UEF (Residential)	TE % (Commercial)	Standby Loss, Btu/h (Commercial)
0.0	Varies	0.95	0.95	NA
33	100	0.90	NA	NA
50	100	0.88	NA	NA
120	400	NA	0.95	1200

Table 5-19 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 in the market that deliver and EF higher than 3.0. Ratings for indoor Air-source heat pump water heaters assume that the heaters are drawing heat from a space at a temperature near to comfort temperature and thus are able to achieve a relatively high Coefficient of Performance independent of exterior conditions

Table 5-19 (WH4) Indoor Air-source Water-to-Water Heat Pump Performance Requirements

Storage Volume (gal)	UEF (Residential) Energy Star	UEF Recommended
≤55	2.0	3.45
>55	2.20	3.45

Outdoor air-source heat pumps, on the other hand have widely varying levels of performance based upon the outdoor ambient air temperature. Newly available heat pump units utilizing CO_2 refrigerant are capable of maintaining full capacity to ambient air temperature as low at 5°F, even though the COP drops significantly as the temperature decreases. Heat pump units can maintain at least 75% of nominal capacity down to an ambient temperature of -13°F. Outdoor air-source heat pumps for domestic hot water have the same defrosting issues as described for similar units used for space heating, as described in HV7. Performance of an outdoor air heat pump water heater at various ambient conditions is shown in Table 5-20.

Table 5-20 Outdoor Air-source Water-to-Water Heat Pump Performance Requirements

Outdoor Air Temperature	COP
5°F	2.0
20°F	2.9
50°F	4.3
75°F	4.6

Performance of water source heat pumps for domestic water heating depends upon the temperature of the water source and the supply water temperature (typically 140°F to 150°F). Both central and individual systems draw heat from either circulating water thermally coupled to the ground or sewer water. Groundsource heat pumps will experience a more varying heat source, typically at a much lower temperature than sewer water, and thus will typically have a lower COP. (See Table 5-21)

Table 5-21 Water-to-Water Heat Pump Performance Requirements

Heat Source	Capacity, kBtu/h	COP	Tank Size (gals)	Standby Loss, Btu/h (Commercial)
Ground Water (30°F ELT)	71.8	2.3	75	850
Ground Water (50°F ELT)	86.8	2.48	75	850
Sewer Water (64°F ELT)	120	2.7	120	1200
Sewer Water (75°F ELT)	120	3.0	120	1200

WH7 Minimizing System Losses

Conservation strategy for reducing energy consumption of the hot water system should include not only reduction in hot water consumption, and improvement in hot water production efficiency, but also minimization of hot water distribution thermal losses. Water efficient fixtures and appliances are by far the most effective measures for reducing consumption. Even so, addressing reduction of thermal losses through the distribution system can achieve further gains in efficiency. Strategies to reduce these losses include increased insulation for distribution piping, especially for main distribution pipes in central hot water systems and avoidance or minimization of pumped recirculation systems used to reduce latency in delivery of hot water to fixtures. A study commissioned by the Public Interest Energy Research Program in California found that in a group of 28 multi-family residential buildings using gas-fired central domestic water heating systems, 65% of the energy of the natural gas entering the water heaters was lost before hot water was delivered to the dwelling units for use. Of that 65% loss, approximately half was attributable to losses in the recirculation system. (Heschong Mahone Group, "Multi-Family Central Domestic Hot Water Systems", California Energy Commission, 2013). A study by NREL (J. Dentz, E. Ansanelli, H. Henderson, and K. Varshney, "Control Strategies to Reduce the Energy Consumption of Central Domestic Hot Water Systems", USDOE EERE, 2016), showed that combining demand control with temperature modulation (reducing hot water temperature during periods of low demand could reduce energy for domestic hot water supply as much as 15%.

For all domestic hot water piping in the building with a pipe size greater than 1", consider applying the insulation for the temperature category 141°F to 200°F, rather than the lower temperature category. Also, apply insulation to the entire extent of the hot water piping, even for non-recirculating distribution systems.

Domestic water heating usage in residential buildings follows a typical pattern across the day, with very high usage in the early morning, a moderate spike in usage at the middle of the day and another high spike in usage in the early evening. During these high usage periods, the heat value of the consumed hot water overwhelms any thermal losses through the piping of the distribution system, even for central hot water service systems. During these high usage periods, furthermore, depending upon the exact configuration of the hot water distribution system, latency of hot water delivery may not be a problem. Avoiding latency for central systems using pumped recirculation does result in significant thermal losses during periods of lower usage. However, several strategies can reduce these losses, including local user-activated recirculation pumps and, for central systems small tank-type intermittent electric resistance heaters for initial hot water delivery. The PIER study cited previously identified recirculation system controls as an effective means of reducing losses for these systems, with demand control algorithms that activate the recirculation pump based on hot water demand and on hot water return temperature as the most effective. A simple control mechanism for very well insulated distribution risers is to disable the circulating pump when the water temperature at the top of the riser rises to within 5°F of the mixing valve outlet temperature. A well-insulated riser will take some time to drop to that temperature during periods of no usage.

Hot water distribution piping design can also contribute to reducing losses of the distribution system by reducing the surface areas of the pipes to reduce heat losses and by reducing the volume of the pipes to reduce the mass of water that cools down when there is no hot water flow. Design to achieve these goals also has the benefit of reducing the overall cost of the hot water distribution system. Ideal distribution design with all fixtures requiring hot water located adjacent to the hot water vertical riser require recirculation for the riser only. Using individual dedicated piping runs to each fixture minimizes the latency time for hot water delivery to the fixture by maximizing the water velocity across the entire piping run from the riser to the fixture.

Locating this mixing valve required by code to eliminate scalding risk at the outlet of the storage tank for a central water heating system reduces the temperature of the water in the distribution system, thereby reducing thermal losses. The piping system may require a minor redesign to incorporate higher hot water flow necessitated by the lower distribution temperature, but these larger pipes further minimize thermal losses by lowering ratio of pipe surface area to cross-sectional area of the pipe. Larger pipe sizes, furthermore, allow the use of higher water velocity in final distribution piping, possibly decreasing latency time for hot water delivery.

In cases where lateral distribution is required to serve widely distributed apartments on each floor, consider installing a manually activated recirculation system along the lateral piping run to each apartment, in addition to the automated control vertical riser recirculation system. Manually activated re-circulation systems typically are activated by a push button, and only operate until a temperature sensor senses hot water at the fixture. A typical application might be for a bathroom, for which latency is a significant issue. On entering the bathroom, the user would push a button to activate the recirculation pump, at the same time energizing a lamp to notify the user that the pump is in operation. When hot water reaches the bathroom, the pump stops and the lamp goes out to indicate hot water is available. The hot water delivery to fixtures in the bathroom should be close-coupled to the recirculation loop connection such that latency from the final few feet of distribution piping is minimal. Figure 5-53 shows these distribution strategies applied to a central multiple pass domestic water heating system. This distribution system is for what is called a multiple pass system where the system raises the temperature of the incoming city water to the desired tank temperature over several passes through the heat pump unit. Because of this design, the system is more tolerant of elevated inlet temperature water that might occur during periods of low usage with significant elevation of the water temperature at the bottom of the tank by the returning recirculated water.

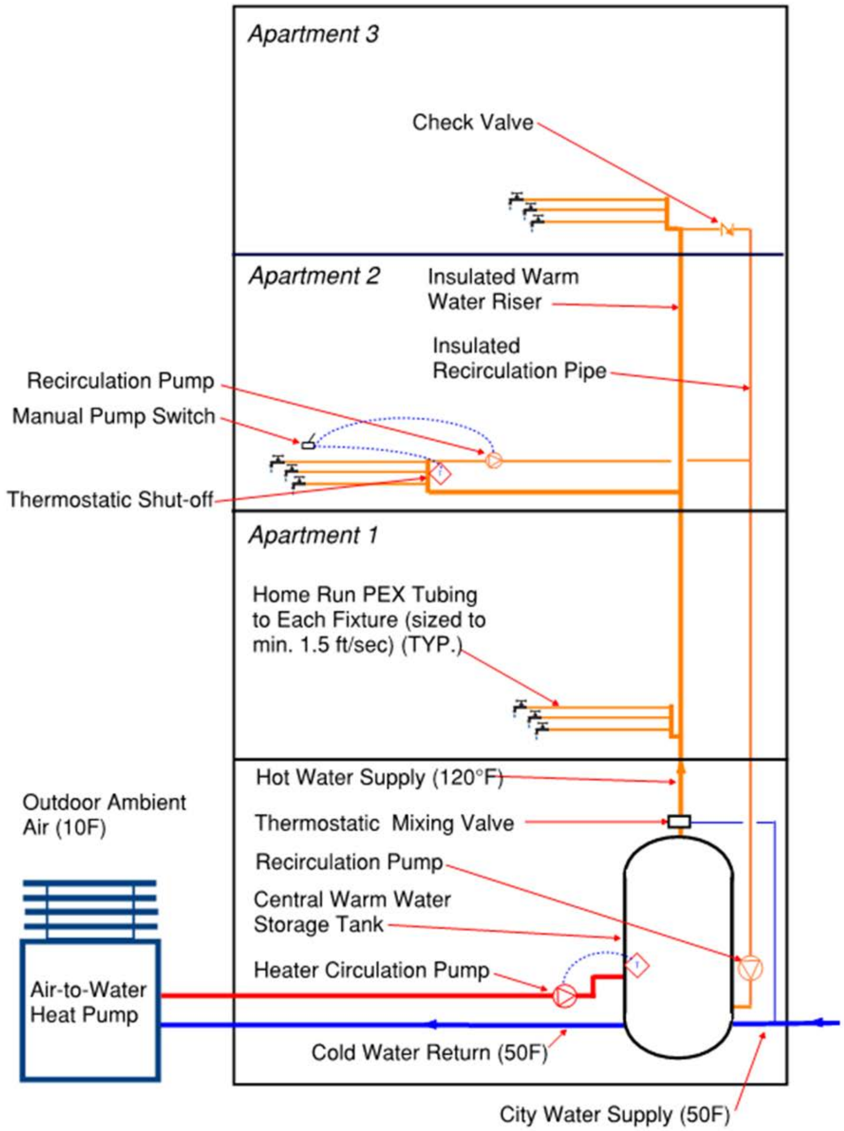


Figure 5-53 (WH6) Central Domestic Water Heating Distribution System Layout with Multiple-Pass Heat Pump

Return of lower temperature recirculated water to the hot water storage tank can have a detrimental effect on the performance of some types of heat pump water heaters. Heaters know has “single-pass” systems, typically have limited ability to reduce heating capacity (commonly referred to as “unloading”). These systems typically operate best with low temperature inlet water coming directly from the street and operate less efficiently and with a higher supply temperature when inlet water temperature is elevated. As mentioned previously, multi-pass heat pump water heaters are better able to deal with the temperature maintenance. The configuration for a single pass heat pump system is shown in Figure 5-54. A buffer tank is used to receive the returning recirculated hot water, preventing elevation of the water temperature at the bottom of the main storage tank. The heat pump runs only when hot water is flowing to fixtures and cold water is introduced to the tank from the street supply. When no water is used and the recirculation pump is operating, the temperature of the water in the buffer tank slowly falls, but since the temperature at the top of the tank is maintained at a minimum of 140°F by the central heater during usage periods in order to avoid biological growth, a lengthy period of non-usage is required to drop the temperature of the buffer tank below the desired supply temperature.

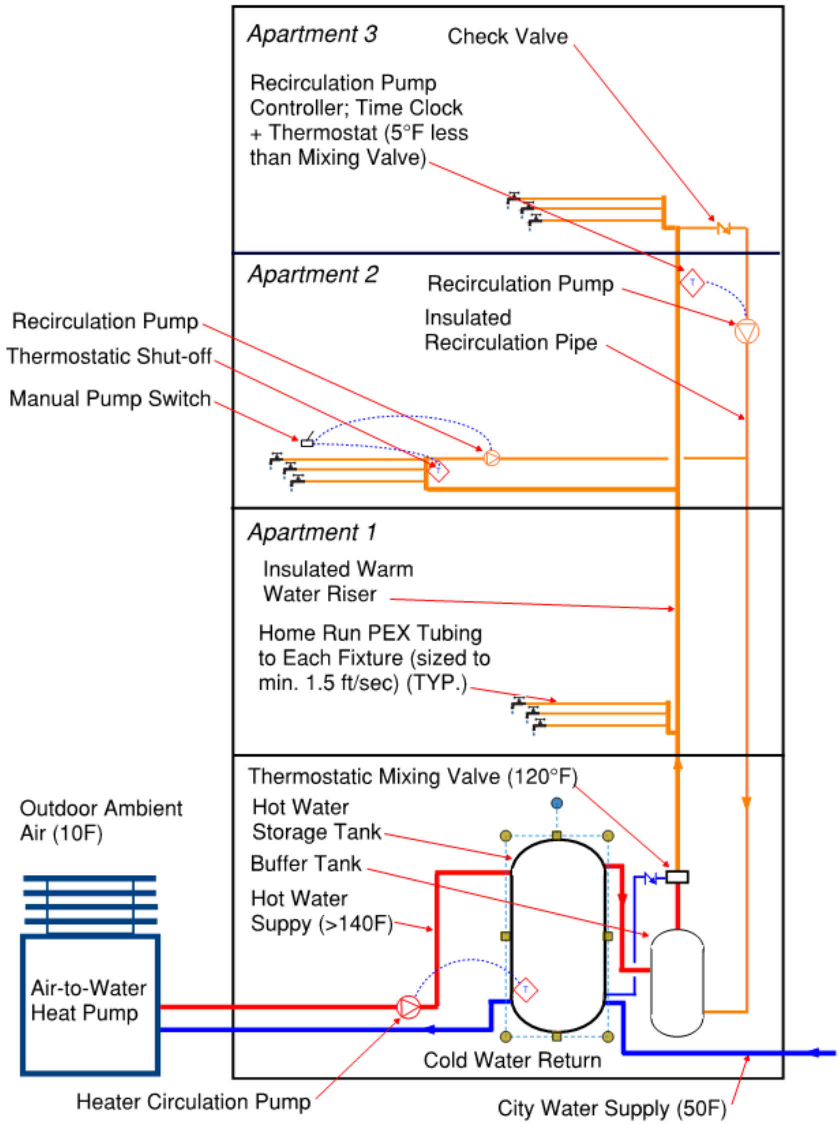


Figure 5-54 (WH6) Central Domestic Water Heating Distribution System Layout with Single -Pass Heat Pump

Tank storage design is another key element of a high-efficiency heat pump water heating system, as the ability of the tank to properly stratify plays a key role in achieving the promised high efficiencies of heat pumps. Consider the use of water diffusers within the tank to reduce mixing and increase the likelihood of stratification. Overall piping configuration also plays a strong role in tank stratification. Single pass heat pumps can have the heat pump hot water supply return to the top of the storage tank, as the delivered water temperature is always at the desired tank storage tank temperature. For multi-pass heat pumps, the heat pump piping connections should occur in the bottom 1/3 or the tank. This strategy helps reduce destratification of the storage tank. Consider the use of hydronic diffusers within the tank to further reduce destratification

WH8 Solar Hot-Water Systems

Simple solar systems are most efficient when they generate heat at low temperatures. Because of the high hot-water demands associated with dwelling units, solar hot-water systems are often viewed as important strategies in reducing energy bills. However, solar thermal systems compete for roof space with solar PV panels, which typically fill the majority of the roof area in a zero energy multifamily building. Solar PV panels can offset the electricity use of heat pump water heaters and pair better with them. Solar thermal systems are best paired with condensing gas-fired water heaters.

General suggestions for solar hot water systems include the following:

- It is typically not economical to design solar systems to satisfy the full annual domestic water heating load
- Systems are typically most economical if they furnish 50%–80% of the annual load. A larger solar fraction likely means that the system must reject heat at times because the water storage has reached maximum temperature.
- Properly sized systems will meet the full load on the best solar day of the year.
- Approximately 1–2 gal of storage should be provided per square foot of collector.
- 1 ft2 of collector heats about 1 gal per day of domestric water at 44° latitude.
- Glazed flat plate systems often cost in the range of $100–$150 per square foot of collector.
- Collectors do not have to face due south. They receive 94% of the maximum annual solar energy if they are 45° east or west of due south.

The optimal collector tilt for domestic water heating applications is approximately equal to the latitude where the building is located; however, variations of ±20° only reduce the total energy collected by about 5%. This is one reason that many collector installations are flat to a pitched roof instead of being supported on stands.

The optimal collector tilt for building heating (not domestic water heating) systems is approximately the latitude of the building plus 15°.

Collectors can still function on cloudy days to varying degrees depending on the design, but they perform better in direct sunlight; collectors should not be placed in areas that are frequently shaded.

Solar systems in most climates require freeze protection. The two common types of freeze protection are systems that contain antifreeze and drainback systems.

Drainback solar hot-water systems are often selected in small applications where the piping can be sloped back toward a collection tank. By draining the collection loop, freeze protection is accomplished when the pump shuts down, either intentionally or unintentionally. This avoids the heat-transfer penalties of antifreeze solutions.

Closed-loop, freeze-resistant solar systems should be used when piping layouts make drainback systems impractical.

In both systems, a pump circulates water or antifreeze solution through the collection loop when there is adequate solar radiation and a need for domestic water heat.

Solar collectors for domestic water heating applications are usually flat plate or evacuated-tube type. Flat plate units are typically less expensive. Evacuated-tube designs can produce higher temperatures because they have less standby loss, but they also can pack with snow and, if fluid flow stops, are more likely to reach temperatures that can degrade antifreeze solutions

The insulation should be protected from damage and should include a vapor retarder on the outside of the insulation.

As mentioned earlier, solar thermal systems do not always work well with heat pump water heaters. Heat pump water heaters see their highest efficiency when they have a high temperature difference across their heat exchangers. Because solar thermal systems are typically designed as a "pre-heat" strategy, they reduce the temperature difference across the heat exchangers, thus reducing the efficiency of the heat pump over all. This can be even more problematic with CO2 based heat pump water heaters, which are designed as single-pass heat pumps. They are unable to achieve their required minimum lift in water temperature when the entering water temperature is too high. This causes the units to trip-out with a hot gas warning. Repeatedly cycling in this manner can cause serious damage to the units and dramatically reduce the system efficiency.

REFERENCES AND RESOURCES

ASHRAE. 2019. ANSI/ASHRAE/IES Standard 90.1-2019, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASPE. 1988. *Temperature limits in service hot water systems*. RF Report 88-01. Rosemont, IL: American Society of Plumbing Engineers Research Foundation.

CEE. 2008. CEE high efficiency specifications for commercial dishwashers. Energy Efficiency Program Library. Boston: Consortium for Energy Efficiency. https://library.cee1.org/content/cee-high-efficiency-specifications-commercial-dishwashers/.

EPA. n.d. WaterSense. Washington, DC: United States Environmental Protection Agency. https://www.epa.gov/watersense.

EPA. 2019. ENERGY STAR overview. Washington, DC: U.S. Environmental Protection Agency. https://www.energystar.gov/about.

ICC. 2018. *International green construction code* (IgCC), Powered by ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2017. Washington, DC: International Code Council.

EIA 2015. Residential Energy Consumption Survey. https://www.eia.gov/consumption/residential/

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, water recirculation, and outdoor air ventilation. This section includes guidance for common HVAC system types, and other general HVAC guidance, regardless of the types of systems used. Common best practices are expected and where misapplication or misuse would greatly affect the outcome, guidance is given. It is important to note that the HVAC systems chosen are common, readily available systems, this is purposeful in that the guide is meant to be used in multiple climates and for experienced and inexperienced design teams. Therefore, systems that are only applicable to one climate, building type or design experience have not been considered.

HV1 Human Comfort for Residential Buildings

A primary purpose of HVAC systems for all buildings is to enhance human comfort within the building when outdoor conditions are outside the boundaries that are considered comfortable. For residential buildings, especially when systems are under the direct control of individuals, maintaining indoor conditions may have a wider latitude than for some other occupancies, such as offices or schools. The impact of elevated velocity of airflow across the human body has long been recognized as a means of achieving comfort with higher allowable indoor air temperature and humidity levels. Figure 5-55 (source: ASHRAE Standard 55-2017) demonstrates this impact. For residential buildings, increased air velocity can easily be achieved with low energy consumption using various types of ceiling fans. These fans are designed to create a large field of relatively low velocity airflow, such that areas of both intense draft and stagnation are avoided. The result is improved comfort at higher indoor air and surface temperatures and decreased energy consumption for comfort cooling.

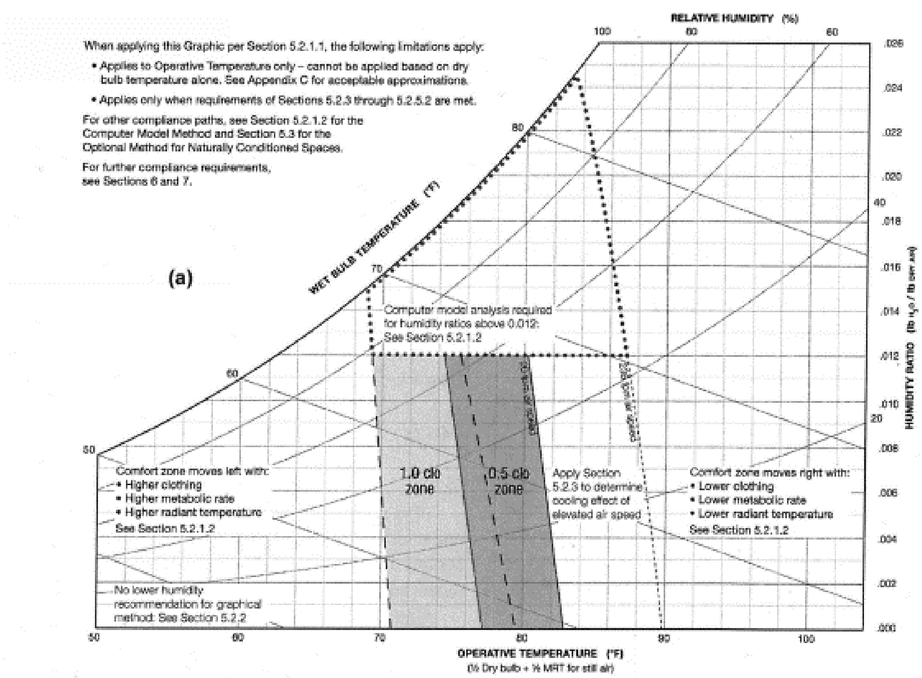


Figure 5-55 (HV1) Comfort Zone Showing Impact of Increase Air Speed Across the Body

Source: ASHRAE Standard 55-2017

ASHRAE Standard 55 incorporates a method of assessing comfort in naturally ventilated spaces that results in higher allowable operative temperature limits for naturally conditioned spaces when outdoor temperatures are higher as shown in Figure 5-56.

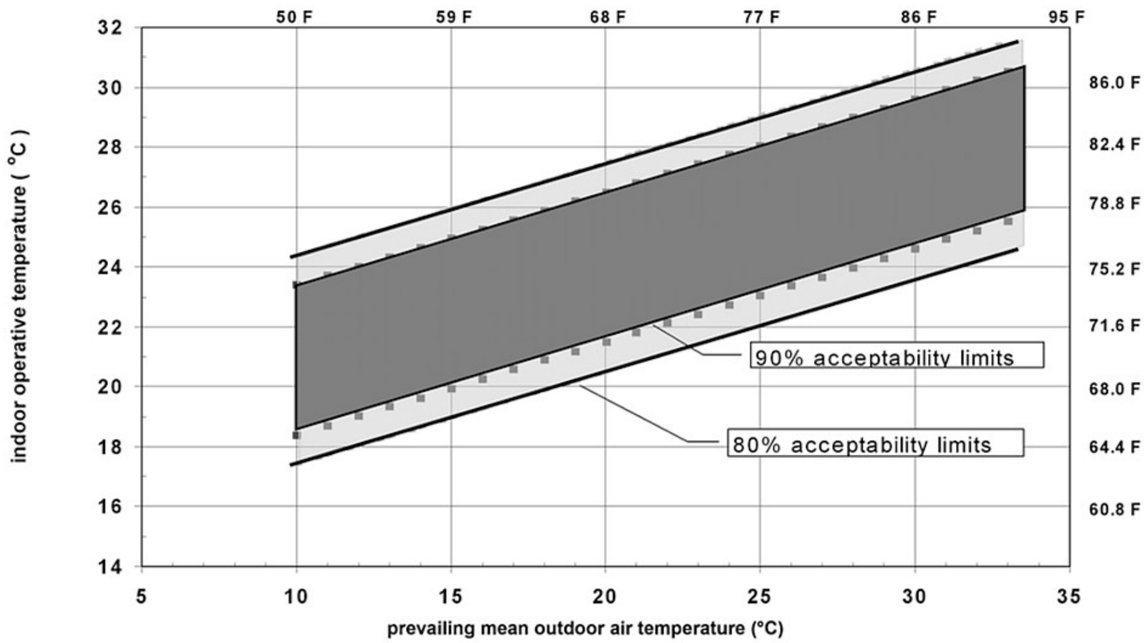


Figure 5-56 (HV1) Comfort Zone Showing Impact of Outdoor Air Temperature

While the impact of this effect is difficult to incorporate into automatic comfort controls, users of the space, when they aware and motivated to help achieve the Zero Energy goal, can incorporate this strategy into the operation of the HVAC systems in their dwellings.

SYSTEM DESCRIPTIONS

HV2 Systems for Building Common Spaces

The most economical way to address HVAC in the common space areas will be to tie them into the same overall system used for the dwelling units. Common spaces may however have additional requirements depending on the spaces served. Small retail areas may have kitchen services and the need for additional make up air and kitchen ventilation. A gym may have similar requirements. Hallways, typically, will require sensible cooling only and have minimal loads. Stairwells, in buildings classified as high-rise, also have the requirement for smoke exhaust in the case of fire. This may be tied into the HVAC system, or a separate system altogether. For the concept of zero energy building, we have included the HVAC systems in the overall systems for the whole building.

HV3 System Descriptions for Dwelling Units

Several different types of HVAC systems used in multifamily buildings are discussed in this Guide. System selection depends on building configuration, owner preference, zone configuration, and the magnitude of the loads to be served. It is important to recognize that zero energy is achievable with commonly available system types such as those recommended in this

Guide, in order to encourage zero energy adoption for a larger audience of building owners. Systems considered in this Guide are as follows:

- System A—Airsource Heat Pump Multisplit
- System B –Watersource Heat Pump (WSHP)
- System C—Four Pipe Hydronic Systems

All systems described in this guide incorporate a dedicated outdoor air system (DOAS). Design guidance for DOAS are provided in HV20.

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.

Table 5-20 (HV3) Minimum Efficiency Recommendations by System Type

SYSTEM A – AIR SOURCE HEAT PUMP MULTISPLIT	
Air-source VRF multisplit (cooling mode)[3]	< 65,000 Btu/h; 20.0 SEER;
	> 65,000 Btu/h and < 135,000 Btu/h; 13.1 EER; 15 IEER*
	> 135,000 Btu/h and < 240,000 Btu/h; 11.0 EER; 14.0 IEER*
	< 240,000 Btu/h; 10.5 EER; 12.8 IEER*
Air-source VRF multisplit (Heating Mode)[3]	< 65,000 Btu/h; 14 HSPF*
	> 65,000 Btu/h and < 135,000 Btu/h; 3.7 COP*
	> 135,000 Btu/h and < 240,000 Btu/h; 3.2 COP*
Terminal Fan	ECM fans and < 0.38 W/CFM at Design
SYSTEM B – WATER SOURCE HEAT PUMP (WSHP)	
WSHP with Boiler/Closed Circuit Cooler	
WSHP Cooling Efficiency	>18.2 EER at 86°F entering water temperature
WSHP Heating Efficiency	>5.4 COP at 68°F entering water temperature
Terminal Fan	ECM fans and <0.38 W/cfm at design
Compressor capacity control	VSD compressor
Water circulation pumps	VSD and NEMA premium efficiency <20W/gpm at design
Cooling tower/fluid cooler	VSD on fans
Boiler efficiency	Condensing boiler, >94% efficiency (include measures to maintain part load efficiency)
Ground Source Heat Pump (GSHP)	
GSHP Cooling Efficiency	>25 EER at 59°F entering water temperature
GSHP Heating Efficiency	>5 COP at 50°F entering water temperature
Terminal Fan	ECM fan and <0.38 W/cfm at design
Compressor capacity control	VSD compressor

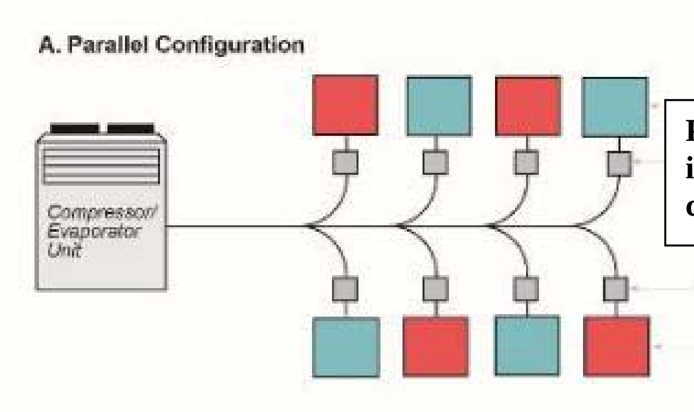
Water circulation pumps	VSD and NEMA premium efficiency <20W/gpm at design
Water Source Variable Refrigerant Flow	
Cooling Efficiency	>20 EER at 86°F entering water temperature
WSHP Heating Efficiency	>6.0 COP at 68°F entering water temperature
Terminal Fan	ECM fans and <0.38 W/cfm at design
Compressor capacity control	VSD compressor
Water circulation pumps	VSD and NEMA premium efficiency <20W/gpm at design
SYSTEM C – FOUR PIPE HYDRONIC SYSTEMS	
Air-source heat pump chiller efficiency	< 150 tons; 11.5 EER; 15 IPLV @ AHRI Conditions
	< 150 tons; 15 EER; 18 NPLV @ 55°F Chilled Water
Heating Efficiency	>3.5 COP @ 45°F Outdoor Air Drybulb Temperature 110°F Hot Water Supply Temperature
Compressor capacity control	VSD compressor
Water circulation pumps	VSD and NEMA premium efficiency <20W/gpm at design
Terminal Fan	ECM fans and < 0.38 W/CFM at Design
Boiler Efficiency (only as back up heating)	Condensing boiler, >92% efficiency
DEDICATED OUTDOOR AIR SYSTEM	
Air Cooled DX Efficiency	> 5.2 ISMRE @AHRI 920 Conditions
Compressor Capacity Control	Multi-stage or VSD compressor Minimum Turndown ≤ 20% of compressor capacity
Supply Fan	Minimum Turndown ≤ 30% of design flow
Exhaust Energy Recovery[3]	A (humid) zones and C (marine) zones : 72% enthalpy reduction; B (dry) zones: 72% dry-bulb temperature reduction
DX Heat Pump	> 3.8 ISCOP @AHRI 920 Conditions
Gas Heat	Gas Heat AFUE > 84%, modulating

* *Minimum recommended levels, 1) Certification with ISO standards, 2) AHRI Standards,*

SYSTEM A— AIR SOURCE HEAT PUMP MULTISPLIT

HV4 Description—System A

This system is comprised of a fancoil in each thermal zone with air source heat pump units located outside the occupied space. This type of equipment is available in pre-established 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 5-57 and recommendations for the system are shown in Table 5-21.



Picture to be edited to 3 indoor units and all to be in cooling or heating, not both

Figure 5-57 (HV4) System A—Air Source Heat Pump Multisplit

Attributes that distinguish multisplits systems from other DX system types are multiple indoor units connected to a common outdoor unit to achieve scalability, variable capacity, distributed control (ASHRAE 2016b). The advantage is the ability to have individual zone control and complete autonomy for operating and maintenance costs for each dwelling unit or leasable space.

Terminal units are typically installed in each conditioned space, either in the space or recessed in a ceiling cavity. 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.

Table 5-21 (HV4) Recommendations for System A—Air Source Heat Pump Multisplit

CZ	System Designation	System A Air Source Heat Pump Multisplit
1	Primary Mechanical Cooling source	Air-source DX
	First Stage Heating Source	Air-source DX
	Second Stage Heating Source	Not required
2	Primary Mechanical Cooling source	Air-source DX
	First Stage Heating Source	Air-source DX
	Second Stage Heating Source	Not required
3	Primary Mechanical Cooling source	Air-source DX
	First Stage Heating Source	Air-source DX
	Second Stage Heating Source	Not required
4	Primary Mechanical 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 Mechanical 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 Mechanical 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 Mechanical Cooling source	N/A
	First Stage Heating Source	N/A
	Second Stage Heating Source	N/A
8	Primary Mechanical Cooling source	N/A
	First Stage Heating Source	N/A
	Second Stage Heating Source	N/A

HV5 Sizing Indoor with Outdoor Units—System A

Outdoor units are sized based on the higher of the peak cooling load or the peak heating load. A provision for supplemental heating is needed in climate zones where the outdoor ambient heating design temperature routinely falls below –4°F and should be included in the sizing of the outdoor condenser systems. Derating of the outdoor systems also should 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. VSDs 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. Provision of dehumidified ventilation air to the unit reduces interior latent load and de creases total cooling capacity of the fan coil, even though it enables the unit to maintain a lower dew-point temperature in the space. (ASHRAE 2016a).

HV6 Refrigerant Safety—System A

All systems should comply with ANSI/ASHRAE Standard 15 (ASHRAE 2019c) to provide safeguards to protect occupants from the dangers of leaked refrigerants. This requirement is that the smallest space in which any indoor unit or piping is located has the ability to safely disperse the entire refrigerant charge of the multisplit system in the event of a leak or failure. Typical spaces that should be examined include bathrooms, small rooms, and closets if these are spaces are directly ducted from the system. For a multifamily structure that has just a few indoor units that serve just the common spaces, the concern is much less, however the calculations should be done regardless. 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 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.

Long piping runs for this system can be avoided by attention to this issue early in the design phase. The strategy of serving a single dwelling unit with multiple outdoor condensers each with a set of indoor units can sometimes reduce both piping lengths and the amount of refrigerant contained within the system.

HV7 Ambient Condition Considerations—System A

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 require design considerations for low ambient conditions. These considerations could include 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 that commonly have ambient temperatures below -4°F typically require a back-up heating system. This system 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. Additionally, the sizing of the outdoor air-source condensers need to take into account the capacity during defrost. While these are often sized for the cooling load requirements, a check to ensure enough capacity will exist during a heat cycle and a defrost cycle is necessary. In some climates this may require slightly larger capacities. Alternatively, in heating dominated climates, installation with louvers, or indoors is often considered to help during the low ambient conditions. Whether installing the system indoors or using a defrost cycle, considerations for heating during low ambient air conditions should be a part of the design. Alternatively, a water-source unit may be considered, details on this system are included in system B – Water source heat pumps.

SYSTEM B— WATER SOURCE HEAT PUMP WITH BOILER/CLOSED CIRCUIT COOLER AND WATER SOURCE VRF

HV8 Overview—System B

A WSHP system can be a set of water to air or water to refrigerant heat pumps that are attached to either a closed circuit cooler and a boiler or an exterior ground coupled heat exchanger. Both were examined for this guide. An exterior ground coupled heat exchanger could be either a vertical borehole with a vertical U-tube, a horizontal trench with buried coils of tubing, or coils of tubing submerged in a surface water feature, along with a circulating pump and connection to the water-source heat pumps. Recommendations for System B are shown in Table 5-22.

In systems where a ground loop is used, the ground loop eliminates the need for boiler/cooling tower maintenance and chemical treatment, services that owners must contract to multiple service vendors. The noise source of a cooling tower is removed, along with the hazard of a boiler. These advantages must be evaluated against the added cost of the ground heat exchanger.

Table 5-22 (HV8) Recommendations for Zone Terminal Systems with DOAS

CZ	System Designation	System B Water Source Heat Pump
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

A single water to air heat pump is likely to be installed for each dwelling unit. Ducting from that unit to a few areas would provide adequate cooling or heating for each space. In the case of a water to refrigerant multi-split, a few indoor zones can be piped to each water source unit, giving additional control in several areas of the dwelling unit. This may be considered a high end benefit that tenants are willing to pay more for.

A WSHP system offers several other advantages for multifamily buildings. Since the overall rejection of heat is to a common condenser system (the ground or the boiler/tower system) heat can be exchanged between units and improve energy efficiency of the overall building. Buildings in the most southern climates (CZ 1&2) may find they have no need for a boiler to be installed at all and can save on capital cost. A disadvantage for WSHP systems in cold climates utilizing a boiler as make-up heat source is that often all zones require heat simultaneously, so that no heat recovery is possible. As a result, energy must be provided for the make-up heat for the circulating loop and energy must be provided for the heat pump to convey the heat from the loop to the occupied space, significantly increasing the amount of energy required to deliver space heating

HV9 Types of Ground-Source Heat Pump Systems

The simplest system utilizes multiple single package water-source heat pumps that are connected to the ground via the 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 pre-established 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. This system employs a compressorized or “outdoor” unit that is connected to the ground circulating loop and multiple fan coils in the zones connected with 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 and cooling), the smaller of the two load modes may be met with very little additional energy consumption. While this system is beneficial for many types of buildings, it may not be cost-effective in residential buildings where simultaneous heating and cooling in different zones rarely occurs. Depending upon 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 Dedicated Outdoor Air Systems (DOAS) to manage ventilation. Heat pump units within the DOAS to condition ventilation air may also be connected to the ground loop. See HV13 Dedicated Outdoor Systems for additional information.

One further 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 further advantage that no refrigerant is conveyed through the conditioned space, enabling the conditioning of very small volume spaces without a refrigerant purge system.

HV10 The Ground as an Annual Thermal Battery

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 variation 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 significantly fan energy compared with centralized air distribution because the pressure drop through the fan coils is significantly less than for central air handling units.

The water piping loop allows heat transfer between the heat pump units and the ground. For these systems, the mass of ground that is thermally coupled to the heat exchanger, acts as an annual thermal battery. During the heating season, heat is extracted from the ground by supplying the heat exchangers with water that has been cooled below ambient ground temperature.   The ground warms this water, increasing its temperature before it is circulated back through the heat pump unit where it is chilled again. The heat pump unit conveys the heat extracted from the water to the conditioned space for space heating. In the summer, the process works in reverse. Water that is warmer than the ambient ground temperature is pumped through the heat exchanger where it is cooled and then returns to the heat pump unit where it is again heated by the heat exchanger with heat that has been extracted from the conditioned space for space cooling.

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 a calculated parameter thermal diffusivity. 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.

HV11 Hybrid Ground-Coupled Systems

Hybrid heat pump systems are designed for use in climates where a conventional approach cannot achieve an annual thermal balance with the ground. In colder climates, annual storage of heat by collecting solar heat during the summer to lift the local ground temperature well above the normal level can be an effective strategy. This heat can then be extracted during the winter heating season by a conventional ground coupled heat pump system. Similarly, in warmer climates, a cooling tower could be used to dispose of the excess rejected heat from summer air-conditioning to diminish the amount of heat rejected into the ground and achieve an annual thermal balance with heat extracted for winter heating. Many installations in all climate zones can also benefit from a hybrid approach since it can save on the size of the ground loop where space is of concern. Completing an annual load balance and loop sizing calculation is necessary to make the right determination for each building type. This will help ensure the right size of loop is designed and the annual imbalance that occurs and needs to be corrected using a hybrid ground coupled system.

HV12 Water Piping and Pumping Strategies

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 will all effect the design efficiency. Good water quality is important to minimize fouling factor and avoid clogging of heat exchangers. A steel piping system will require chemical treatment to inhibit corrosion. The heat transfer fluid may be water with some additives, or it may be a water/anti-freeze mixture. Anti-freeze 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. Successfully designed piping systems that can reduce the total system pressure drop below 46 feet TDH flowing 3 GPM/ton are Graded as "A" by the ASHRAE HVAC Applications Handbook, 2015, Chapter 34. (ASHRAE 2015a)

Two water pumping strategies are most common, centrally pumped or distributed/decentralized pumped. The centrally pumped system should be configured with variable speed pumps and heat pump devices should be equipped with shut off 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), or 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 utilizes 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.

SYSTEM C—FOUR PIPE HYDRONIC SYSTEMS

HV13 Overview—System C

In this system, a separate fan coil, radiant panel or chilled beam unit is used for each thermal zone. Components are factory assembled and include heating and cooling coils, controls, and possibly OA and return air dampers. Fan coils will also include a fan and filter. Recommendations for System C are shown in Table 5-22.

Hydronic units are typically installed in each conditioned space, surface-mounted, recessed into a ceiling cavity, or in a closet or hallway adjacent to 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.

All the hydronic units are connected to a common water distribution system. Cooling is provided by a centralized water chiller or air-to-water heat pump operating in cooling mode. Heating is provided by either a centralized boiler, air-to-water heat pump in heating mode 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, and it may be more cost effective to use electric resistance heating or solar hot water heating in lieu of a hot-water heating system because of the minimal heating requirements.

Table 5-23 (HV13) Recommendations for Hydronic Fancoils or Radiant Panels

CZ	System Designation	System C Hydronic Fancoils
1	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chiller
	Second Stage Heating Source	Not required
2	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chillers
	Second Stage Heating Source	Not required
3	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chillers
	Second Stage Heating Source	Not required
4	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chillers
	Second Stage Heating Source	Not required
5	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chillers
	Second Stage Heating Source	Not required
6	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chillers
	Second Stage Heating Source	Supplemental boiler
7	Primary Cooling Source	Air-cooled chiller or air to water heat pump
	First Stage Heating Source	Heat pump chillers
	Second Stage Heating Source	Supplemental boiler
8	Primary Cooling Source	Not required
	First Stage Heating Source	Boiler
	Second Stage Heating Source	Supplemental boiler

OA for ventilation is conditioned and delivered by a separate DOAS system. This system may involve ducting the OA directly to each fan coil or each active chilled beam, or, for radiant panels, separately ducting it directly to the occupied spaces. Depending on the climate, the DOAS unit may include components to filter, cool, heat, dehumidify, and/or humidify the outdoor air.

The primary difference between systems that utilize fan coils and systems that utilize radiant panels or chilled beams is that fan coils can assist the outdoor ventilation airflow from the DOAS in providing humidity control for the dwelling unit, while for radiant and chilled beam systems, all dehumidification must be provided by the ventilation airflow. Section VR19 discusses success factors for radiant systems.

HV14 Chilled Water Equipment

The cooling equipment, heating equipment, and fans should meet or exceed the efficiency levels in Table 5-20.

Chillers should include variable speed drives 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 multi-family residential buildings considering water-cooled chillers should follow the ASHRAE Green Guide (2018a)

HV15 Hot Water Equipment

Hot water for space heating for hydronic terminal units used in System C can be either air-to-water heat pumps or condensing boilers. With either type of equipment, the terminal units should be selected for the lowest possible supply temperature consistent with a reasonable delta-T across the equipment. In general, that means selected heating coils that are more robust (more rows and/or more fins per inch) than conventional selections. In general, the efficiency of air-to water heat pumps is increased by lowering the supply hot water as much as possible, while the efficiency of condensing boilers is more sensitive to the return hot water temperature.

Some types of ai-to-water heat pumps and some types of condensing boilers benefit from the installation of a buffer tank to allow heat delivery to the space to be provided at a lower part load than the heating equipment can provide. Some air-to-water heat pumps are unable to operate at low part load, during low temperature ambient conditions, while supplying the required hot water supply temperature. These heat pumps benefit from a buffer tank that allows them to operate intermittently at a high part load, while the hot water supply system operates continuously at a low part load. Similarly, condensing boilers may require more excess outdoor combustion to sustain firing rates less than 20% of full load. In a condensing boiler, additional excess combustion air lowers the dew-point temperature of the products of combustion, decreasing the amount of latent heat that can be harvested and decreasing the efficiency of the boiler. Buffer tanks will allow the boilers to operate intermittently at a sufficiently high firing rate than flame quality can be maintained with a relatively low excess air rate.

Part load considerations would direct the designer to size the hot water supply system based upon an accurate calculation of the required capacity without excessive safety factors and to configure the supply system as multiple units to allow lower part loads to be delivered efficiently

Given the electrification trend in the design of zero energy buildings, a designer selecting a fossil fuel fired condensing boiler should configure the hot water supply system to be consistent with later substitution of an air-to-water heat pump. These considerations would include the supply hot water temperature required by the heating delivery system, the size of the buffer tank and the size of electrical service to the building

HV16 Variable Primary Flow

Careful consideration to reducing the pump energy on2 and 4 pipe hydronic systems is critical to achieving the lowest EUI possible. Variable speed pumps in a chiller system offer significant operating costs savings as the pumps will be optimized to respond to the changing load conditions. Chillers should be selected for large turn-down in chilled water flow to enable pump energy savings are low part load conditions. To optimize pump energy savings reset the differential pressure to maintain discharge air temperature at the terminal units or air handlers with at least one control value in a fully open condition. This strategy will provide adequate flow to every unit while achieving pump savings at low load conditions (ASHRAE 2015b).

HV17 Two Pipe vs. 4 Pipe Considerations

The benefit of a two pipe system is the reduced first cost of installation. Two-pipe distribution requires that the system have a changeover between heating and cooling. Some systems can accomplish this within a few hours allowing a cool morning to have the building in heating, while a warm afternoon the building can provide heating. However, the thermal mass of systems with extensive piping may prevent diurnal changeover, without energy inefficient reheating or recooling of water during the changeover process. Many multifamily spaces are well suited to a two pipe installation as operable windows also aid in the comfort of building occupants and the range of temperatures acceptable to tenants is larger, allowing the time-period between changeover events to be sufficiently long that the circulating water can return naturally to a neutral temperature between changeovers. . In CZ 8, a two pipe system supplying heat only with no cooling would be considered very common. A four pipe system can provide heating and cooling to different zones of the building simultaneously. On a cool clear day, tenants on one side of the building may have excess solar load, requiring cooling, while tenants on the other side of the building, in shadow, may require heating. A four pipe system has the ability to satisfy all tenants. Combined with a heat pump system that can recover the heat will provide a highly efficiency system.

HV18 Ambient Condition Considerations for air source chillers—System C

Air source chillers with heat pump or heat recovery cycles are a good option for multifamily installations, in many climate zones, because they offer the ability to provide heating and cooling from one piece of equipment without the need of a secondary system for heating such as a boiler. CZ 6, 7, and 8 will likely require a supplemental boiler system due to the heating load requirement. In addition to the heating load requirement, air source systems require a defrost cycle during which heating may be limited or unavailable. These systems are commonly rated to 20F or 0F depending on the manufacturer, and capacity at these lower temperatures should be taken into account for sizing the supplemental boiler. (see HV7 for similar considerations)

HV19 Radiant heating and cooling Success Factors—System C

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. These systems typically improve comfort by maintaining the Mean Radiant Temperature (MRT) in the space closer to the air temperature than do all-air systems. 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.

Figure 5-53 (HV19) Radiant System in Multifamily

Radiant heating and cooling systems do not ventilate or dehumidify. They are coupled with a DOAS to provide outdoor 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, even with a relatively low maximum allowable surface temperature..

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. Radiant ceilings can also be created by embedding polymeric tubing in floor slabs to thermally activate both sides of the slab. 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.

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. In general, space-air thermostats should never be used to control capacity or change-over for these systems. Instead, the slabs should be controlled to maintain a setpoint temperature and that setpoint temperature should be reset slowly, based on operative temperature averages over a longer span of time. Heating and cooling changeover is much more of a concern in these systems because of the thermal mass in which the tubing is embedded. The time constant for these slabs often exceeds 24 hours, precluding diurnal changeover. 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. 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). Other useful resources include ASHRAE Handbook: HVAC Applications - 2019, Chapter 55, Radiant Heating and Cooling and ASHRAE Handbook: HVAC Systems and Equipment – 2016, Chapter 6, Radiant Heating and Cooling

DEDICATED OUTDOOR AIR SYSTEMS

HV20 System Overview—DOAS

There are many advantages of using a dedicated outdoor air system (DOAS) with a zero energy multifamily residential building. DOASs can simplify ventilation control and design, improve humidity control, and provide improved indoor air quality. DOASs primarily reduce energy use in three ways:

- They allow heat recovery to reduce required conditioning of incoming outdoor ventilation air
- With constant-volume zone units (heat pumps, fan-coils), they allow the unit to cycle with load without interrupting ventilation airflow.
- They decouple sensible cooling from humidity control, allowing more optimal energy efficiency for each of these tasks.

DOAS systems can be either centralized, serving multiple dwelling units, or individual, each unit serving a single dwelling unit. A DOAS 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.

The choice between a centralized DOAS system serving multiple dwelling unit or individual units each serving a single dwelling unit is dependent on building design and designer preference. However centralized DOAS systems can be susceptible to long duct runs and pressure drop must be watched to achieve the low energy design of this system. Further information on best practices for duct design should follow the ASHRAE Handbook of Fundamentals (ASHRAE 2017d)

Table 5-26 (HV20) Recommendations for DOAS

CZ	Compatible Systems	Air Source Heat Pump Multisplit	Ground Source Heat Pump	4 Pipe Hydronic
		SYSTEM A	**SYSTEM B**	**SYSTEM C**
	Primary Cooling source	Air Source DX	Water source DX w/ supplemental cooling tower	Air Cooled Chiller or Heat Pump Chiller
	First Stage Heating Source	Exhaust Energy Recovery	Exhaust Energy Recovery	Exhaust Energy Recovery
	Second Stage Heating Source	Not Required	Not Required	Not Required
2	Primary Cooling source	Air Source DX	Water source DX w/ supplemental cooling tower	Air Cooled Chiller or Heat Pump Chiller
	First Stage Heating Source	Exhaust Energy Recovery	Exhaust Energy Recovery	Exhaust Energy Recovery
	Second Stage Heating Source	Optional Air Source DX	Ground Source DX	Electric resistance heat (opt)
3	Primary Cooling source	Air Source DX	Ground Source DX with optional supplemental cooling tower	Air Cooled Chiller or Heat Pump Chiller
	First Stage Heating Source	Exhaust Energy Recovery (Not Required Region 3C)	Exhaust Energy Recovery (Not Required Region 3C)	Exhaust Energy Recovery (Not Required Region 3C)
	Second Stage Heating Source	Air Source DX	Ground source DX	Condensing Boiler
4	Primary Cooling source	Air Source DX	Ground source DX	Air Cooled Chiller or Heat Pump Chiller
	First Stage Heating Source	Exhaust Energy Recovery	Exhaust Energy Recovery	Exhaust Energy Recovery
	Second Stage Heating Source	Air Source DX	Ground source DX	Condensing Boiler
5	Primary Cooling source	Air Source DX	Ground source DX	Air Cooled Chiller or Heat Pump Chiller
	First Stage Heating Source	Exhaust Energy Recovery	Exhaust Energy Recovery	Exhaust Energy Recovery
	Second Stage Heating Source	Air Source DX	Ground source DX	Hydronic Heating Coil

CZ	Compatible Systems	Air Source Heat Pump Multisplit	Ground Source Heat Pump	4 Pipe Hydronic
		SYSTEM A	**SYSTEM B**	**SYSTEM C**
6	Primary Cooling source	Air Source DX	Ground source DX	Air Cooled Chiller or Heat Pump Chiller
	First Stage Heating Source	Exhaust Energy Recovery	Exhaust Energy Recovery	Exhaust Energy Recovery
	Second Stage Heating Source	Air Source DX + Supplemental Electric Resistance	Ground source DX	Condensing Boiler
7	Primary Cooling source	NA	Ground Source DX	Air Cooled Chiller
	First Stage Heating Source	NA	Exhaust Energy Recovery	Exhaust Energy Recovery
	Second Stage Heating Source	NA	Ground Source DX w/ Supplemental Boiler	Condensing Boiler
8	Primary Cooling source	NA	NA	Air Cooled Chiller (opt)
	First Stage Heating Source	NA	NA	Exhaust Energy Recovery
	Second Stage Heating Source	NA	NA	Condensing Boiler

A DOAS includes two ductwork systems, one to supply outdoor air to the dwelling unit and the other to exhaust air from the dwelling unit. The system may be variable flow if exhaust rates are also variable as could happen with intermittent enhanced kitchen or bathroom exhaust. Typically, bathroom and kitchen exhaust are routed to the heat recovery system, while exhaust from clothes dryers is not. Where possible, DOAS units should be located within the building thermal envelope to maximize the available roof area for solar systems.

There are many possible DOAS configurations (see Figure 5-59 for a few typical ones).

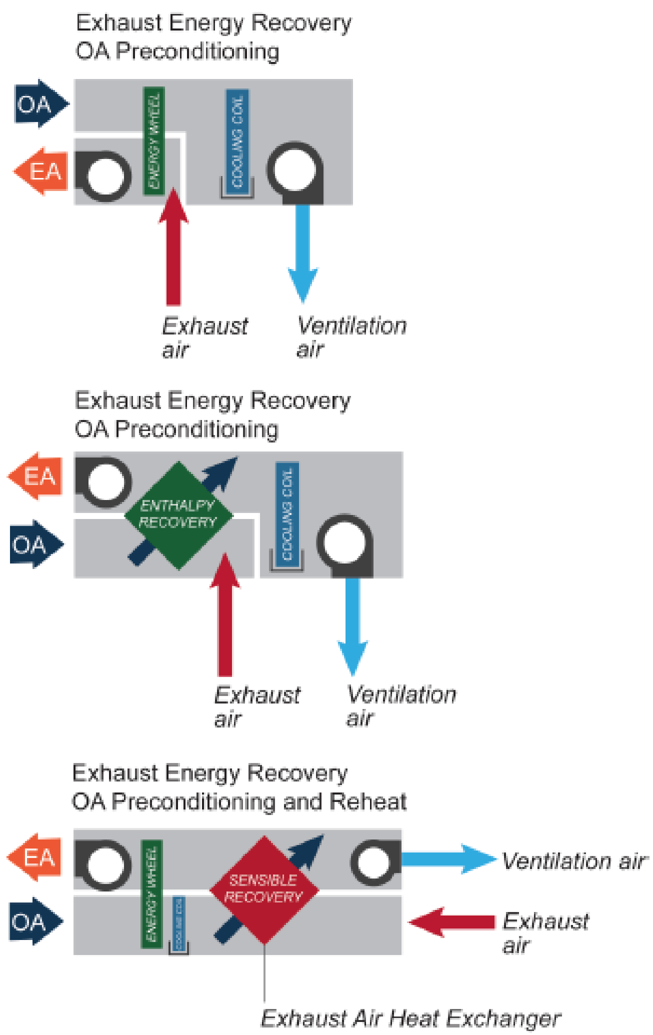


Figure 5-59 (HV22) Example Exhaust Air Energy Recovery Configurations

HV21 Sizing a DOAS for Dehumidification

A DOAS should be configured so that it does not introduce any latent load into the dwelling unit. Typically, sensible loads in dwelling units in zero energy buildings are very low, while internal latent loads may be only slightly affected. As a result, during cooling season in humid climates, the space conditioning systems in these buildings may suffer from a low sensible cooling ratio, resulting in a high interior dew-point temperature. Increasing the interior latent load by introducing outdoor air at a dew-point higher than the target interior value serves only to make this problem worse. Dehumidifying the outdoor ventilation air to a dew-point temperature below 55°F (the dewpoint temperature of 75°F, 50% RH air) will reduce the interior latent load, increasing the sensible heat ratio and enabling better humidity control in the dwelling. Typically, latent loads in residences, including cooking, bathing, in addition to occupants, are too high to be offset just by the ventilation airstream, even if it is dehumidified to a low dew-point temperature. Sharing the dehumidification load between the DOAS-supplied ventilation air and the indoor conditioning system is the best way to insure effective humidity control for all, except arid, climates.

HV22 Air Delivery for Zone-Level Ventilation

The most important aspect of delivering ventilation air to the dwelling units is to insure that the air is well distributed and that no spaces are stagnant. Not only will stagnant areas lead to poor indoor air quality in those spaces, but it could also lead to inadequate dehumidification in those areas. The most effective way to insure good distribution is to locate ventilation air inlets and exhaust outlets such that the air traverses the entire space while moving from the inlet to the outlet, avoiding “short-circuits” that leave much of he area unventilated. The two primary areas for exhaust outlets from the space will be bathrooms and kitchens, so ventilation air inlets should be located in other spaces, such as across the bedroom from the bathroom, or across the living room from the kitchen. While internal airflow from fan coils likely will produce much mixing of the ventilation air in the space, improper location of inlets with respect to outlets can still result in inadequate ventilation for some areas of the dwelling unit.

HV23 Discharge Air Temperature Control for DOAS

Conditioned outdoor air delivery to dwelling units can offer significant comfort challenges especially during cool humid periods. Dehumidification of air requires that the air be cooled to below the desired dewpoint temperature of the conditioned space. During cool rainy or damp; weather (60°F - 70°F) dehumidification of the ventilation air is critical, especially because sensible cooling loads to the space will be reduced. Delivery of air to the space at 54°F to 58°F however (target dewpoint temperature of the space is between 56°F and 60°F) may result in discomfort due to drafts. Three techniques can successfully overcome this discomfort issue:

1. Delivering outdoor air to the space through a fan coil, such that the outdoor air is mixed with recirculating room air to raise the temperature of the mixed supply air that is delivered to the space, thus avoiding cold air drafts.
2. Passive reheat of the cold, dehumidified ventilation air using sensible heat recovery (as shown in the bottom diagram in Figure 5-59). This strategy removes heat from the exhaust air and uses that heat to warm the cold air leaving the coil, resulting in a low dewpoint temperature and higher dry bulb temperature for the ventilation air delivered to the space. Because the exhaust air is precooled by the sensible heat exchanger, the enthalpy wheel provides transfers additional energy and further reduces the load on the cooling coil.
3. Hot gas reheat takes hot refrigerant from the compressor and through a separate coil, tempers the dehumidified ventilation air. By recycling heat from the compressor, no additional energy is used by the system to warm the cold air leaving the cooling coil. It stops the system from having to employ a secondary heating source. A modulating hot gas reheat system is even more efficient by not using any more heat than is necessary and potentially overheating the outdoor air and provides more precise temperature control.

When dehumidification of the ventilation air is delivered to the space is not required, the delivery dry-bulb temperature should be kept neutral, (between 65°F and 70°F) to minimize conflicts with the space conditioning system and its setpoints.

HV24 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 minimize cross-leakage of the intake and exhaust airstreams. For rotary heat exchangers, minimizing cross-leakage 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. Continuous exhaust from both kitchens and bathrooms should be routed to the DOAS for heat recovery. Residential kitchen exhaust is not considered “grease” exhaust and therefore does not have the stringent requirements of commercial kitchen exhaust.

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).

HV25 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 dewpoint 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. As shown in Figure 5-64, buildings with very high performance envelope systems often have a very low balance point temperature, requiring cooling even when the outdoor ambient dry bulb temperature is as low as 40°F. Energy recovery in the heating mode can be controlled to allow the ventilation air dry bulb temperature to fall as low as 60°F, when free cooling is required, without danger of causing discomfort drafts. If warmer 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).

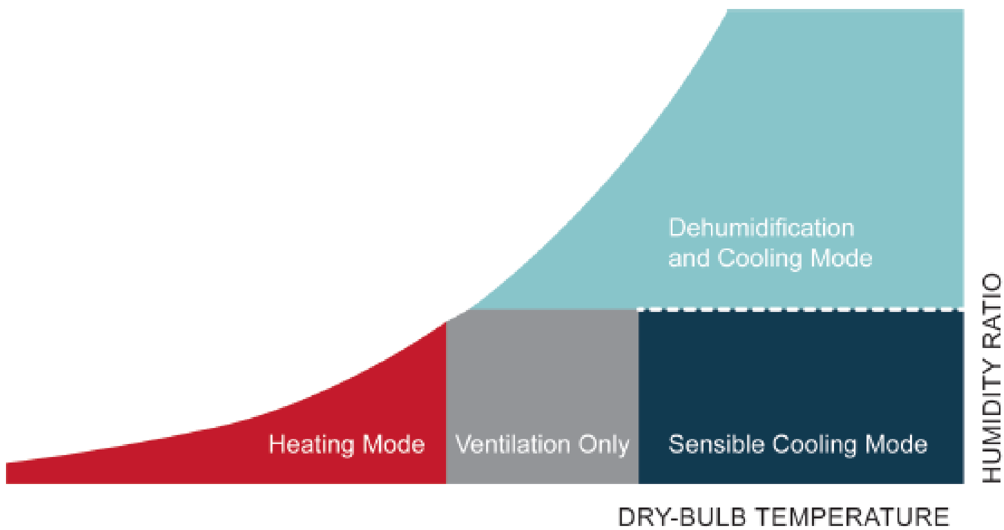


Figure 5-60 (HV25) DOAS Unit Control Modes

Adapted from Figure 5.3, ASHRAE 2017a

Table 5-27 (HV25) 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

HV26 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) such that it adds no latent load to the dwelling paces. 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. For systems with sensible-only cooling devices (radiant), it is critical to keep the space below the required dew point to prevent condensation from forming. One caveat: use caution when resetting the DOAS supply air dew point upward during humid weather season. Warmer s air leaving the cooling coil 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 dwelling unit exceeds 60%. If SAT reset is used, include one or more zone humidity sensors to disable the reset if the relative humidity within the dwelling unit exceeds 60%.

HV25 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, or 62.2 depending upon the building type 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 62.1or 62.2 (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.

Exhaust systems for most residential projects should include both continuous exhaust for kitchens and bathrooms and intermittent exhaust for kitchen range hoods and bathroom showers. These intermittent exhaust systems should be interlocked with dampers in the ventilation system to allow greater ventilation airflow for exhaust make-up when these exhaust systems are activated. In most cases, the designer could assume that the intermittent bathroom exhaust and the kitchen range exhaust were not operating simultaneously, so that only two stages of ventilation air deliver are required.

HV27 Exhaust Air Systems

Zone exhaust airflows (for bathrooms and kitchens) should be determined based on the most recent edition of ASHRAE Standard 62.1 or 62.2, but should not be less than the values required by local code unless approved by the authority having jurisdiction. Each dwelling unit should be provided with a continuous exhaust system meeting the minimum requirements and may be provided with supplemental exhaust in the form of a range hood or additional bathroom exhaust.

Central exhaust systems for dwelling units should operate continuously. 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. For residential applications, the exhaust system will run continuously. Design exhaust ductwork to facilitate energy recovery from exhaust taken from spaces. The exhaust fan must have variable-speed capability to deal with varying pressure drops across the filters used to protect the energy recovery devices and with intermittent exhaust requirements.

Incremental supplemental exhaust provisions may be provided for both bathrooms and kitchens to improve indoor air quality and to avoid excess humidity. These supplemental exhausts should be activated by a manual on-off timer switch with a maximum run time of 30 minutes or less to avoid the problem of the intermittent exhaust running unsupervised for long periods of time. The supplemental exhaust s may be provided with individual local fans, discharging into the main exhaust shaft, or they may be served by an enlarged local ductwork feeder with a two-position damper activated by the control switch. In either case, the main exhaust fan is controlled to maintain a constant static pressure setpoint in the exhaust shaft.

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. The building envelope should be sealed properly (see EN27 through EN29) so the HVAC system and DOAS unit can work effectively.

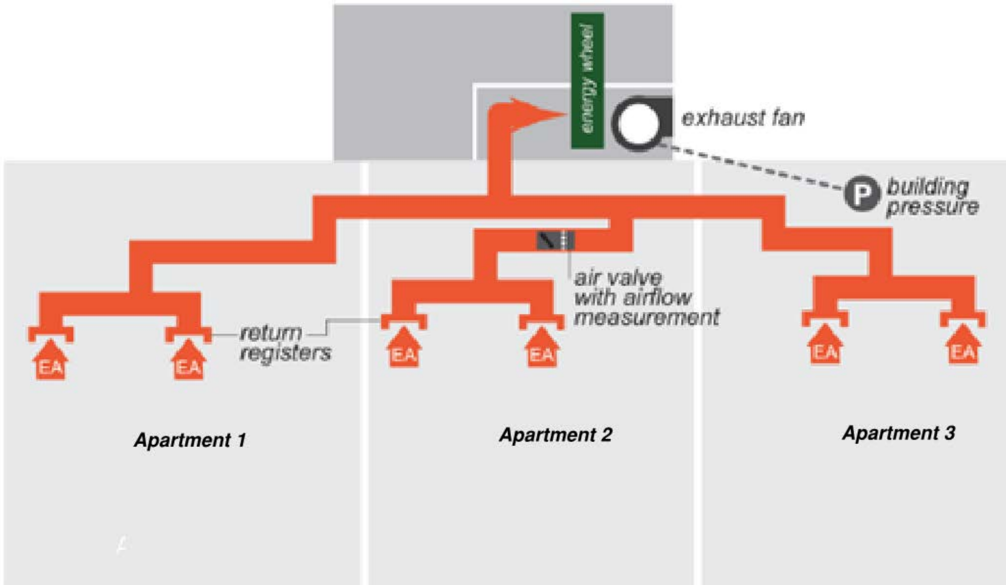


Figure 5-61 (HV27) Exhaust Air Measurement

HV28 Kitchen Exhaust Hoods

The primary purpose of residential kitchen hoods is to improve indoor air quality in the residence. Kitchen hoods are of two varieties, recirculating and exhausting. Recirculating hoods pass a large volume of air through a filter to remove some contaminants generated by the cooking process. Exhausting hoods should be configured to capture as much as possible of the convective updraft from the cooktop using minimum of exhaust air to remove those contaminants entirely from the dwelling unit.

The recirculating hood is suitable for use only with electric cooktops, and not for gas-fired cooktops, because the filtering elements in the recirculating hood do not remove carbon monoxide that may be generated by a gas-fired device. The recirculating hoods also do not remove steam, presenting difficulties in humid climate zones. In general, recirculating hoods utilize filters to remove particulates and some organic vapors. The two most common types of filters are activated charcoal (carbon) or aluminum mesh. Activated charcoal filters provide the best removal of contaminants generated by the cooking process but must be replaced every few months. Aluminum mesh filters can be washed and re-used but only remove the largest suspended grease particles and are ineffective against odors.

Exhausting hoods should also be equipped with an aluminum mesh filter to prevent large grease particles from entering the exhaust duct and ultimately contaminating the energy recovery wheel on the Dedicated Outdoor Air System (DOAS). Exhausting hoods typically move less air than recirculating hoods and thus are more sensitive to placement with respect to the cooktop and to other air sources in the kitchen.

The residential kitchen hood should be located over the cooktop to catch heat, vapors, smoke and steam generated by the cooking process. To achieve these ends, good capture of hot air rising from the cooktop is a must. Several design factors improve hood capture. These include:

- Location of the cooktop against a wall, instead of in an island, such that airflow into the hood is from 3 sides rather than 4.
- Location of the hood directly on the back wall to avoid a pathway for hot gases to rise up past the hood.
- Selection of a hood that extends out above the front heating elements of the cooktop
- Location of air conditioning diffusers in the kitchen such that they do not interfere with the upward buoyant plumes rising off the cooktop.
- Use of a cooktop, such as an induction cooktop or electric resistance element cooktop that concentrates heat delivery into the container holding the food with minimal heat bypassing the container into the space.

The minimum required flow rate for a vented range hood in ASHRAE Standard 62.2-2019 is 100 cfm. This flow rate should be adequate for use with low-heat cooktops (induction), assuming that the kitchen and cooktop ar arranged to maximize hood capture.

HV28 Energy Recovery Frost Control

Energy recovery heat exchangers have a risk of frosting, especially a concern for climate zones 4–8. Frosting occurs when the exhaust air is cooled below the dew-point temperature. 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 residential space 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 should be preheated to –3°F (not 32°F) to prevent frosting.

Note that utilization of supplemental exhaust systems for bathrooms and kitchens will result in greater exhaust airflow and lower relative humidity of the exhaust air, resulting in less need for defrosting of the energy recovery device

Table 5-28 (HV28) Example Frost Point for Energy
(with 75% Total Effectiveness and 70°F Space Conditions)

Exhaust Air Relative Humidity	Outdoor Air Temperature
40%	5°F
30%	-3°F
20%	-14°F
15%	-22°F

HV29 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.

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 HV21.

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.

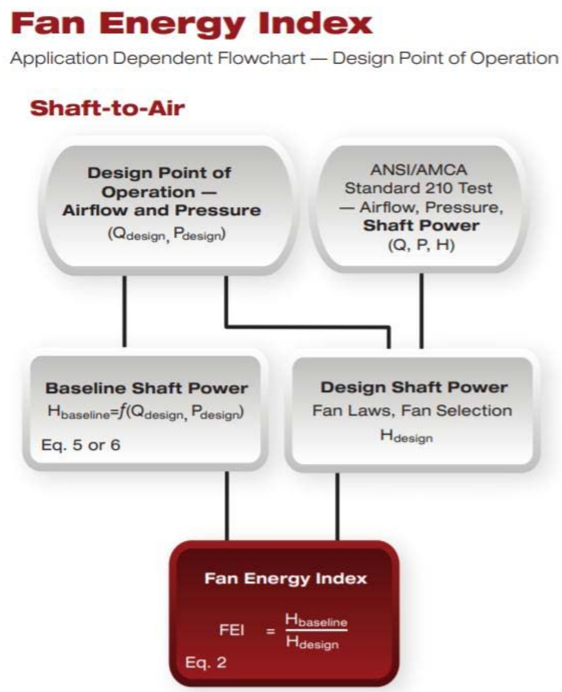
Indirect evaporative coolers should be selected for at least 90% evaporative effectiveness for the evaporatively cooled airstream and for at least 65% heat transfer efficiency between the two airstreams.

Indirect evaporative coolers should also be selected to minimize air pressure drop through the heat exchangers.

HVAC TIPS FOR ALL SYSTEM TYPES

HV30 Fan Selection

Fans, when separately selected and individually rated, should be selected for premium efficiency using the Fan Energy Index (FEI) as described in ANSI/AMCA Standard 208-18, Calculation of the Fan Energy Index (AMCA 2018). This metric has been included in ASHRAE Standard 90.1-2019 and included in an addendum to ASHRAE Standard 189.1-2017. To be consistent with the zero energy design goal, fan selection should follow section 7.4.3.6.2 Fan Efficiency, which requires a FEI at the design point of 1.10 or greater. FEI is defined according the equation shown in Figure 5-61, extracted from “Introducing the Fan Energy Index”, An AMCA International White Paper, AMCA International, 2016. The metric ensures that fans are selected for near optimal efficiency based upon pressure rise across the fan and airflow rate.



$$FEI = \frac{\text{Baseline Fan Electrical Input Power}}{\text{Fan Electrical Input Power}} \quad \textbf{Eq. 2}$$

For fans tested with ducted discharge:

$$H_{baseline} = \frac{(Q + Q_0)(P_t + P_0)}{6343 \times \eta_{t,target}} \quad \textbf{Eq. 5}$$

For fans tested without a ducted discharge:

$$H_{baseline} = \frac{(Q + Q_0)(P_s + P_0)}{6343 \times \eta_{s,target}} \quad \textbf{Eq. 6}$$

Figure 5-62 (HV31) Fan Energy Index Calculation

HV31 Energy Efficient Electric Motors

Electric motors are key components for the successful and energy efficient operation of HVAC systems. Historically, the motor of choice, large or small, for these systems has been the induction motor. For larger, three-phase motors, solid state “soft” starters and variable frequency drives have enabled this motor type to be the motor of choice for the most systems with the highest energy efficiency aspirations. For smaller, single-phase motors, electronically commutated motors (ECMs), now offer the energy efficiency and longevity advantages previously only available in large motors. ECMs also offer the advantage of inherent energy efficient variable speed operation, facilitating the implementation of variable volume and variable flow system. Improvements in efficiency and reliability of these motors have also increased the attractiveness of systems and components previously burdened by the shortcomings of single-phase induction motors. These systems and components include fan coils, both refrigerant and electric, parallel fan-powered terminals and small circulating pumps.

HV32 Rightsize Equipment (GA) (RS) (RT)

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, as knowledge concerning loads becomes more complete and accurate, the need for safety factors decreases. 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. Diversity within a residential occupancy primarily will apply to estimations of heat gain from cooking, exhaust and make-up airflow requirements for demand -controlled exhaust for kitchen hoods and bathrooms. 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 requirement 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 Decentralized Systems and Multi-tenant Issues

A common practice in commercial buildings is to provide a night setback or other unoccupied mode setbacks to save heating and cooling energy when a space is not occupied (see HV35). This is more difficult in a multi-family building as it requires each tenant to adhere to unoccupied setbacks on decentralized equipment and an overall building control strategy is not employable here. Furthermore, tenants may not be aware of other energy use throughout their space either when the space is occupied or unoccupied. System controls that alert each occupant as to their energy habits, daily, monthly and annually will be required to achieve energy savings as designed. A reward system that encourages positive behaviors will further allow the building to achieve its energy targets. These are often in the form of tokens that can be exchanged for rewards such as laundry cycles or other building amenities. These systems need to take into account all the areas that occupants are responsible for such as plug loads (HV XX), HVAC set points (HV35) and ventilation including the opportunity to use natural ventilation through operable windows (HV39)

HV34 Thermal Zoning (RS) (CC)

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 such as the common areas of the multifamily structure. Spaces that may be common gathering spaces such as gyms and party rooms may want to be consolidated to one area or floor. This minimizes the equipment needed to operate and limit the DOAS unit ventilation air supplied during these periods.

HV35 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. This is more difficult to achieve in individual spaces (see HV33), however system level controls are convenient for common areas.

Controlling energy usage is most successful when the usage culture can be changed. This requires education and continued engagement of the building residents. See also the *Engage and Educate Occupants* section of Chapter 3.

Control systems should include the following:

- Control sequences that easily can be understood and commissioned.
- A user interface that facilitates understanding and editing of system operating parameters and schedules.
- 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.

HV36 Employing Proper Maintenance in Multi-tenant Structure

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. The difficulty with Multifamily dwellings includes the number of occupants or tenants that need to be trained on the operation and maintenance of the dwelling unit systems. The owner or tenant will need access to detailed O&M system manual and be required to continue to update themselves on their equipment. 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.

HV37 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.

HV38 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). It is difficult to avoid installation of air-conditioning or heat pump units near occupied spaces as each space needs separate systems; however, locations above less critical spaces such as storage areas, corridors, etc. should be considered (see Figure 5-63). This may be considered in conjunction with HV 30 Employing proper maintenance as installation for maintenance may follow similar considerations to noise control.

Chapter 48 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015c) is a potential source for recommended background sound levels in the various building spaces. Residential spaces require high consideration of noise control as little noise is generated within the space and several hours of a typical daily occupancy would be designated for rest.

Systems where the compressor is located outside of the space will be best for noise considerations, this includes Systems A and C. Chilled beam and radiant panels with minimal air volumes would also eliminate noise from fan powered systems. Low sound options should be required for System B such as compressor blankets or insulated panels.

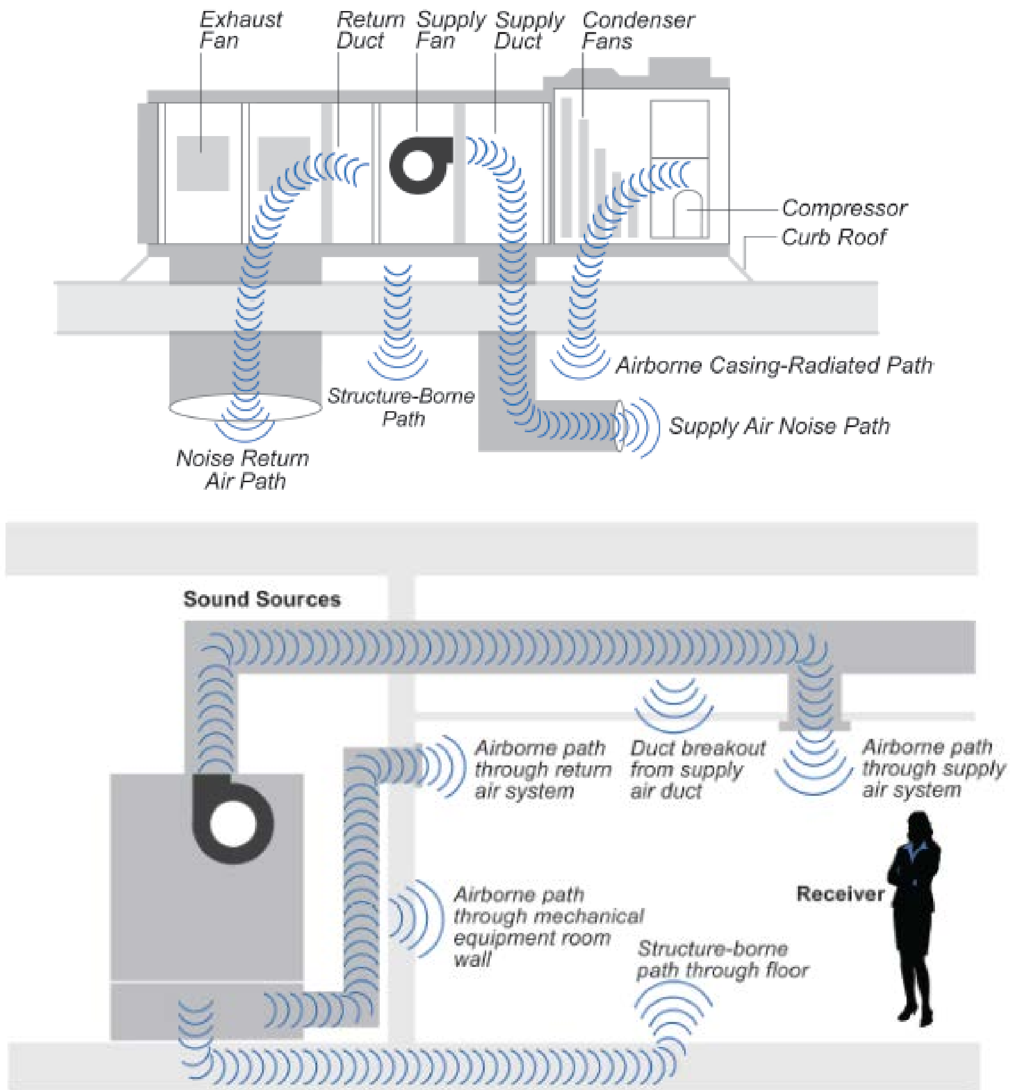


Figure 5-63 (HV38) Typical Noise Paths for Interior-Mounted HVAC Units

HV39 Natural Ventilation and Free Cooling (RS)

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. For multifamily residential buildings, operable windows, required in most locations by the building code provide the opportunity for natural free-cooling. A zero energy multifamily residential building should have a mechanical ventilation system to provide required ventilation flow, while utilizing energy recovery to minimize the energy required to condition the ventilation air.

Figure 5-64 shows how the balance point temperature of the dwelling unit decreases as the building envelope thermal performance increases. As a result, internal heat gains may require cooling even when the external dry-bulb temperature falls below 40°F. During these periods, natural free cooling is available merely by opening the windows. In some locations, outdoor noise may make operable windows undesirable, and operable through-wall vents with acoustical treatment may be required. In other locations, outdoor air quality may be unacceptable, and local regulations may prohibit operable windows. In that case, additional operable exhaust for kitchen and bathrooms can be utilized to provide free-cooling, but occupants must be educated how to make use of this resource.

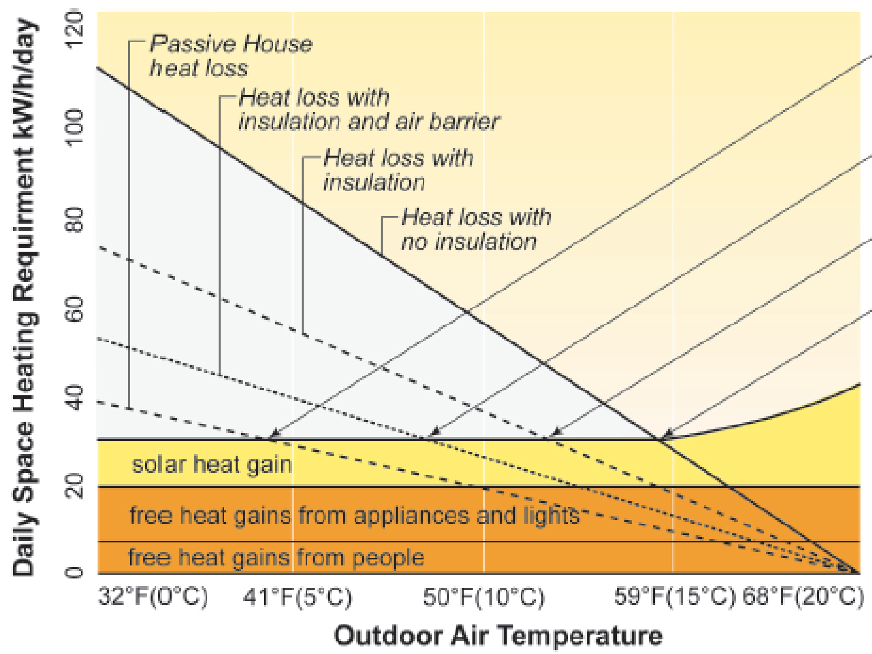


Figure 5-64 (HV39) Outdoor Air Balance Point Temperatures for Different Envelope Performance Levels

Natural ventilation through operable windows and operable vents in the building envelope can be a very effective energy-conservation strategy. In residential buildings, occupant comfort consideration usually ensure that the windows are operated in a fashion that effectively minimizes energy consumption. Clearly, excess outdoor air inflow to the building, when exterior conditionings are inopportune, increases building energy consumption, but the resulting discomfort likely will encourage occupants to close them

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 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.

THERMAL MASS

HV40 Thermal Mass Concept Overview (GA) (RS) (CC)

The thermal mass of the building structure can enhance the effectiveness of the building conditioning system in several ways, both to improve comfort and to reduce energy consumption by time-shifting and damping heating and cooling loads. The effectiveness of thermal mass in reducing peak heating and cooling loads is a function of how well the thermal mass is coupled to the interior environment. For example, a massive concrete floor slab is relatively ineffective as passive internal mass if it is covered on the top by deep carpeting and covered on the bottom with a porous acoustic absorption finish. Utilization of passive thermal mass both inside the building and external to the building thermal envelope is discussed extensively in EN9 through EN11.

HV41 Active versus Passive Thermal Mass (CC)

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. Sometimes, the air temperature variation necessary to charge or discharge the passive internal thermal mass pushes conditions outside of the desired comfort zone. An example of this effect would be overnight ventilation to cool internal mass. A sufficiently low air temperature to chill the internal mass might result in an unacceptably low interior temperature when the residents arise in the morning.

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. 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 dehumidifies, so that the ventilation air systems is required to meet all dehumidification needs. 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.

REFERENCES

AMCA. 2018. ANSI/AMCA Standard 208-18, Calculation of the Fan Energy Index, 2018, Air Movement and Control Association International Inc.

ASHRAE. 1995. *Commercial/institutional ground-source heat pump engineering manual*. Atlanta: ASHRAE.

ASHRAE. 2015a. Chapter 34, Geothermal energy. *ASHRAE handbook—HVAC applications*. Atlanta: ASHRAE.

ASHRAE. 2015b. Chapter 42, Supervisory control strategies and optimization. *ASHRAE handbook—HVAC applications*. Atlanta: ASHRAE.

ASHRAE. 2015c. Chapter 48, Noise and vibration control. *ASHRAE handbook—HVAC applications*. Atlanta: ASHRAE.

ASHRAE. 2016a. Chapter 18, Variable refrigerant flow. *ASHRAE handbook—HVAC systems and equipment*. Atlanta: ASHRAE.

ASHRAE. 2016b. ANSI/ASHRAE/IES Standard 90.1-2016, *Energy standard for buildings except low-rise residential buildings*. Atlanta: ASHRAE.

ASHRAE. 2016d. ANSI/ASHRAE Standard 62.1-2016, *Ventilation for acceptable indoor air quality*. Atlanta: ASHRAE.

ASHRAE. 2017a. ANSI/ASHRAE Standard 111-2008 (RA 2017), *Measurement, testing, adjusting, and balancing of building HVAC systems*. Atlanta: ASHRAE.

ASHRAE. 2017b. *ASHRAE design guide for dedicated outdoor air systems*. Atlanta: ASHRAE.

ASHRAE. 2017d. Chapter 21, Duct design. In *ASHRAE handbook—Fundamentals*. Atlanta: ASHRAE.

ASHRAE. 2018a. *ASHRAE GreenGuide: Design, construction, and operation of sustainable buildings*, 5th ed. Atlanta: ASHRAE.

Moffitt, R. 2015. Dedicated outdoor air system with dual energy recovery used with distributed sensible cooling equipment. Presented at the 2015 ASHRAE Annual Conference, June 27–July 1, Atlanta, Georgia.

Nall, D. 2013a. Thermally active floors, Part 1. *ASHRAE Journal* 55(1):32–46.

Nall, D. 2013b. Thermally active floors, Part 2: Design. *ASHRAE Journal* 55(2):36–46.

Nall, D. 2013c. Thermally active floors, Part 3: Making it work. *ASHRAE Journal* 55(1):54–61.

Shank, K., and S. Mumma. 2001. Selecting the supply air conditions for a dedicated outdoor air system working in parallel with distributed sensible cooling terminal equipment. *ASHRAE transactions* 107(1):562–71.

Watson, R. 2008. *Radiant heating and cooling handbook*. NY: McGraw Hill Companies, Inc.

Zhang, C., W. Yang, J. Yang, S. Wu, and Y. Chen. 2017. Experimental investigations and numerical simulation of thermal performance of a horizontal slinky-coil ground heat exchanger. *Sustainability* 9, 1362.

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. 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.

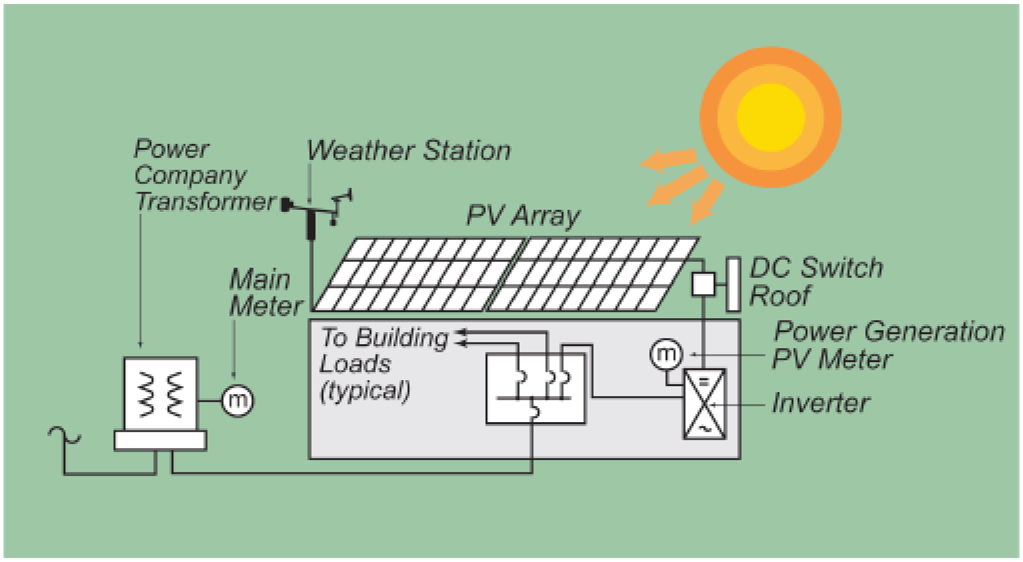


Figure 5-64 (RE1) Typical PV AC System Diagram

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 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.

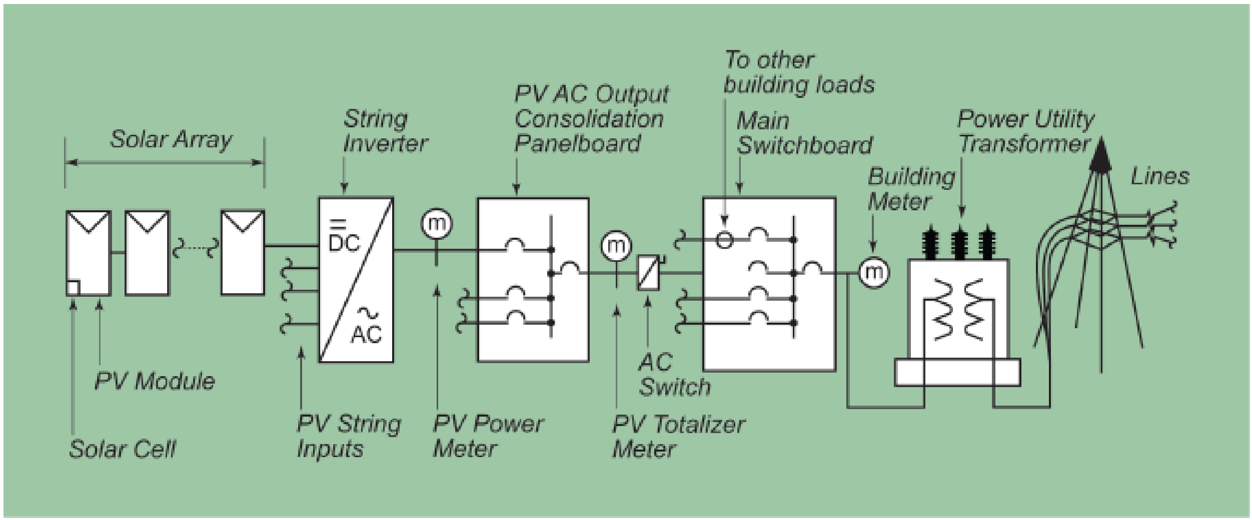


Figure 5-65 (RE1) Typical PV Single-Line Diagram

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 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 (GA) (RS)

PV panels are specified with two distinct guarantees: performance and manufacturing. Manufacturing guarantees are fairly self-explanatory. 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 information on calculating the amount of PV 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 (GA) (RS)

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. See also the *Grid Considerations and Energy Storage sidebar* in Chapter 2.

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/ft2 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**.**

Figure 5-66 (RE5) Ground-Mounted PV Installation
Photograph by Paul Torcellini, NREL 55603

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.

Figure 5-67 (RE5) Canopy-Mounted PV System
Used with Permission from CMTA, © Dish Design

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 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.

REFERENCES AND RESOURCES

EERE. 2019. *Wind energy basics*. Washington, DC: U.S. Department of Energy, Office ofEnergy Efficiency and Renewable Energy. https://www.energy.gov/eere/wind/windenergy-basics.

Fu, R., D. Chung, T. Lowder, D. Feldman, K. Ardani, and R. Margolis. 2016. *U.S. solar photovoltaic system cost benchmark: Q1 2016*. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy16osti/66532.pdf.

IEA. 2019. *2019 snapshot of global PV markets*. IEA PVPS, Task 1—Strategy PV Analysis and Outreach, Report IEA-PVPS T1-35: 2019. Paris: International Energy Agency. http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_T1_35_Snapshot2019-Report.pdf.

IWBI™. 2019. Certification links. WELL Building Standard™ v1. NY: International WELL Building Institute™. https://www.wellcertified.com/certification/v1/standard.

Jossi, F. 2017. Industry report: Midwest and Great Plains lead wind energy expansion. The Energy News Network, Midwest. http://midwestenergynews.com/2017/04/19/industryreport-midwest-and-great-plains-lead-wind-energy-expansion/.

Lisell, L., T. Tetreault, and A. Watson. 2009. *Solar ready buildings planning guide*. Technical Report NREL/TP-7A2-46078. https://www.nrel.gov/docs/fy10osti/46078.pdf.

NASA. 2019. How do photovoltaics work?. NASA Science webpage. Washington, DC: National Aeronautics and Space Administration. https://science.nasa.gov/science-news/science-at-nasa/2002/solarcells.

NREL. 2014. System Advisor Model (SAM). Golden, CO: National Renewable Energy Laboratory. https://sam.nrel.gov/.

NREL. 2019a. Net metering. State, Local, & Tribal Governments webpage. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/state-local-tribal/basicsnet-metering.html.

NREL. 2019b. PVWatts® Calculator. Golden, CO: National Renewable Energy Laboratory. http://pvwatts.nrel.gov/.

SEIA. 2019. Model Leases and PPAs. Washington, DC: Solar Energy Industry Association. https://www.seia.org/research-resources/model-leases-and-ppas.

SEIA. 2017. Solar Power Purchase Agreement template, ver. 2.0. Washington, DC: Solar Energy Industry Association. https://www.seia.org/sites/default/files/2017-10/SEIA%20C%2BI%20PPA%20v2.0.docx.

UL. 2016. UL 924, *Standard for emergency lighting and power equipment*. Northbrook, IL: UL LLC.

Watson, A., L. Giudice, L. Lisell, L. Doris, and S. Busche. 2012. *Solar ready: An overview of implementation practices*. Technical Report NREL/TP-7A40-51296. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy12osti/51296.pdf.

Appendix A Envelope Thermal Performance Factor

[Table will be updated prior to next review.]

The envelope information in the tables in the guide present 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 *ASHRAE Handbook—Fundamentals* (ASHRAE 20xx), and expanded U-factor, C-factor, and F-factor tables are presented in Appendix A of ASHRAE/IES Standard 90.1 (ASHRAE 20xx).

Alternate constructions found in ANSI/ASHRAE/IES Standard 90.1-2016, Appendix A provide an equivalent method for meeting the specifications of this Guide provided they are less than or equal to the thermal performance factors listed in Table A-1.

OPAQUE CONSTRUCTION OPTIONS					
Walls, Above Grade				**Roof Assemblies**	
R	**U**	**R**	**U**	**R**	**U**
Mass Walls		**Steel Framed**		**Insulation Above Deck**	
Wood Framed Walls					
				Slabs	
				R-in (vertical)	**F**
				Unheated	
				Heated-Fully Insulated	

Note: All information in this appendix is in Inch-Pound (IP) units. For Slabs, the "in" refers to the depth of the vertical slab edge insulation. See Standard 90.1 for additional explanation. All units used in the table are defined in the Abbreviations and Acronyms of the Guide.

Appendix B International Climatic Zone Definitions

ANSI/ASHRAE Standard 169-2013 has 60 pages of tables that indicate the Climate Zone for locations throughout the world. That information is reproduced in an Annex in ANSI/ASHRAE/IES 90.1-2016. Standard 169-2013 indicates that those are the climate zones that should be used for those locations. The methodology shown below is the climate zone definition for locations that are not provided in the standard and is from A3 Climate Zone Definitions. Weather data is needed in order to use the climate zone definitions for a particular city. Weather data for a number of cities in Canada and Mexico are available on the AEDG webpage (under Additional Information). Weather data by city are available for a large number of international cities on the 2013 Handbook-Fundamental CD.

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/Artic	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

Determine the moisture zone (Marine, Dry or Humid)

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 CDD50ºF $\leq$ 4500, climate zone is Marine (3C).
2. If thermal climate zone is 4 and CDD50ºF $\leq$ 2700, climate zone is Marine (4C).
3. If thermal climate zone is 5 and CDD50ºF $\leq$ 1800, climate zone is Marine (5d).

Marine (C) Zone Definition – Locations meeting all four of the following criteria:

a. Mean temperature of coldest month between 27°F (–3°C) and 65°F (18°C)

b. Warmest month mean < 72°F (22°C)

c. At least four months with mean temperatures over 50°F (10°C)

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 – 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, oF

Summer or high sign = April through September in the Northern Hemisphere and October through March in the Southern Hemisphere.

Period

Winter or cold season = October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

Humid (A) Definition – Locations that are not Marine (C) and not Dry (B).