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ZERO ENERGY

ACHIEVING ZERO ENERGY

Advanced Energy Design Guide for K–12 School Buildings

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

Advanced Energy Design Guide for K-12 School Buildings

Achieving Zero Energy

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

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Acknowledgments

The Advanced Energy Design Guide for K-12 School Buildings: Achieving Zero Energy is the first Advanced Energy Design Guide (AEDG) to provide strategies and recommendations for achieving a zero energy building; that is, a building that can produce as much on-site renewable energy as it consumes. This a monumental shift from the previous 50% Advanced Energy Design Guides as it shifts the paradigm that buildings must consume energy to one of balance between consumption and production. This guide is the result of many professionals spending countless hours to help advance energy efficiency in K–12 school facilities while enhancing the educational mission of schools.

The guide was primarily written by the 12 committee members of ASHRAE Special Project Committee 139 (SP-139) representing ASHRAE, the American Institute of Architects (AIA), the Illuminating Energy Society (IES), the U.S. Green Building Council (USGBC), and the U.S. Department of Energy (DOE).

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

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

The project committee met 4 times in person and held 24 conference calls over the course of the special project. The chair would especially like to thank the families of the committee members as their dedication to this project meant time away from family activities. In addition, the chair acknowledges the support from the project committee member's employers: the Arlington Public Schools, Virginia; ClimateCraft Inc.; CMTA Inc.; DEVITA; Eastern Connecticut State University; Eley Consulting; Harley Ellis Deveraux; IMEG, Corp; M.E. Group;

Owens Corning; National Renewable Energy Laboratory; Syska Hennessy Group; and Thrive Architecture.

The project committee's efforts were guided by the AEDG Steering Committee, consisting of members from the AEDG partnering organizations (AIA, ASHRAE, IES, USGBC) with support from DOE. These members provided the direction and guidance to complete the guide within 12 months. They provided the focus for the guide as well as an outstanding project committee to do the work. They also were a source of constant encouragement during the process.

In addition to the voting members of the project committee, a number of individuals played key roles in the guide's success. Specifically, thanks to the meeting staff at ASHRAE and Teri Spinuzzi at NREL for organizing meetings and providing meeting space and to Cindy Michaels for the final prepublication work on the document. In addition, thanks to Anoop Honnekeri and David Goldwasser of NREL for providing invaluable OpenStudio and EnergyPlus energy modeling support for the committee, and to Shanti Pless and Bill Livingood of NREL for their expertise and guidance.

Two open peer reviews were also conducted with more than 30 people participating in each review. Their comments, both at the 65% draft level and the 90% draft, provide valuable feedback for this first zero energy guide. They provided thoughtful input and insights that further strengthened this document and many of which are reflected in this final text.

Thanks also go out to the authors of the previous AEDGs that paved the way for this type of work. While this is the first zero energy guide, many of the thoughts, recommendations, and presentation have their roots in the 30% and 50% AEDG series. Using these templates helped to bring this guide to completion in a timely fashion.

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

The chair hopes that this guide provides inspiration to build zero energy schools and shifts buildings from consumers to producers of energy. It should provide confidence that zero energy is possible and not a dream, and that together we can change the way buildings use energy.

Paul Torcellini
Chair, Special Project 139

September 2017

Abbreviations and Acronyms

A/E	Architectural/engineering
AIA	American Institute of Architects
ASE	Annual sunlight exposure
ASTM	American Society for Testing and Materials
ANSI	American National Standards Institute
AWEF	Annual walk-in energy factor
BOD	Basis of design
BP	*Advanced Energy Design Guide* code for Building and Site Planning
Btu	British thermal unit
CD	Construction documents
CHW	Chilled water
c.i.	Continuous insulation
Cx	Commissioning
CxA	Commissioning authority
cfm	Cubic feet per minute
COP	Coefficient of performance, dimensionless
CRI	Color rendering index]
CRRC	Cool Roof Rating Council
db	Dry bulb, °F
DL	*Advanced Energy Design Guide* code for Daylighting
DOAS	Dedicated outdoor air system
DOE	Department of Energy (United States)
DX	Direct expansion
EA	Exhaust air
EC	Electronically commutated
ECM	Electronically commutated motor
EEV	Electronic expansion valves
EER	Energy efficiency ratio, Btu/W·h
EF	Energy factor
EIA	Energy Information Agency
Et	Efficiency, thermal
ETOP	Extended transition to operations
EL	*Advanced Energy Design Guide* code for Electric Lighting

EN	*Advanced Energy Design Guide* code for Envelope
EUI	Energy use intensity
F	Slab edge heat loss coefficient per foot of perimeter, Btu/h·ft·°F
FC	Filled cavity
FPT	Functional performance testing
GSHP	Ground-source heat pump
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
IES	Illuminating Engineering Society
IEER	Integrated energy efficiency ratio
IPLV	Integrated part load value
kBtu/h	Thousands of British thermal units per hour
KE	*Advanced Energy Design Guide* code for Kitchen Equipment
kW	Kilowatt
LBNL	Lawrence Berkeley National Laboratory
LED	Light emitting diode
LPD	Lighting power density, W/ft^2
Ls	Liner systems
NEMA	National Electrical Manufacturers Association
NFRC	National Fenestration Rating Council
NREL	National Energy Renewable Laboratory
NZEB	Net zero energy buildings
OA	Outdoor air
O&M	Operation and maintenance
OPR	Owner's project requirements
PF	Projection factor
PL	*Advanced Energy Design Guide* code for Plug Loads
ppm	Part per million
psf	Pounds per square foot
PV	Photovoltaic
QA	Quality assurance
R	Thermal resistance, $h \cdot ft^2 \cdot °F/Btu$
RE	*Advanced Energy Design Guide* code for Renewable Energy
SCT	Saturated condensing temperature
sDA	Spatial daylight autonomy
SEER	Seasonal energy efficiency ratio, Btu/W·h
SHGC	Solar heat gain coefficient
SP	Special project
SRI	Solar reflectance index
SWH	Service water heating
TAB	Test and balance
U	Thermal transmittance, $Btu/h \cdot ft^2 \cdot °F$
USGBC	U. S. Green Building Council
VSD	Variable-speed drive
VT	Visible transmittance, dimensionless
W	Watts
wb	Wet bulb
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
ZES	Zero energy school

Foreword: A Message to Administrators

By Jean-Claude Brizard

A few years ago I was invited to talk about Career and Technical Education (CTE) at the Association for Learning Environments' (A4LE) national conference in Portland, Oregon with two K–12 school architects, one in private practice, the other responsible for new schools in a rapidly growing suburban school district. The two architects talked a lot about how high performance learning environments, which are fundamental to this guide, contribute to teaching, learning, and student success. I confess that I had not previously given much thought to physical school design. After our talk, at the insistence of the two architects, we piled into a car and drove south to Mount Angel Seminary to visit the extraordinary library, one of the very few works in the United States by the 20th century Finnish architect Alvar Aalto. I walked in and exclaimed "now I understand what you were talking about!" The natural light flooding the central space from above, the views within the space and to the mountains beyond, the intimate scale of the spaces and the warmth of the natural finishes, together created delight in an environment where anyone of any age would want to settle in and learn.

I have always believed that the views of John Dewey's are the ones that all educators should embody—that students must interact with their environment in order to learn; that schools should employ an interdisciplinary curriculum, or a curriculum that focuses on connecting multiple subjects, where students are allowed to freely move in and out of classrooms as they pursue their interests and construct their own paths for acquiring and applying knowledge. In other words, a child-centered approach to education that places the emphasis of learning on the needs and interests of the child[1]**.** I have only spent time in one zero energy school, Discovery Elementary in Arlington, VA, but it is my opinion that what is being achieved there by the principal, the students, the parents, and the architecture/engineering team embodies these philosophies.

I had to ask myself if zero energy distinguishes what is going on in this school in any way from what is going on in other high performance schools with outstanding leadership and teachers. The answer, it seems, is that achieving zero energy the first year, and then every year thereafter, inspires the Discovery community around a common goal, so that even kindergartners grasp their role in achieving it. Discovery students are immensely proud that their school has achieved zero energy. They are steadfast in their love for their school, the curriculum that they are engaged with, and what it all means for the earth, their community, and their lives.

1. https://www.biography.com/people/john-dewey-9273497

"It's like going to a museum where you get to play, make and do things. We get to think!" commented an animated group of fourth graders I met.

I learned that zero energy prompted the Discovery team, with some help from students in a high school CTE program, to develop a new tool, the Energy Dashboard, to integrate teaching and learning with how the building responds to the natural environment around it. Recently, fifth grade students working on a biodiversity unit used the Energy Dashboard to ask questions, develop hypotheses, apply the scientific method to investigate their hypotheses, and generate recommendations. One group of students used the Dashboard to find out what the mean monthly energy production had been to date. They then wondered how energy consumption could be reduced. One recommendation they came up with was that students, teachers and staff turn lights off manually when leaving a room rather than leave them to turn off automatically, which would have, in their words, "no significant negative impact" on the school. Another group asked how energy could be saved in the HVAC system. They analyzed data from the Dashboard and found that HVAC use on the weekends was higher than expected given the lighter use of the building. So they wondered if it would be possible to further shut down or scale back the HVAC system at times when the building is less heavily occupied. A third group wondered about general energy reduction on weekends. The students used the Dashboard to come up with some very specific data, and were surprised at the amount of power being used by plug-in devices. Among other things, they wondered if the practice of unplugging devices before going home for the weekend each Friday could be instituted. These fifth grade students are in fact using the same data and asking exactly the same questions that the architecture/engineering/operations team asks as it continually seeks to improve the building's performance and reduce its energy consumption.

It is easy to see how the social emotional competencies of the school's 5th graders matched their academic tenacity. Dr. K. Brooke Stafford-Brizard outlines in the Building Blocks for Learning[1] that self-direction, curiosity and civic identity are the top pillars for learning. Civic identity is formally defined as a multifaceted and dynamic notion of the self as belonging to and responsible for a community or communities[2].

Schools like Discovery Elementary, with high-performance learning environments designed by first understanding a philosophy of the child at the center and as maker, a curriculum that is collaboratively created while responding to world-class standards, and a focus on building the eco-civic identity of students, will become a model from which we all can learn, copy, and replicate. Zero energy may not be essential to the success of such schools, but in the hands of creative, innovative educators it provides abundant opportunities for authentic, problem-, and project-based learning.

Jean-Claude Brizard is Partner and Vice President at Cross & Joftus where his work is focused on supporting schools and school systems across the country. He is the former Chief Executive of Chicago Public Schools and Rochester City (NY) Public Schools. He is a Fellow of the Broad Center, a Fellow of the third class of the Pahara-Aspen Institute Education Fellowship, and a member of the Aspen Global Leadership Network.

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Introduction

1

Zero energy buildings are about balance. Zero energy buildings are designed to balance low energy consumption with on-site renewable energy production to meet their entire energy loads over 12 months. Zero energy buildings are usually connected to the utility grid to provide 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 school.

The qualities of a zero energy school, and the process required to create it, can encourage student learning and student success, create healthy, high-performance learning environments, provide sound fiscal management of community resources, and demonstrate environmental leadership in minimizing the impact of the built environment.

WHY BUILD A ZERO ENERGY SCHOOL?

STUDENT LEARNING AND STUDENT SUCCESS

Teaching, learning and student success are the fundamental goals of educators. Zero energy schools support these goals by integrating learning, design, sustainability and environmental stewardship in a more comprehensive way than a typical high performance school by focusing the entire school community (students, teachers, staff and parents) on achieving and maintaining an achievable measurable goal—zero energy performance. As they learn how to collaborate with one another around zero energy, members of a zero energy school community may become advocates for sustainability and environmental stewardship beyond the school itself. The students themselves may become the lifelong advocates.

Student cognition is increased in healthy, high performance learning environments (Eitland et al.), and students learn more when they and their teachers are not absent for health reasons. Many of the key features of high performance learning environments described below also contribute to the low energy use intensity (EUI) required to achieve zero energy.

SOUND FISCAL MANAGEMENT

In many communities, public schools are among the greatest investments and treasured assets. Most public schools are maintained for the long term. Because they are coupled with inconsistent and often challenging annual school budgets and constantly rising energy costs;

reducing and controlling the operating costs of school buildings, particular energy and maintenance costs, is highly attractive. Zero energy schools can both reduce energy consumption dramatically and mitigate the risk of future energy cost volatility.

Funding, hiring, compensating, and retaining highly skilled maintenance technicians is challenging for many school districts. So the more durable and often less complex integrated heating, ventilating, air conditioning and control systems that come with zero energy may be operated and maintained by less highly skilled technicians, who are generally easier to recruit. Maintenance costs are further reduced because the wall, window and roof systems that achieve the low EUI essential to affordable zero energy schools, and the testing and commissioning needed to ensure that they are constructed and perform as designed, should be more durable and require less long-term maintenance than standard construction. Zero energy schools have lower life-cycle costs than other schools, and continue to conserve resources throughout their lives. Zero energy schools provide sound fiscal management of community resources in the long term.

ENVIRONMENTAL STEWARDSHIP

Completing a zero energy school, or a school with the low EUI required to be ready for zero energy when renewable energy sources are added, demonstrates leadership and the clear commitment of a school district and the community in which it is located to sustainability and environmental stewardship. A zero energy school signals a shift toward recognizing and protecting natural resources and mitigating climate change to the entire community.

ZERO ENERGY DEFINITION

There are a number of different terms in common use to describe buildings that achieve this balance between energy consumption and production, including zero energy, zero net energy, and net zero energy. The term used throughout this guide is zero energy for consistency with the United States Department of Energy's (DOE's) definition of zero energy

The specific definition of a zero energy building used in this guide is based on source energy, as defined by the Department of Energy (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.*

The DOE 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 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, using this definition also facilitates alignment with federal policy and incentives as well as with many state and municipal initiatives.

The guide provides target EUI information in both source energy and site energy. Both site and source energy 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. It takes into account the efficiency of this process for each fuel source. 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 to its greater efficiency.

The need to determine a specific energy boundary for a zero energy building and the use of the DOE definition in calculating an energy balance is discussed in Chapter 3. Finally, achieving zero energy is an operational goal that gets its basis in creating a building that is well designed and achieves success during the operation—year after year. Unlike design goals, having a zero energy building is long-lasting proof that the goal has been achieved.

GOAL OF THIS GUIDE

The goal of this guide is to demonstrate that zero energy schools are attainable, and to provide direction through recommendations, strategies, and solution packages for designing and constructing zero energy schools in all climate zones. Unlike the Advanced Energy Design Guides that preceded this one, there is no baseline model as zero energy is the absolute energy target.

This guide provides design teams with a methodology for achieving energy-savings goals that are financially feasible, operationally workable, and otherwise readily achievable. Energy efficiency and renewable energy technology is changing rapidly and what did not make sense financially or technically a few years ago is feasible today. The results is a zero energy school can be completed within a typical budget. This guide provides a pathway to zero energy and will help lead the way 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 key to success. Setting measurable goals is the first commitment a school district will make toward completing a successful zero energy school while maintaining a reasonable budget. The guide is written from two key perspectives:

- Achieving very low 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
- Achieving zero energy performance in the first year of operation makes no sense if the school is not maintained for the long term.

The intended audience of this guide includes, educators, school administrators, architects, design engineers, energy modelers, contractors, 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.

SCOPE

The guide was developed through a collaboration of the ASHRAE, the American Institute of Architects (AIA), the Illuminating Engineering Society (IES), the U.S. Green Building Council (USGBC), with support from the U.S. Department of Energy (DOE). A project committee that represents a diverse group of professionals and practitioners in HVAC, lighting, architectural, and school administration drafted the guidance and recommendations presented in the guide.

This guide provides user-friendly guidance for the construction of new, low energy school buildings for kindergarten through twelfth grade (K–12) school buildings. That guidance addresses processes, polices, strategies, and includes energy efficient targets and how-to recommendations. The guide provides strategies and recommendations to help design and construction buildings to be ready to accept renewable energy systems to meet their low energy loads. 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 in which a particular school building is to be constructed. In addition, there are many pathways to zero energy and as technologies improve more pathways will be developed. Therefore, the guide provides ways, but not the only ways, to achieve energy-efficient and zero energy school buildings.

This guide applies to all sizes and articulations of K–12 school buildings, including elementary, middle, and high schools. Space types covered by the guide include administrative and office areas, classrooms, hallways, restrooms, gymnasiums, locker rooms with showers, assembly spaces, libraries, dining and food preparation areas. The guide does not cover atypical spaces, such as indoor swimming pools, laboratories, career and technical education (CTE), and other spaces with higher energy loads and ventilation requirements.

The primary focus of this guide is new construction. Much of the guide may also be applicable to schools undergoing complete or partial renovation, additions, and or changes to one or more building systems; however, upgrading existing exterior building envelopes to achieve the low EUIs needed to make achieve zero energy is likely to be very challenging.

The features of high-performance learning environments described in Chapter 2 support the prime mission of K–12 school buildings, which is teaching and learning to achieve student success. It is critical that these features not be compromised in pursuit of energy-saving measures, by, for example, providing classrooms without daylight and views to the outside. The energy-saving measures described in this guide are therefore intended to complement teaching and learning in zero energy schools. In many cases, a school building that consumes less than or equal to the energy that it produces can become a tool for teaching and learning, as is seen in some of the case studies presented in this guide. Indeed, in the United States there may be more zero energy school buildings than any other building type, which demonstrates the synergy between zero energy, teaching, and learning as discussed in Chapters 2 and 3.

While this guide focuses on energy consumption and energy production, it also strives to improve other important aspects of sustainability, such as acoustics, indoor air quality (IAQ), water conservation and quality, landscaping, and transportation. A zero energy building should not compromise indoor environmental quality and should maintain minimums as defined by other standards which will be discussed in Chapter 2. Improving many of these sustainability attributes also contributes to improving the educational experience of the students and the work environment of the faculty and staff.

ENERGY TARGETS AND BASELINE BUILDING

To establish reasonable energy targets for achieving zero energy performance in all U.S. climate zones, two prototypical school models were developed and analyzed using hourly building simulations. These building models include an 82,500 ft^2 elementary school (2 stories) and a 227,700 ft^2 secondary school (3 stories), each of which was carefully assembled to be representative of construction for K–12 school buildings of its class. Information was drawn from a number of sources, including various K–12 school templates. A typical elementary school layout is shown in Figure 1-1.

One set of hourly simulations was run for each prototype using the recommendations in this guide (Torcellini et al. 2017). The prototypes were simulated in the climate zones adopted by the International Energy Code Council (IECC) and ASHRAE in developing the energy codes and standards. These include nine primary climate zones subdivided into moist, dry, and marine regions for a total of 19 climate locations. All materials and equipment used in the simulations are commercially available from two or more manufacturers.

The simulation results led to the determination of a target EUI for each of the 19 climate locations. The target EUIs are shown in Figure 1-2. Figure 1-2(a) shows the site comparison by climate zone for both the primary and secondary school buildings and Figure 1-2(b) shows the source EUIs for both the primary and secondary school buildings. The specific EUI target values are shown in Chapter 3 (Table 3-1).

The EUI was verified to not exceed the amount of renewable solar energy that could be generated by photovoltaic panels, reasonably accommodated on the roof of the prototype building. These EUIs are intended not as a prescriptive requirement, but as a starting point of mini-

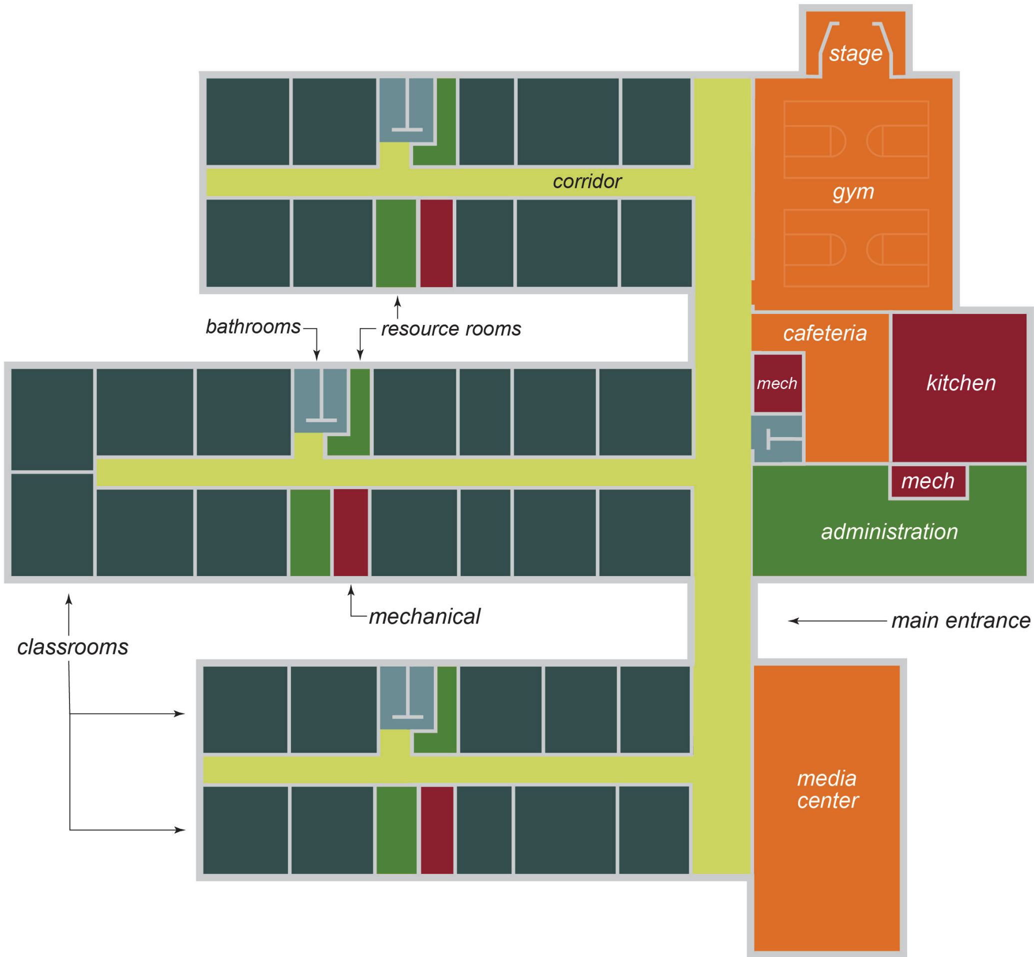

Figure 1-1 Typical elementary school floor plan.

mum performance that could be cost-effectively attained. Further optimization through building simulation and integrated design is recommended to reach the lowest possible EUI for the specific conditions of a particular project.

To facilitate reaching these EUI targets, the guide then provides recommendations for the design of the building configuration and of building components, including the building outside envelope; fenestration; lighting systems (including electrical interior and exterior lights and daylighting); heating, ventilation, and air-conditioning (HVAC) systems; building automation and controls; outdoor air (OA) requirements; service water heating (SWH); renewable energy generation systems, and plug and process loads, including kitchen equipment. These recommendations are described in Chapter 5.

HOW TO USE THIS GUIDE

This chapter (Chapter 1, Introduction) outlines the case for zero energy schools, how the guide was developed, a general idea of what to expect in the guide, and how to use it.

Chapter 2, The Rationale for Zero Energy, identifies the major stakeholders and outlines what is important to achieve a high-performance, zero energy school and identifies the main principles fundamental to implementing zero energy schools.

Chapter 3, Zero Energy Schools: Keys to Success, outlines how to achieve a zero energy school from a process standpoint, the critical steps necessary to plan, design, build, and occupy

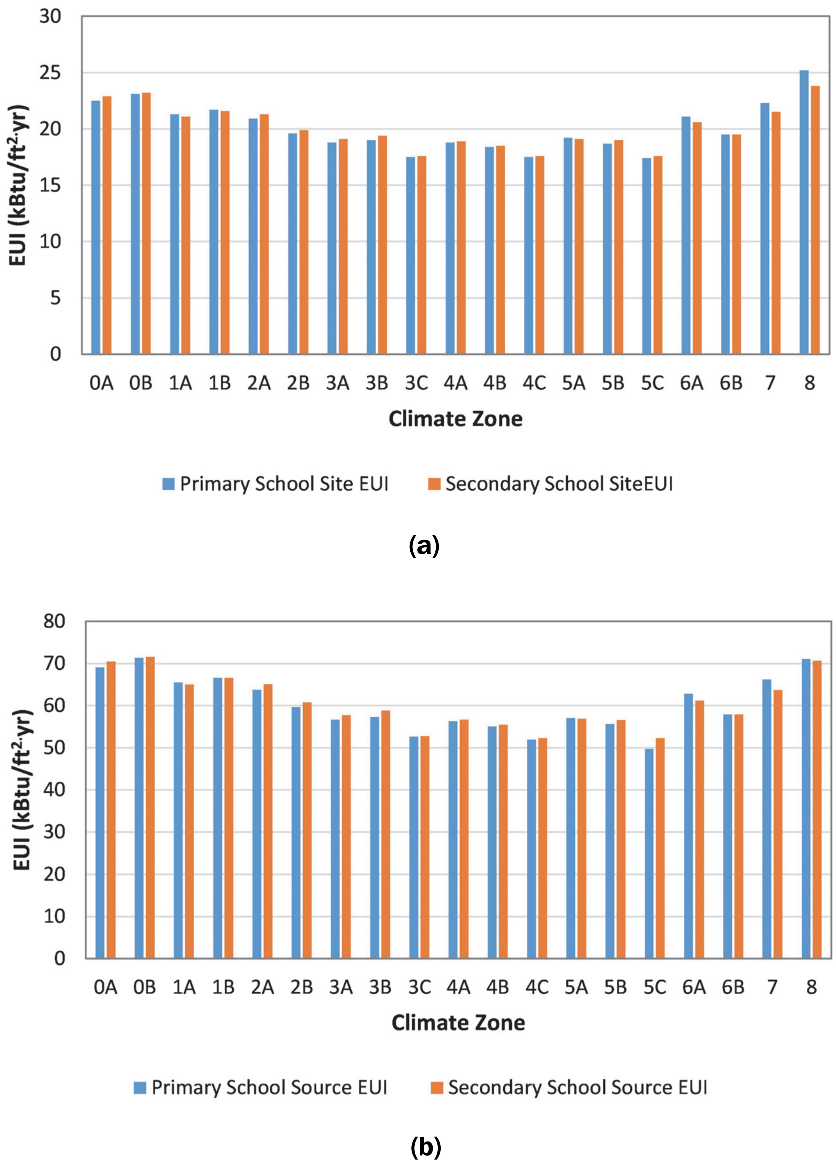

Figure 1-2 (a) Site EUI comparison by climate zone, (b) source EUI comparison by climate zone.

a zero energy school, and how the many stakeholders need to interact and collaborate during the process. The chapter discusses how to determine a target EUI and provides recommended EUI targets in both site and source energy.

Chapter 4, Building Performance Simulation, provides information on how to incorporate building simulation into the design process. While 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 schools. 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 tips.

Appendices provide additional information:

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

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

The Zero Energy Buildings Resource Hub provides additional information, resources, and case studies for zero energy school buildings. (www.zeroenergy.org). The website also provides access to the Zero Energy Schools Accelerator (www.zeroenergy.org/zero-energy-schools-accelerator/).

Note that this guide is presented in Inch-Pound (I-P) units only; it is up to the individual user to convert values to the International System (SI) as required.

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

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DEARING ELEMENTARY SCHOOL

The innovative design of this elementary school incorporates opportunities for teaching and learning into every aspect of the school. Grade levels are organized into pod communities. The classrooms surround a central flex space used for team teaching or large group activities. The pod communities are organized around an open plan discovery zone, which is used as the library, gymnasium, and cafeteria. This zone serves as the heart of the school and changes traditional common spaces into interactive, collaborative places for learning.

Digital displays show the building's energy usage, integrating sustainability with day-to-day activities. A large group instruction room is housed in a cubic space suspended from the second floor.

The school has an energy management system to manage the building's systems, provide metering and monitoring functions for data gathering, and allow informed decisions about future energy activities.

CLIMATE ZONE 2A

EUI
23.5

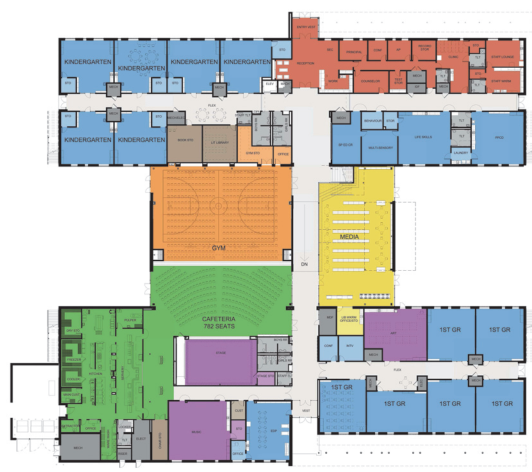
Pflugerville, TX

Pflugerville Independent School District

KEY ENERGY EFFICIENCY AND SUSTAINABLE FEATURES

- LED lighting
- Daylighting and dimmable lighting in student spaces
- Time clock and motion sensor lighting controls after hours
- Energy management system to monitor usage and feed digital displays
- Geothermal heating and cooling
- High efficiency kitchen
- Low-flow plumbing fixtures
- Rainwater and condensate catchment and storage to be used for irrigation
- Ecological garden featuring cisterns, planters, a water feature, and a human sundial

Open plan discovery zone library.
Photo reprinted with permission of Stantec



School floor plan.
Image reprinted with permission of Stantec

Project Data	Building Envelope
Site area: 10.8 acres Conditioned gross area: 93,376 ft^2 Building footprint: 53,189 ft^2 No. of floors: 2 Grade levels: K–5th grade	Roof type: Single ply with rigid insulation Overall R-value: R-21
Occupancy: Standard, extended day, summer camp Context: Suburban No. of occupants: 920 No. of students: 850	Wall construction: Insulated concrete forms (ICF) with masonry veneer Insulation type: Continuous Overall R-value: R-31
Year completed: 2014 Project delivery: Construction management at risk Financing model: Public bonds Construction cost: $17,150,000	Window type: Aluminum, thermally broken, storefront and curtain wall Window assembly U-factor: 0.15 Solar heat gain coefficient: 0.25 Visible transmittance: 0.25 Glazing percentage: 23.35% Modeled airtightness: 0.008 cfm/ft^2
Energy Data	**Building Systems**
Predicted EUI: 19 kBtu/ft^2·yr Predicted net EUI: 19 kBtu/ft^2·yr	HVAC systems: Variable speed and multistage geothermal heat pump (HP), dedicated outdoor air unit with enthalpy energy recovery wheel and demand control ventilation
Actual EUI: 23.58 kBtu/ft^2·yr Actual net EUI: 23.58 kBtu/ft^2·yr Zero energy status: Low EUI and zero energy ready	**Project Team**
	Architect: Barry Nebhut Engineers: CMTA, Inc; Stantec; Gil Engineering Contractor: Bartlett Cocke General Contractors

2

Rationale for Zero Energy

There are many stakeholders in a new school project: students, parents, teachers, elected officials, school district administrators, facility and energy managers, the design team, construction contractors, community leaders, and members of the larger community. All of these stakeholders view the school as an important asset for their community, but may not see energy consumption and zero energy as a primary goal. This chapter highlights why zero energy schools are important and the principles for successfully achieving the zero energy goal.

HIGH PERFORMANCE LEARNING ENVIRONMENTS

The design features described below should be considered when designing and developing simulations for zero energy schools, and, none of them should be compromised in pursuit of zero energy buildings. Sometimes the goals will work against each other—it is the role of the design team to work with the owner to creatively achieve the goals for the project.

In many cases indoor air quality (IAQ), thermal comfort, acoustics, and vibration are interrelated. Each one has criteria for success. While standards and best practices exist for each parameter, they are also interrelated. See ASHRAE Guideline 10-2016, Interactions Affecting the Achievement of Acceptable Indoor Environments (ASHRAE 2016a)for more information.

INDOOR AIR QUALITY

Student cognition and health may be impaired by poor air quality in learning environments. Mechanical ventilation systems should be designed to control buildup of carbon dioxide, chemicals and odors. Occupants are many times the best "sensors" and having features such as operable windows can be an effective ventilation strategy. Reducing source contaminants is critical, especially in new construction; construction materials, finishes, furniture, furnishings, equipment and supplies with low or no emissions of volatile and semi-volatile organic compounds should be selected. Building construction and mechanical systems should be designed to avoid moisture penetration and condensation that may cause mold to grow. Enhanced commissioning protocols should be followed for all heating, ventilating and air conditioning equipment, along with regular maintenance and filter changes to ensure that all systems function and continue to function as designed.

ANSI/ASHRAE Standard 62.1-2016 (ASHRAE 2016b) defines minimum requirements for the design, installation, operation, and maintenance of ventilation systems, but IAQ encompasses more than just ventilation. For more information, refer ASHRAE's *Indoor Air Quality Guide: Best*

Practices for Design, Construction, and Commissioning (ASHRAE 2009), which provides specific guidance for achieving the following key objectives:

- Managing the design and construction process to achieve good IAQ
- Controlling moisture in building assemblies
- Limiting entry of outdoor contaminants
- Controlling moisture and contaminants related to mechanical systems
- Limiting contaminants from indoor sources
- Capturing and exhausting contaminants from building equipment and activities
- Reducing contaminant concentrations through ventilation, filtration, and air cleaning
- Applying more advanced ventilation approaches

THERMAL COMFORT

Student and teacher cognition is also impaired if learning environments are too hot, too cold, too humid, or too dry. High-efficiency heating and cooling systems designed to achieve the low energy use intensity (EUI) needed to achieve zero energy must meet appropriate thermal comfort standards for temperature and humidity. They must also be designed to keep thermal conditions at appropriate levels whenever the school is in use. Most schools (and commercial buildings) have fairly narrow dead bands for temperature. The occupied set points can be expanded to coincide with ANSI/ASHRAE Standard 55 (ASHRAE 2017), especially when considering radiant heating and cooling systems and natural ventilation Ideally, the building envelope should be the first line of defense for thermal comfort—not the HVAC system.

ANSI/ASHRAE Standard 55-2017, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2017), defines the combinations of indoor thermal environmental factors and personal factors that produce conditions acceptable to a majority of occupants. For example, appropriate levels of clothing, the cooling effect of air motion, and radiant cooling or heating systems can increase occupant comfort efficiently.

ACOUSTIC COMFORT

Student and teacher cognition are impaired if acoustic conditions limit the intelligibility of speech. Proper acoustics is especially important for children, because their ability to hear and listen differs from that of adults. Providing good acoustics improves learning for all students (ASA 2010). The exterior building envelope, walls, roofs, windows and doors should be selected to control penetration of outdoor noise. Interior construction and finishes should be selected to reduce reverberation and penetration of sound. HVAC and other equipment should create minimal background noise. Excessive sound is often a sign of inefficiency, as it takes energy to make sound. Proper acoustics should be a priority in all design decisions and can help make a building more efficient. When acoustics is not considered during the design, it is a costly retrofit to address the issue during occupancy. See Chapter 5, HV30 for additional information on noise control in regards to HVAC equipment.

VISUAL COMFORT AND DAYLIGHTING

Providing controlled daylight to as many spaces as possible in a school increases student and teacher cognition and should reduce energy consumption (PG&E 1999). Effective daylighting achieves its maximum benefit if it provides high-quality lighting such that electric lighting can be reduced without compromising lighting quality or illumination levels. Visual comfort should be maintained by avoiding and/or controlling glare from daylight and electric lighting. In addition to daylighting, views to the outside, preferably of nature, should be provided in spaces where students spend long periods of time.

If designed and integrated properly, daylighting and electric lighting can maximize visual comfort in learning environments. Providing light levels that are too high or too low can cause eye strain and loss of productivity. Direct sun penetration should be minimized in work areas because the resulting high contrast ratio causes discomfort.

Design for daylight and electric lighting should accommodate classroom activities that may change many times over the course of a day. While technology is not stagnant, the move is toward high-contrast screens and away from projections devices. This minimizes the need for complete room darkening and provides some flexibility in lighting and daylighting design. Eye strain should be considered and the screen technology should be integrated with the lighting and daylighting designs.

Larger areas of clear glass on exterior facades provide views into entrance lobbies, cafeterias, libraries and gymnasiums reinforce schools as welcoming centers of community, especially at night. Blinds and other devices should be provided for safety and security, and to control glare when needed. These areas should be strategically located as they can increase energy consumption and are a source of thermal discomfort from solar gains and temperature variations. The concept of a covered outside space shading the inside space from the sun on the south and east faces of the building is illustrated in the Dining Commons area at Discovery Elementary School as shown in Figure 2-1.

Additional information on visual comfort is covered in the electric lighting section in Chapter 5 (see EL5). See also Chapter 5 for guidance on recommended window to wall ratios (EN42).

LEARNING ENVIRONMENT

Technology

Robust technology infrastructure is now considered essential to teaching and learning. It allows anywhere inside, outside, and beyond the school to become a learning environment. Providing adequate power for the ever increasing number of personalized and interactive learning devices must be considered when developing energy models.

Figure 2-1 Dining commons at Discovery Elementary School.
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Refer to the plug and power distribution systems section in Chapter 5 for guidance on plug loads and plug load management.

Adaptability

Changes in pedagogy, technology, instructional programs, and enrollment are the only constant in education. Many existing school facilities have adapted or been adapted to such change, and continue to have useful lives. New schools must be equally adaptable to accommodate constant change with as little disruption and cost as possible. Energy models; heating, ventilating, air conditioning, and power systems; and technology infrastructure for low and zero energy schools should all take this need for adaptability into account. Just as important is the need to design learning spaces and the furniture and equipment within them so that teachers and students can rearrange the spaces as often as needed during the school day to accommodate different learning activities and groupings of students.

Curriculum

Building a zero energy school creates outstanding opportunities for student learning. When energy-efficient features are incorporated into school curricula, the zero energy school can be an integrated learning tool through which the students themselves become advocates for environmental stewardship throughout their lives. For example, the Virginia Standards of Learning for fifth grade cover research, writing, and public speaking skills. Fifth grade students at Discovery Elementary School in Arlington, VA start the year by researching and writing about Discovery's sustainable and zero energy features, and then act as docents for the school's many visitors. Other examples of integrated learning tools include renewable energy sources and the water use cycle which creates learning opportunities through bio-retention areas and other features. This concept is illustrated in Figure 2-2 which shows students using handheld devices in real time to learn about solar energy in the solar laboratory at Discovery Elementary School.

Figure 2-2 Students in Solar Laboratory.
Reproduced with permission. Copyright Lincoln Barbour.

Leading the Way Forward: Teaching and Learning with Zero Energy

To maintain the engagement of students, staff, and the larger community, a comprehensive energy dashboard that can be accessed freely on-line should be provided. The energy dashboard is an unparalleled source of data about how the building is performing. The energy dashboard is an integral part of the energy management, teaching, and learning at Discovery Elementary School in Arlington, VA.

Energy Dashboard at Discovery Elementary.
Reproduced with permission. Copyright Lincoln Barbour.

Authentic Learning

Data from Discovery's energy dashboard provides authentic learning experiences for its students. Teachers use the dashboard data to create complex learning opportunities. They ask students to solve, think critically, and research elements and aspects of dashboard data. The dashboard is a multidisciplinary tool that raises students' awareness of their own habits, routines, and decision-making processes. Whereas in traditional learning, facts, questions, and problems are decontextualized and exist in a vacuum, the dashboard provides meaningful and relevant numbers that are embedded in the students' school and community.

Students learn through the lens of their own school that learning is not abstract, theoretic, or arbitrary. For example, a worksheet that asks a student to multiply two numbers together does not engage a student as fully as asking a student to determine which months produce the most energy and why. Students and teachers use the data from the dashboard to enrich and deepen their understanding of the curriculum

Active Participation

The dashboard recreates the experience of watching a zero energy school come to life for each new cohort of students. Through the dashboard, students are able to experience the energy-efficient features and the varying conditions of season and weather. The dashboard gives students a synergistic view of how Discovery operates as an integrated system of which they are an essential component. Giving students a portal to the inner workings of their school creates pride and a sense of collective responsibility for their environment. After understanding the why and how of zero energy, and the uniqueness of their school Discovery's students are more likely to engage in other green initiatives.

Eco-Action Team

Instead of a traditional student council, Discovery's students lead through the Eco-Action Team. Students at Discovery support green transportation. Patrols count how many cars pass through the parent drop-off /pick-up, track the number of students riding school buses and the number of bikes on campus, and record the data on the energy dashboard each day. Students weigh school trash, try to pack trash-free lunches, and send uneaten food to the local food bank. Older students make videos to promote recycling and other green initiatives, while younger students help sort recycled objects for the Maker Faire—a hands-on school activity that has become a new tradition of discovering, building, and celebrating upcycling.

Fifth Grade Project

In June 2017, fifth grade students working on a biodiversity unit used the Energy Dashboard to ask questions, develop hypotheses, apply a scientific method to investigate their hypotheses and generate recommendations. One group asked what Discovery's mean monthly energy production had been to date. The students found that the monthly average was 3047 kWh. In their analysis, this group suggested that students, teachers and staff could be more diligent about turning off lights manually, which would have, in their words, "no significant negative impact" on the school. Another group asked how power could be saved in the HVAC system. They found HVAC use on the weekends was higher than expected given the lighter use of the building, and so they wondered if it would be possible to further shut down or scale back the HVAC system when the building is less heavily occupied on the weekends. The last group wondered about general energy reduction on weekends. The students came up with some very specific figures, and were surprised at the amount of power being used by plug-in devices. Among other things, they wondered if the practice of unplugging devices before going home for the weekend each Friday could be instituted.

Planning and Budget

It is important that the scope and fee for developing the dashboard are included in the budget. It is also important that educators in the school district are made aware of the opportunities the dashboard provides as early possible in the design process so that they will support the expenditure, provide valuable participation in the process of developing it, incorporate it into the curriculum, and become strong advocates among their colleagues for constantly finding new ways of using it to enhance student learning and success.

The Discovery Elementary School dashboard was developed by Discovery's architectural/engineering (A/E) team with assistance from Discovery's information technology coordinator (ITC) and students in the high school career and technical education (CTE) program at the Arlington Career Center. The dashboard provides real-time and historical data. It is regularly updated with new features and is freely available on the school's website at http://158.59.255.83/.

PRINCIPLES FOR SUCCESS

FUNDAMENTAL PRINCIPLES

Two fundamental principles distinguish the mindset required to build a zero energy school. The first principle is that zero energy schools can create and reinforce a culture for zero energy among those who use and operate them. The second principle is that zero energy schools demand highly collaborative synergies among those who plan, design, construct, use, operate and maintain them. Strategies to incorporate these principles successfully into the process of conceiving, planning, designing and implementing a zero energy school project are described below and in Chapter 3.

CREATING THE CULTURE

Develop a Persuasive Communications Strategy

A clear but flexible communications strategy is essential to educate, generate enthusiasm, develop new proponents for zero energy, and establish the key expectation that zero energy will be achieved and maintained. The benefits of zero energy are likely to appeal to different stakeholder groups in the following different ways:

- Creative educators will readily grasp the opportunities for learning that zero energy schools offer as they seek innovation in pursuit of student success
- Students, many of whom are already committed advocates for the environment, will enthusiastically embrace their new zero energy school's capacity to improve the quality of their environment and that of the surrounding community
- School board members and district administrators, though concerned about initial construction cost and equity with other schools in the district, will find the long-term savings in operating and maintenance of a zero energy school fiscally responsible, and should also be encouraged by the opportunities for student learning and success
- Citizens who typically vote for new schools in bond referenda will likely also support a zero energy school if the life-cycle savings and risk mitigation are clearly articulated, if it is demonstrated that the low EUI needed for zero energy may be provided for the same or little more cost than a regular school, and if they are aware that other means of funding the renewables will be available if necessary
- Local government officials may be encouraged to see the value of a zero energy school in helping to achieve overall community energy goals and in demonstrating the commitment of their community to sustainability and mitigation of climate change, especially if faced with aging energy infrastructure
- Members of community associations and residents near a proposed zero energy school may be unfamiliar with zero energy concepts, but once educated are likely to embrace them

Build Confidence that Zero Energy Can Be Achieved

It is necessary from the outset to address head on those who believe that a zero energy school will automatically cost more than a typical high performance school, and 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 selecting an A/E team that has the skills and expertise to achieve zero energy and/or a low EUI on a typical school construction budget, and to communicate the benefits of zero energy enthusiastically to all stakeholders. Almost equally important is selecting the construction manager or contractor who will construct the school as early in the process as possible, so that its team members become partners in building confidence among stakeholders that the school can be constructed on time and within the approved budget. Considerations for selecting a team that is capable of achieving zero energy are described in more detail in Chapter 3, Building the Team.

Connect Teaching and Learning to Zero Energy

Planning, designing, constructing and operating a zero energy school signals true culture change and a fundamental shift toward recognizing and mitigating climate change to all the students, teachers, administrators, staff, parents and members of the community in which it is located. It can help to make all of them owners of zero energy performance, and help them all to understand their individual and collective roles in sustaining zero energy performance for the long term. Most importantly, it supports student learning and student success by integrating learning, design, sustainability and environmental stewardship in a more comprehensive way than a typical high performance school. Zero energy champions should consider establishing the expectation from the outset that the school will become and remain an integrated learning tool through which the students themselves will become the greatest advocates for environmental stewardship as they carry what they have learned in and from their school with them through their lives.

DEVELOPING COLLABORATIVE SYNERGIES

Integrated Design

The advantages of integrated design in maximizing synergies across program, site, and system requirements have been noted for many building types, whether or not the goal is zero energy. Extensive guidance on integrated design methodology is available through the American Institute of Architects (AIA 2007) and elsewhere. For zero energy schools, finding synergies through integrated design is not just an enhancement but an essential strategy for achieving the low EUI needed within the budget available for a typical high performance school. Applying integrated design synergies to a zero energy school creates a single integrated system, from which no major component can be removed or substantially altered without raising the EUI.

While prescriptive design guidance is useful to achieve many energy goals, to achieve zero energy as cost effectively as possible prescriptive strategies may no longer suffice. Rather, integrated design is required to reconcile the specifics of microclimate, site, program, available construction options and available renewable energy to develop an optimal solution that balances energy consumption with energy generation. The key steps in this process are described in Chapter 3. With the development of zero energy buildings from performance-based rather than prescriptive criteria, the use of building simulation tools is essential as part of an iterative process of optimizing each system and component. This process is described in Chapter 4

Design Team

Achieving the design synergies essential to this single integrated system demands a high degree of collaboration among all the disciplines within the A/E team. Features of this collaboration include the following:

- Shared enthusiasm for and dedication to zero energy performance
- Understanding the integrated relationships of all design decisions made
- Embracing the unique parameters of each project
- Creativity and openness to innovation
- Learning from what has been achieved on other zero energy schools
- Understanding the degree of complexity that is appropriate to the owner's capacity for maintenance and operations
- Intense focus on achieving low EUI and on lowering EUI for each successive school
- Integration of building simulation with the design from the outset, and through every stage of design
- Post construction update of the energy model to optimize the system sequence of operations and incorporate as-built conditions into energy use and into projections of consumption and generation
- Sharing what has been learned with others and applying the knowledge gained from actual performance on one zero energy school to the next one

STAKEHOLDER COLLABORATION

Collaborative synergies for zero energy extend to all the community stakeholders who will use and operate the school: the students, parents, teachers, elected officials, school district administrators, facility and energy managers, community leaders, and members of the larger community, who will use the school from time to time. They too should be encouraged to engage, integrate and collaborate with the project team during the various stages of design, and experience the culture change that zero energy inspires. They too will contribute to achieving the school's zero energy performance, and once it been achieved and verified to maintaining it year after year. If they do not, all the collaborative efforts of the integrated team will have been wasted.

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Chapter 2

RICHARD J. LEE ELEMENTARY SCHOOL

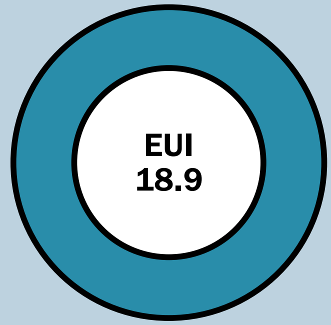
The Coppell Independent School District (CISD) set out to construct a sustainable 21st Century school that is sustainable, while providing the best educational environment for the students. The floor plan is arranged in eight "neighborhoods" with collaborative teaching spaces that each open up into a large multipurpose learning space.

The 358 KW solar photovoltaic (PV) system is composed of approximately 1100 panels, all roof mounted. The entire PV system was constructed within the allocated budget.

KEY ENERGY EFFICIENCY AND SUSTAINABLE FEATURES

- Variable-speed dedicated outdoor air system (DOAS) with demand-controlled ventilation to provide appropriate outdoor air to the learning environment and control building CO_2
- All spaces can control their temperature and lighting
- Geothermal HVAC
- LED lighting with 0.60 W/ft^2 lighting power density (LPD)
- Orientation and windows to maximize natural lighting and students' views
- 2900 W wind turbine
- Recycled products integrated into design
- Reduced construction waste.
- 20,000 gal rainwater storage tank for flushing toilets and urinals

CLIMATE ZONE 3A



Dallas, TX

Coppell Independent School District (CISD)

School Webpage:
www.coppellisd.com/lee

Richard J. Lee Elementary School.
Photo reprinted with permission of Stantec

Library.
Photo reprinted with permission of Stantec

Project Data	Building Envelope
Site area: 10.2 acres Conditioned gross area: 95,633 ft^2 Building footprint: 107,587 ft^2 No. of floors: 2 Grade levels: Pre-K–5th grade	Roof type: Standing seam Overall R-value: R-21
Occupancy: Standard, summer school Context: Suburban No. of occupants: 802 No. of students: 740	Wall construction: Brick with cold formed metal framing (CFMF) Insulation type: 2 in. polystyrene + 2 in. polyurethane Overall R-value: R-28.6
Year completed: 2014 Project delivery: Construction management at risk Financing model: Passing of a bond Construction cost: $20,963,355	Slab edge insulation R-value: R-28 Under slab insulation R-value: R-28
	Window type: Solar control, low-e glass Window assembly U-factor: 0.29 Solar heat gain coefficient: 0.40 Visible transmittance: 74% Glazing percentage: 16%
Energy Data	Modeled airtightness: 0.01 cfm/ft^2
Predicted EUI: 18.5 kBtu/ft^2·yr Predicted RE: 18.3 kBtu/ft^2·yr Predicted net EUI: 0.22 kBtu/ft^2·yr	**Building Systems**
Actual EUI: 18.88 kBtu/ft^2·yr Actual RE: 16.95 kBtu/ft^2·yr Actual net EUI: 2.03 kBtu/ft^2·yr	HVAC systems: Geothermal heat pump (HP) with 2-speed compressors and distributive water pumping, DOAS with total energy wheel, staggered startup. RE type and size: 358 KW roof-mounted PV
	Project Team
Zero energy status: Net Zero Emerging Building (New Buildings Institute) RECS: None purchased Certifications: LEED Gold	Architect: Stantec (formerly SHW Group) Engineers: CMTA, Inc., and Stantec Energy Consultant: CMTA, Inc. Construction manager: Balfour Beatty Construction

3

Zero Energy Schools: Keys to Success

With an understanding in place of the culture and collaborative mindset required to establish zero energy as a target, the success of the process can be facilitated and enhanced through the implementation of several key steps carried out from planning through post occupancy. Chapters 1 and 2 focused on the reasons and establishing zero energy as a target. This chapter will focus on some key process steps to make zero energy a reality.

BUILDING THE TEAM

IDENTIFY A CHAMPION

The most important key to achieving a zero energy school and maintaining its performance is finding individuals with the vision, passion, persistence, and powers of persuasion to be a champion and lead the project through planning, design, construction, occupancy, and ongoing measurement and verification.

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

While most owners have an interest in energy efficiency, many are not at the leading edge of energy efficiency and zero energy design as they don't routinely design and build buildings. There are enough examples and market pull for zero energy schools that experienced A/E teams can deliver a zero energy school for the same budget as a conventional school. These teams try to sell the owner on a value-added basis if they are selected. The owner also needs to become a champion, as zero energy is achieved through successful operations and not just design.

WRITE A COMPELLING REQUEST FOR PROPOSAL

The request for proposal (RFP) sets the stage demonstrating the school district's commitment to zero energy performance. It provides a pathway to select design and contractor teams with the required expertise to achieve the goal. Along with the school district's standard RFP language and the detailed scope of services required, a successful zero energy RFP should include the following information:

- The expectation that zero energy design and performance will contribute to student learning and success.
- The zero energy goal, including a description of the energy boundary. Note that any particular zero energy strategies can be included, but design teams may find more cost-efficient solutions while working through the design process.
- The energy performance considered essential to achieving zero energy performance. While energy use intensity (EUI) is most common, other energy metrics can also be used. A more aggressive, lower EUI should also be noted as an optional goal.
- The nature and extent of oversight, quality assurance, and commissioning expected during design, construction, and close-out, and who will provide it at each stage of the process.
- A process for ongoing monitoring and verification of performance after the official close-out of construction.
- Performance criteria for the building management system, including accommodation of future changes in utility rate structure and policy.
- The expectation that the school district, with the exception of the renewable energy sources needed to achieve zero energy, will achieve the low-EUI target without spending any more on the school than it would on a comparable school.

A detailed RFP that demonstrates the school district's commitment to achieving and maintaining zero energy performance will go a long way towards ensuring that an appropriate A/E team is hired for the project.

HIRE AN EXPERT A/E TEAM

No matter how convincing the school district's champion for zero energy may be, zero energy performance will not be achieved and sustained unless an A/E team with the expertise, creativity, and commitment needed to achieve zero energy goals is hired for the project. To help attract an A/E team with these qualities, communications about the zero energy goal may precede preparation of the RFP for architecture and engineering services to generate interest and excitement about the project.

In addition to the standard A/E team, a successful zero energy team must include a commissioning agent and building modeling expertise. The role of the commissioning agent is described later in this chapter, while the building modeling team includes building simulations expertise to help guide design decisions keeping the energy goal in mind, described in Chapter 4.

MATCH PROCUREMENT TO PERFORMANCE

It is critical to hire a construction contractor or construction management company that understands and is committed to achieving the energy goals for the project. This also applies to their subcontractors and suppliers. Everyone needs to produce quality work for success in meeting the energy goals. As an example, an envelope that doesn't meet the infiltration requirements but is testing within compliance can single-handedly cause the energy goals to fail. Aligning every person that touches the project from design through construction is difficult and a clear management strategy is needed to make this happen. A variety of procurement methods are available for school construction, each with their own pros and cons regarding the achievement of zero energy performance. For any of these methods to be effective, the contracts must be developed carefully to protect the owner's interest and maintain the minimum performance criteria, including energy performance. These contracts can be used to align everyone to the energy goals of the project as well as other critical success elements such as cost and budget.

Design-bid-build is the most common method. The owner or agency contracts with separate entities for design and construction. As a result, there is less opportunity for innovation and optimization through design enhancements integrated with construction technologies and methods. In addition, public school districts typically require selection of 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 do so 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, which adds overhead and complexity to the process. 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.

Performance-based procurement is an alternative to design/build. In this approach, the criteria for the project are performance- or goal-based. Rather than actual solutions, bidders are provided with objectives for a project and the success criteria if the objective has been met. The price for the project is fixed and a contractor team (that includes full design services) is selected based on who can achieve the most objectives for the fixed price. Note that the owner must prioritize the objectives and the objectives must be selected in order without skipping any. It does require that the owner have a clear prioritization of project requirements in the RFP to ensure that the school district's educational specifications and goals were not compromised. The result is that the school district competitively achieves the most prioritized scope for the funding available. The National Renewable Energy Laboratory (NREL) in Golden, CO, used this technique to create a large-scale office building that saved 50% of the energy at no additional cost, including the photovoltaics, which brought the building to zero energy.

Construction manager at risk (CMR) or *integrated project delivery* approach is where the owner, A/E team, and contractor are brought together as one project team as early as possible in the design process. With CMR the owner negotiates a guaranteed maximum price (GMP) or maximum allowable construction cost with the CMR. This option offers a means for the contractor to become part of the integrated project delivery team as early as possible in the process, preferably no later than concept design, and as a result is most likely to deliver a school that achieves and sustains zero energy performance. The general contractor or construction manager is able to advocate for feasible solutions and troubleshoot constructibility questions, while cost control can be maintained through competitive bids of the subcontracts.

Lease/lease back delivery method, another option for public school districts, engages the builder sooner, reducing the level of public risk while allowing the builder to be chosen based on qualifications and not purely on price.

Requirements for procurement vary greatly by state and by district and may dictate which of the above methods is used. It is key to ensure that certain critical elements are part of any procurement method. These include the following:

- A clear delineation of the performance criteria including the EUI target
- A mechanism, including a specific identification of responsibilities, for the owner, design team, and contractor (including subcontractors) to interact and coordinate, to ensure feasibility and operational functionality
- A mechanism to verify the energy performance

Often, energy projections are made with energy models. Today's generation of energy models are highly accurate as long as the inputs match the actual building. As a result, one path for compliance is that the energy model match the as-built condition of the building at the time of construction completion. The value from the energy model would then have to meet or exceed the EUI targets specified in the contract. When there is a variation during operations, a warranty claim can be made to correct the issue. The purpose for warranty claims is to correct issues where equipment or systems are not meeting the specifications outlined by the manufacturer that are also the inputs to the energy model.

In addition, incentives can be provided to the design team and contractor around actual building performance. Examples might include that the building energy bills must be within a certain percentage of the design intent. Warranty issues might arise when the energy performance is much higher than expected or when equipment cannot meet the design temperature criteria.

PROJECT PLANNING

A second key to achieving a successful zero energy school that goes hand-in-hand with building the team is to carefully address the initial planning for the project. This involves setting the project goals, budget, and schedule.

BUDGETING AND PLANNING

A zero energy school may be attractive to many stakeholders, yet still appear too far out of the reach of typical construction budgets. Because of the many differences in how school construction costs are calculated and the large variances in construction costs, drawing useful comparisons of cost among schools built in different school districts at different times is challenging at best. Nevertheless, many owner/design/construction manager or contractor teams that have successfully completed zero energy schools believe that it is possible to spend no more on a school that achieves the very low EUI required before the renewable energy sources are added than a typical high-performance school.

The critical step in achieving zero energy performance within budget is to establish the goal at the beginning of the project. The budget for a zero energy or low EUI school may be no more than for a conventional school if the zero energy goal is set before the RFP is issued, and the school is designed by an integrated A/E team as an integrated system from the concept design phase. However, this requires a continual effort to simplify and to integrate so that dollars spent can contribute to achieving multiple goals at once. Without this push for integration and simplification, the layering of additional systems for controls, monitoring, etc. will easily increase the costs beyond the baseline for conventional schools.

On some school projects, the low EUI required to make renewable energy sources cost effective may be achievable within available funding, but the renewable energy sources themselves may not. As described in the renewable energy section of Chapter 5, other sources of funding for the renewable energy sources needed to achieve zero energy may be located. Nevertheless, the integrated design and construction essential to achieving zero energy will cause the percentage breakdowns of total project cost of standard hard construction cost and other soft cost components to vary from those found on more typical school construction projects.

- A/E fees may be higher than normal. During the design phases, additional analysis and coordination is required to optimize an efficient design and to document it adequately to ensure excellent implementation. During and after construction, extra oversight is needed to make sure that the building is constructed as designed and continues to operate as designed throughout its life.
- Fees for testing, commissioning, measurement, verification, and ongoing commissioning will be higher because of the exacting standards required to achieve and maintain low EUIs (see the quality assurance and commissioning section below).
- Extended transition to operations (ETOP) services, under which the nature and frequency of all preventative maintenance items are defined and scheduled, should be included in the budget to facilitate ongoing zero energy performance.
- The higher cost of high-performance envelope measures, which is a key step in achieving low EUIs, may be offset by reduced capacity and cost of the HVAC system, and may contribute to reducing the size of mechanical rooms and the overall footprint and cost of the building.

- Because higher efficiency lighting, including light-emitting diode (LED) lighting, is needed to achieve zero energy performance, initial lighting costs may be somewhat higher, but their low heat output reduces the capacity and cost of the air conditioning system and may even reduce the size of spaces required for air conditioning equipment and consequently the overall footprint and cost of the building.
- Additional training will be required for staff who will operate the various systems of a zero energy school, including the building automation system (BAS) and energy dashboards, renewable energy systems, HVAC systems, irrigation controls, and cafeteria equipment.
- Contingencies for unexpected costs may be reduced because the additional quality assurance steps necessary to ensure ongoing zero energy performance should reduce unexpected expenditures needed to mitigate schedule delays, cost overruns, and poor-quality construction.

The result of these and other variances from percentage component cost breakdowns found on typical school construction projects may result in higher bid or guaranteed maximum price costs and some shifting of soft costs to hard construction costs, without increasing the total project cost before the renewable energy sources are added. When presenting costs of zero energy school projects it is always helpful to emphasize the following long-term effects on the school district's operating budget.

- Utility costs will be reduced by the energy savings
- The risk of long-term volatility and increases in energy costs will be mitigated
- With downsized HVAC systems, maintenance costs may be lowered
- The ongoing focus on maintaining zero energy will maintain the high performance learning environments conducive to student success

School districts often find that completing a small, pilot zero energy school project is helpful to become familiar with the process and to establish budgetary guidelines for larger projects or for the district, as well as to build consensus among stakeholders regarding the benefits of zero energy schools. These pilot projects can be especially effective when combined with an Energy Master Plan for the district (see discussion in the Establish District and Campus Energy-Efficiency Priorities section below).

Comparing Costs for Zero Energy Schools to Costs for Other Equivalent Schools

School stakeholders frequently attempt to compare school construction costs in their school districts to costs in other school districts to determine if they are paying too much for their new schools. These comparisons are very hard to make, because so many factors affect the total cost of a project. Comparisons between the costs of zero energy schools and other schools are even harder to make. At least for now, the cost of renewable energy sources is likely to make construction costs of zero energy schools higher than those of other schools, while the total life cycle costs of zero energy schools should always be lower than those of other schools. Recommendations for comparing school construction costs with or without renewable energy sources are provided below.

1. **Identify the costs of the renewable energy systems and determine whether or not they have been included.**
   The goal should be to complete a school with the low EUI required for zero energy at no greater cost than any other equivalent school before the renewable energy sources are added. The costs of the renewable energy sources should therefore always be identified when comparing the costs of zero energy schools to those of other schools.

2. **Distinguish between hard construction and soft costs.**
How these items are assigned may vary somewhat between school districts. Soft costs typically include architecture, engineering, permitting, testing, commissioning and other fees, furniture, furnishings and equipment, and contingencies. In some school districts, they may also include technology infrastructure, classroom technology, personalized learning devices and other audio-visual and computer equipment, plus new school startup costs.
3. **Use final construction costs; when this is not possible, compare costs for the same stage of design or construction.**
The construction cost changes during the life of a project from the estimated cost at the inception of the project through updated cost estimates at various stages of design, to the bid or guaranteed maximum price cost at award of the contract for construction, and finally to the final construction cost after the project is complete and all costs associated with it have been accounted for.
4. **Do not attempt to compare the costs of new construction projects to renovation or renovation and addition projects.**
It is almost impossible to make meaningful cost comparisons between new construction and addition or renovation projects because the scope of work for addition and renovation projects varies so greatly from project to project.
5. **When comparing projects completed or to be completed at different times, normalize costs to account for escalation through a common date.**
Though there have been recent exceptions, construction costs normally escalate over time. Construction cost estimates should therefore include anticipated escalation percentages per year, usually from the date on which the estimate is made through the mid-point of construction.
6. **When comparing school projects in different locations, normalize the costs to a single location.**
Local market conditions for labor and materials vary greatly between cities and regions throughout the United States. For example, in 2010 on a baseline of 100%, construction costs were at 113.7% in Philadelphia, 97.3% in Washington, D.C., and 78.8% in some rural areas of Virginia (Chadwick 2010).
7. **Take into account the scope of on- and off-site work.**
The scope of site work varies considerably between school projects. Some schools may incur extensive off-site work, while others may incur none. For example, the scope and cost of site work for a multistory school on a restricted urban site requiring structured parking and synthetic turf athletic fields will likely be very different from those of a single-story school on an expansive suburban or rural site with surface parking lots and natural grass athletic fields.
8. **Take maximum class size into account.**
Low class sizes increase construction costs per student, while high class sizes reduce them. The maximum number of students permitted in a classroom varies by school district and state. Assuming that classroom sizes remain the same, the number of students can have substantial impact on the number of classrooms or teaching stations, and hence on the area per student and total area and construction cost of the school.
9. **Consider educational specifications.**
Educational specifications determine the types of spaces to be provided in a school in accordance with the educational program that it is designed to accommodate. Educational specifications vary widely and differences in educational specifications can lead to large differences in the area provided per student in a school. For example, some school districts provide specialist staff and spaces, such as art rooms, music rooms and multiple spaces for individual and group learning in addition to regular classrooms, while others do not. Some high schools are equipped with swimming pools and fully equipped theaters, while other school districts cannot afford such amenities.
10. **Consider intensity and hours of use.**
How a school is used affects the size and cost of the building, the amenities provided in and around it, and the amount of energy it consumes. Some schools are used only during the school day. Other schools offer extended day programs, typically available before school at 7:00 a.m. and after school until 6:00 p.m., as well as summer programs, and summer camps. Many schools are con-

ceived as centers of community to be used extensively outside normal school hours for evening and weekend adult education, athletic programs and other community activities.

11. **Consider any high-performance rating system used and the EUI targeted or achieved.** School stakeholders often think that seeking certification for a new school under a high performance rating programs will automatically increase construction costs; however, there is often little or no connection between a rating system and energy use. It does appear that, if achieving high energy performance with a low EUI target is set as a high priority at the inception of a school project and maintained as a priority through construction, the project may be constructed at costs similar to those of otherwise comparable schools.

Summary

No single data point, such as cost per ft^2, should be used to compare the costs of school buildings. At a minimum the following data points should be used:

- Construction cost per square foot
- Square feet per student
- Construction cost per student
- EUI
- School usage including extended day activities, summer school or summer camps, and evening and weekend community activities

SCHEDULING DESIGN AND CONSTRUCTION

A number of considerations specific to zero energy schools affect the way that design and construction are scheduled. The pressure to complete a school on time, usually at the beginning of the school year, must be carefully balanced with the need to provide adequate time during design and construction for the quality assurance that is essential to zero energy performance. Concept and schematic design phases may take longer than for a typical school because the most fundamental steps towards achieving zero energy through integrated design—site layout, orientation and massing of the building; selection of wall, window, and roof assemblies; selection of HVAC and other building systems; and balancing EUI predictions with available surface area for mounting solar renewables—occur during these phases.

Permitting prior to construction and inspections prior to occupancy may take longer than normal because reviewers and inspectors may be less familiar with the construction assemblies and building systems specified for zero energy. Adequate time is required to research utility provider incentives and requirements for zero energy and net metering, and to negotiate rates, connectivity and maintenance charges, and other conditions with them.

Creating an unrealistic period for construction and delays during construction often lead to rushed construction, which jeopardizes the high quality of construction needed to achieve zero energy, while also jeopardizing indoor air quality by shortcutting steps that reduce the risk of mold and leaving insufficient time to ventilate the building properly prior to occupancy.

SETTING PROJECT GOALS

The predesign and design process for a zero energy school does not need to be radically different than that of a conventional school. However, several small but critical shifts in the process are valuable to help ensure success in constructing a zero energy school with a rigorous level of quality. These are described below.

Use a Collaborative and Iterative Process

The extensive integration of multiple aspects of a zero energy school requires a collaborative process to maximize synergies for effective solutions. This process begins at the earliest stages, incorporating more detailed data and technical analysis when setting goals and developing the performance criteria. As predesign evolves through design and construction, an iterative process characterized by feedback loops, cycles between data analysis, building simulation, and design, to gradually optimize the design as more design data emerges. The repeated cycles through building simulation analyses to optimize the design are illustrated in Figure 3-1. Ultimately the feedback does not stop with occupancy but is carried over into post occupancy as the occupants develop the most efficient ways to run the building.

Plan for Full Usage

An important variable that has impacts to the energy performance and overall success of a school in its community is the school's usage. As part of the initial planning for a school, the district must establish its assumptions and goals for the use of the school, both in the short and long term. School districts that provide extended day programs to support busy, working parents, provide summer support and enrichment programs for students, regularly open their schools during evenings and weekends to adult education programs, and welcome community use of gymnasiums, theaters, cafeterias, classrooms, athletic fields, and playgrounds outside normal school hours demonstrate sound environmental stewardship. They recognize that their schools are valuable community assets. They recognize that their schools are vital centers of community that in turn support the success of all students. By demonstrating that the most sustainable approach is in fact to use their schools as much as reasonably possible, such districts are models for those that do not.

If such a school district grasps the opportunity to construct a zero energy school, it would likely consider using that school even more intensively simply because it is less expensive to oper-

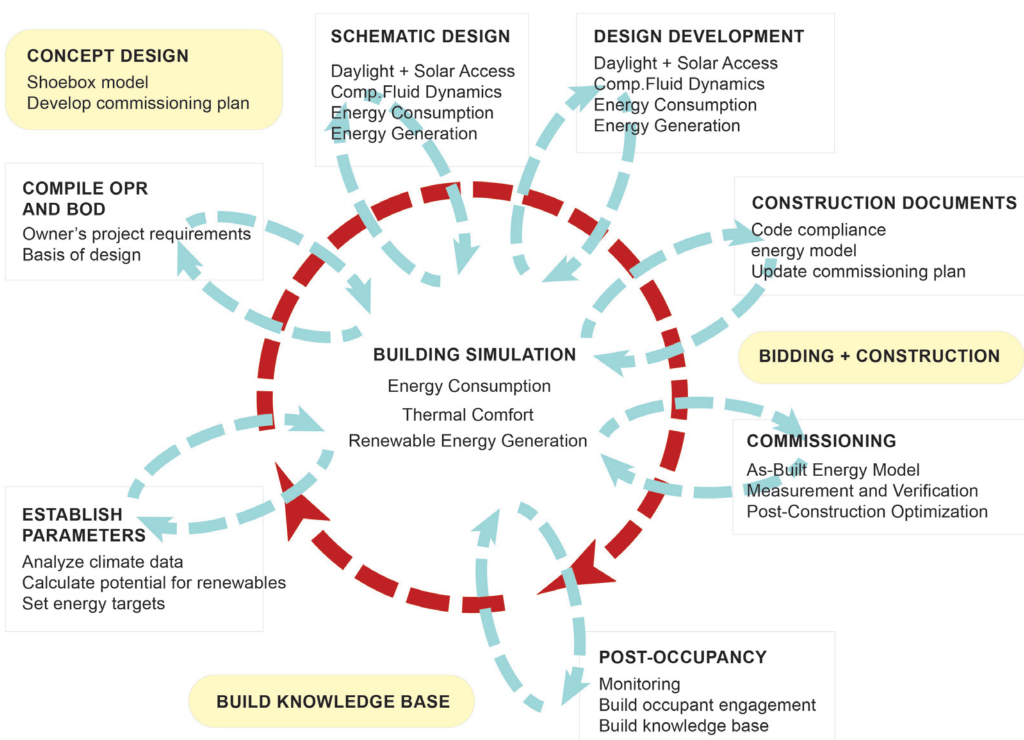


Figure 3-1 Integrated design process for a zero energy building.

ate and maintain than its other schools. It is important therefore to resist any temptation to limit the utilization of a zero energy school in order to achieve zero energy performance. Rather zero energy schools that will not be used this intensively when they first open should be designed to allow additional renewable energy sources, for example roof-mounted solar arrays, to be installed to support increased use at a later date.

Develop the Owner's Project Requirements

A key step in the development of a zero energy school is the creation of the owner's project requirements (OPR). The OPR establishes the owner's expectations for the project including basic operational expectations, the purpose of the project, and fundamental educational goals. Therefore, it is appropriate that the OPR also establish building performance criteria, including energy performance goals or targets such as site EUI or zero energy.

A well-written OPR is a useful instrument for providing the design and construction teams with insight into the true targets they need to achieve and describing the role of zero energy in achieving that vision.

An OPR should be a living document that is updated as the project progresses. Depending on the procurement process for the project, the OPR may be developed either during the RFP preparation phase or during predesign. Some owners include the initial OPR as part of the documents they use to hire architects and contractors. The OPR provides a concise summary of critical project requirements, clarifying priorities and ensuring implementation. Topics important for the success of the zero energy strategies include the following:

- Energy-efficiency, environmental, and sustainability goals
- Commissioning schedule and budget
- Natural ventilation
- Lighting—daylight and electric lights
- Metering requirements
- Indoor environmental quality
- Plug load management
- Equipment and system maintainability expectations
- Warranty requirements
- Personnel training requirement
- Operation and maintenance criteria

To be effective in the long run, the OPR must be aligned with the skills and budget of the facility management, incorporating input from district and school operations and maintenance staff when available. With the tendency for zero energy building systems to become increasingly complex, due to systems integration, responsive control mechanisms and extensive metering and monitoring needs, the team is well-advised to continually push to simplify systems and assemblies.

A quality OPR also becomes the document from which the design team will form its basis of design (BOD). The BOD essentially is the design team's approach for achieving the requirements outlined in the OPR. Because the OPR sets the goals to which the design team is responding, it is critical that the document be created as early as possible.

Engage the Stakeholders

On a typical high-performance school, the A/E team may strive to meet or exceed energy codes and achieve high scores on a checklist. On a zero energy school, not only the A/E team, but all the stakeholders involved in planning, designing, constructing, using, and operating the building should collaborate to find synergy for the low EUI needed for zero energy at every stage of the process from planning and design through construction, occupancy and long-term operations. This collaboration among the students, parents, teachers, elected officials, school district administrators, facility and energy managers, community leaders, and members of the larger community can lead to long-term culture change.

Basis of Design (BOD)

A basis of design (BOD) document should summarize the design team's approach to meeting the OPR. A good BOD explains why the design meets the OPR in as plain a language as possible so that it is understandable to non-experts. Some really well-crafted BODs can take a simple approach, such as the following:

What does the OPR Require?
The OPR limits CO_2 levels in a classroom space to no more than 800 ppm.

Explain what you designed:
A dedicated-outdoor air system (DOAS) ducts supply air to each classroom. The outdoor air is a demand-controlled ventilation system, controlled via a variable air volume (VAV) box connected to a CO_2 sensor in the classroom. The air supply was increased 30% above ASHRAE 62.1 levels.

Explain why you designed it that way.
The DOAS system combined with a demand-control ventilation system allowed us to achieve the OPR requirements in an energy-efficient manner. The air supply increased above ASHRAE 62.1 levels because calculations showed that an increased supply of air was required during periods of peak occupancy. This had a slightly negative impact on energy performance, increasing the EUI by 0.5%.

As the project gets under way, it is a critical period to solidify consensus around the zero energy goals and to integrate these goals with the larger vision for the school. This is also a critical juncture for bringing in the full team and strengthening relationships between team members, so as to facilitate the collaboration required for a successful solution. An excellent way to build consensus and agreement amongst stakeholders and the design team is to hold visioning workshops that combine presentations of material regarding the opportunities and challenges of the site and program, along with more interactive activities to engage the stakeholders and draw out their preconceptions, observations, and creative ideas. Once documented and compiled, these will generate a prioritization of mandatory goals and enhanced, or stretch goals, as a framework to structure the upcoming design work.

Typically facilitated by the design team or a third party, these 1- to 2-day workshops bring all of the vested stakeholders on the project together to set goals and expected outcomes. A typical workshop will include a diverse perspective represented by the design team, construction manager or cost estimator, quality assurance (QA) team, school administrators, teachers, and community members. A well-managed workshop will extract goals and aspirations from these stakeholders. Often, synergies between very different perspectives are found, which can represent breakthrough moments in solving potential challenges on the project.

Following the completion of the workshop, a report documenting the process should be completed. Additionally, the OPR should be updated to reflect any changes that are relevant. This OPR will continue to guide the team during the design and construction process.

DEVELOPING ENERGY BUDGET AND KEY PERFORMANCE CRITERIA

With the project budget established, and predesign program definition and concept design beginning 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 CMR project or as part of writing the RFP for a design/build project. This predesign process involves two types of tasks: data analysis which looks at project parameters (consumption data from similar projects, climate data for the site, etc.) and building simulation which simulates projected performance of the facility and impacts of various energy-efficiency measures. The building simulation process is described in Chapter 4. Additional information and resources are provided in the NREL guide to zero energy buildings (Pless and Torcellini 2010).

The key steps to an integrated zero energy design process are summarized below. In an integrated process, these steps are typically iterative; that is, as each task is completed, they inform subsequent and previous tasks, requiring additional rounds of analysis as information becomes more complete.

Define the Energy Boundaries

The equation for the zero energy balance of a school building or campus depends on the boundaries of energy consumption and energy generation of the facility. A boundary may be located at the building footprint, or more commonly, at the property line, including the area covered by utility meters or by fuel deliveries. Where energy consumption or generation are shared among buildings, the DOE definition for zero energy campus, zero energy portfolio, or zero energy community can replace that for zero energy building. More details on the energy boundary can be found in the DOE publication *A Common Definition for Zero Energy Buildings* and in the *High Performing Buildings* article "Finding Common Ground: Defining Zero Energy Buildings" (DOE 2015; Peterson and Torcellini 2016).

The boundary of energy consumption frequently coincides with the physical boundary of the site, encompassing a single building, a single building with surrounding site area, a group of buildings on a site, or an entire campus. In all cases, the most critical recommendation is to first lower the EUI before adding renewable energy, in order to achieve greater simplicity, ease of use, durability, life cycle cost savings, and resilience.

Establish School District and Campus Energy-Efficiency Priorities

The definition of the energy boundary should go hand-in-hand with establishing district and campus priorities for maximizing energy-efficiency across the school district. Ideally, a school district would not try to be zero energy in a single school, but across the district. Using a district energy boundary has some benefits in that excess energy from one school could be counted in another school.

The best way to accomplish an overall goal is to develop an energy master plan for the district. The energy master plan is a comprehensive strategic plan that aligns and coordinates the short, medium, and long-term energy goals of a school or district with its educational and facilities master plans, and with ongoing campus building and modernization programs. Energy and resource conservation is thus maximized by prioritizing efficiency upgrades with the largest impact, and avoiding short-term investments that are likely to be soon replaced or that prolong the life of inefficient components or buildings.

Key features of an effective energy master plan include the following:

- Document and validate the current energy consumption of each building through building energy simulation
- Establish EUI energy goals for each building
- Coordinate with energy priorities of local regulatory and utility policies, including incentives and rebates
- Incorporate demand management and demand response strategies
- Balance energy conservation with renewable energy production and distributed generation
- Develop a menu of appropriate energy conservation strategies for both modernization and new construction projects
- Prioritize energy conservation projects in alignment with the campus or district facilities master plan
- Specify an appropriate building energy management system to ensure long-term energy tracking and performance.

A successful energy master plan will maximize the return on investment, delivering the greatest long-term energy savings, and thus reducing the second largest operating cost for schools.

Table 3-1 Target EUI

Climate Zone	Site Energy		Source Energy	
	Primary School EUI, kBtu/ft²·yr	Secondary School EUI, kBtu/ft²·yr	Primary School EUI, kBtu/ft²·yr	Secondary School EUI, kBtu/ft²·yr
0A	22.5	22.9	69.1	70.5
0B	23.1	23.2	71.4	71.6
1A	21.3	21.1	65.5	65.0
1B	21.7	21.6	66.6	66.6
2A	20.9	21.3	63.8	65.1
2B	19.6	19.9	59.7	60.8
3A	18.8	19.1	56.7	57.7
3B	19.0	19.4	57.3	58.8
3C	17.5	17.6	52.6	52.8
4A	18.8	18.9	56.3	56.7
4B	18.4	18.5	55.1	55.5
4C	17.5	17.6	51.9	52.3
5A	19.2	19.1	57.1	56.9
5B	18.7	19.0	55.6	56.6
5C	17.4	17.6	49.7	52.3
6A	21.1	20.6	62.8	61.2
6B	19.5	19.5	57.9	57.9
7	22.3	21.5	66.2	63.7
8	25.2	23.8	71.1	70.7

Establish Target EUI

One of the most critical steps in creating a zero energy school is to establish the EUI for the project. The EUI is the annual energy consumption of the project divided by the gross area of the project not including any renewable generation. Establishing the EUI involves evaluating the project parameters to determine a feasible target. To establish the goal:

- Use the recommended values in Table 3-1, which shows targeted EUIs in both site and source energy. These are a function of climate zone and are based on the simulation analysis done for this guide (see Chapter 1, Energy Targets and Baseline Building. These target values are provided for the 19 climate locations—zones and subzones). Climate zones are determined from Figure 3-2 (ASHRAE 2013a).
- Demonstrate support for the EUI with actual examples of schools that have published low EUIs. Case studies in this guide and other case studies can help (DOE n.d.)
- Adjust the EUI based on exceptional loads. First create list of energy end uses. Loads that are not included in the EUIs calculated as part of this guide need further analysis to determine the impact. Examples might include swimming pools, ice rinks, and television quality lighting for sports fields. (See Chapter 1, Scope)
- Consider the facility use intensity. In some cases, adjustments may be made to account for additional occupancy hours, especially if the school is operated completely year-round.

It is important to create realistic EUI targets; however, the higher the EUI target, the larger the on-site renewable energy system to achieve zero energy. The targets presented in this guide 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 for the on-site renewable system.

Identify Energy-Efficiency Measures

Finding synergies through the integrated design of all components impacting the energy demands and energy production of the building is an essential strategy to achieve the low EUIs required for a successful zero energy school. These synergies allow the cost to be brought down to make zero energy feasible. In particular, 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. Figure 3-3 illustrates this concept.

Energy-efficiency measures (EEM) and integrated strategies that have been shown to be effective to achieve these target EUIs for each climate are outlined in Chapter 5of this guide. Some of the major components to be considered include the following:

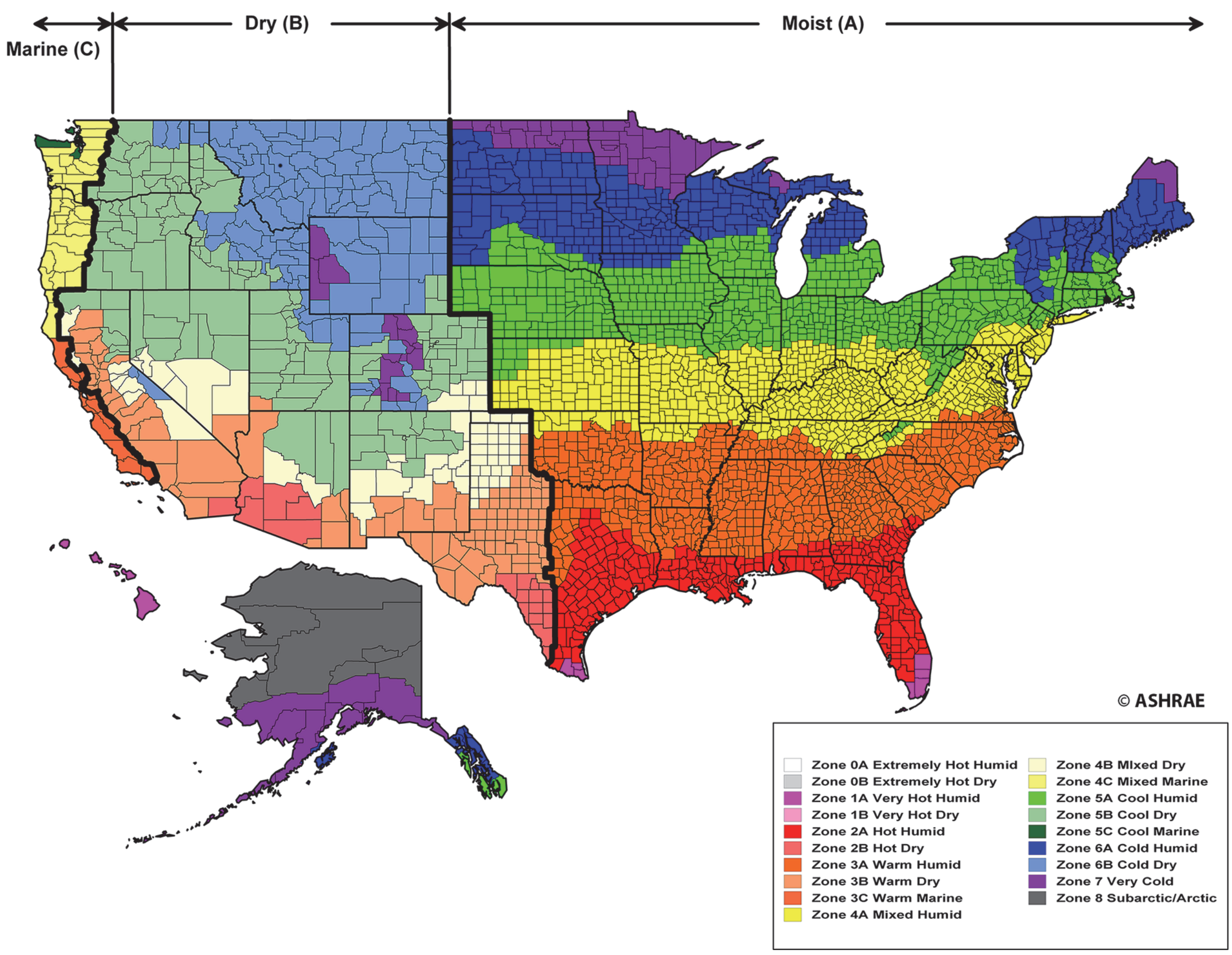


Figure 3-2 Climate zone map for U.S. states and counties.
Source: ANSI/ASHRAE Standard 169, Normative Appendix B (ASHRAE 2013a)

- Location, orientation and microclimate
- Shape of the building
- Glazing surface area and orientation
- Thermal insulation of the building envelope
- Airtightness of the building envelope
- Lighting systems which includes integrated daylighting
- Heat recovery of the ventilation system
- Internal heat gains, from passive solar, occupants, and equipment
- Efficiency of the heating, cooling, and hot water systems
- Plug load management and efficient kitchen equipment
- Configuration of the renewable energy generation systems

Reduce Energy Load

Without reducing the energy loads of the building, it is difficult to achieve a low EUI because of cost and physical constraints of on-site renewable generation. Zero energy may be impossible to achieve in some urban locations with solar renewables due to shading from other buildings and trees. Number of stories is also an impact. Even with these constraints, creating a building that achieves a low-EUI and can take advantage of some renewables moves the school in the right direction. In this case, other definitions can be used such as zero energy communities or a zero energy portfolio of schools. For these it is still critical to minimize the loads and maximize the renewable potential. For these larger boundaries, off-site renewables can also be investigated.

Confirm Through Building Simulation

The EUI serves as a target for the design. Designs are validated against the target using building simulation software. While a variety of simulation tools can be used from simple shoebox models to complex analysis, the objective is to show that the design meets the target. These analysis can include daylight analysis, computational fluid analysis for natural ventilation, whole building energy building, comfort analysis of individual spaces, and analysis of detail assemblies for heat and moisture transfer. As the project moves through the design process, the building simulations provide guidance for design decisions that are used to determine

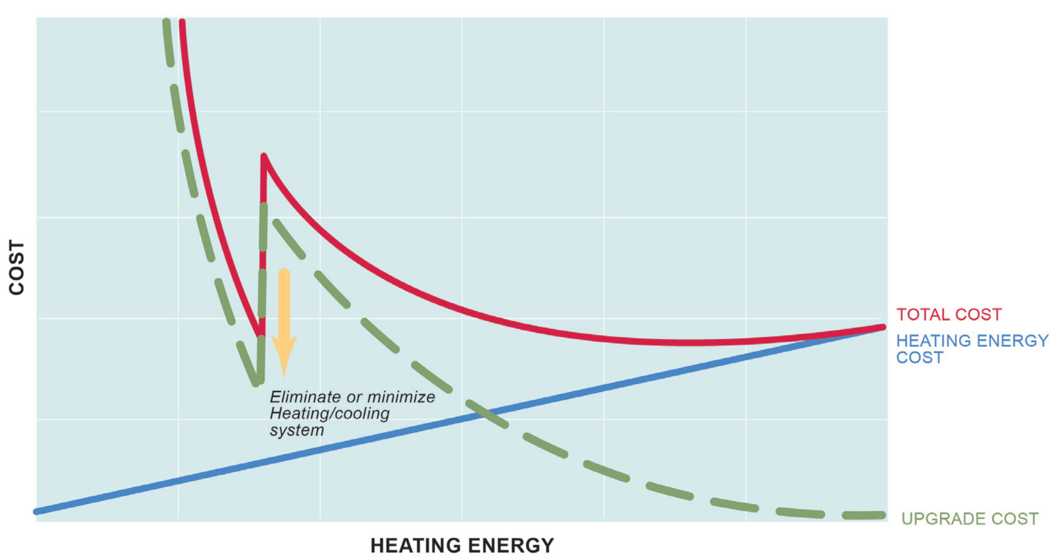


Figure 3-3 Energy synergies graph.

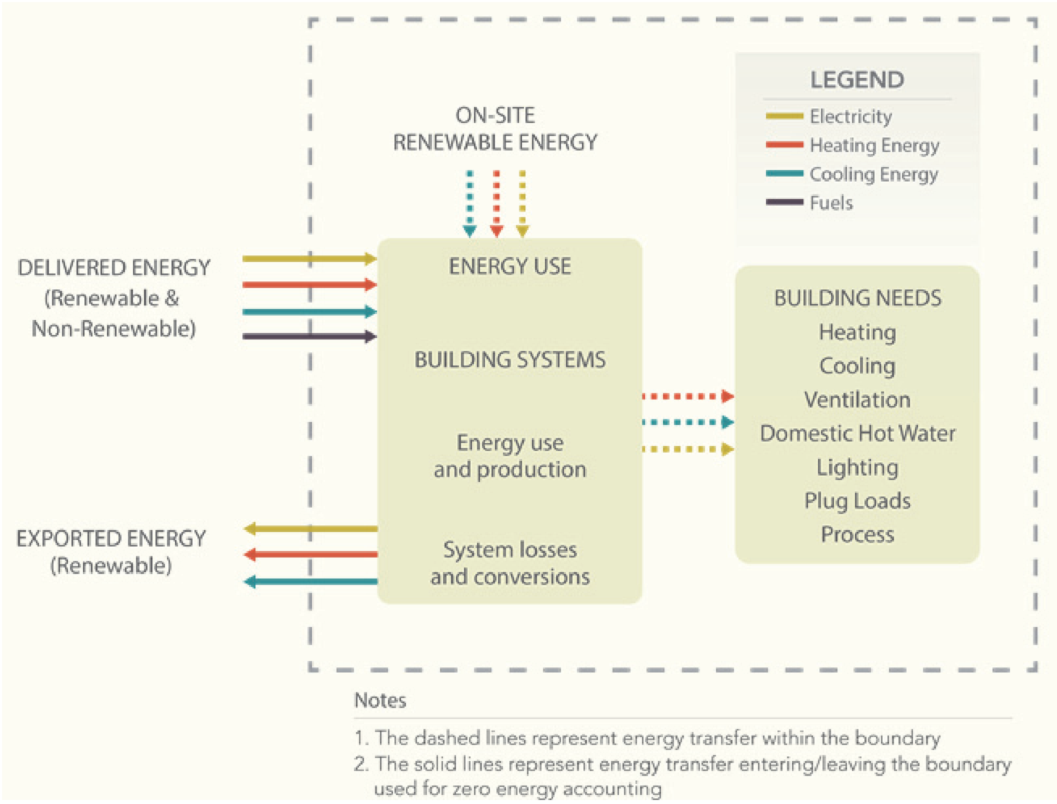


Figure 3-4 Energy balance diagram.
Source: *A Common Definition for Zero Energy Buildings* (DOE 2015)

the layout, to choose among alternatives, and to uncover opportunities for additional enhancements. A discussion of this process is provided in Chapter 4.

Confirm On-Site Renewable Energy Potential

Conduct an analysis of potential renewable energy sources that can be used to generate energy on site and calculate the potential quantity of energy that can be generated.

Especially where opportunities for renewable energy generation are limited, this step may start the process rather than end it, by generating a maximum EUI that can be supported by the available renewable energy production.

Calculate Energy Balance

Once quantities for energy consumption and energy generation have been established, the energy factors 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 3-4 (DOE 2015).

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

- Energy used for charging vehicles is counted as energy exported from the site
- Storing energy in a thermal energy storage tank or in batteries is an important demand management and cost avoidance measure that can increase the feasibility of a zero energy project, however it does not impact the energy balance equation.

Chapter 3

- A project must retain the renewable energy credits (RECs) to be a zero energy project

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

Verifying the Zero Energy Goal

Zero energy is an operational goal and as a result, the success is obtained when the building actually performs to the EUI targets that have been specified and the renewable energy is shown to generate that amount of energy. The simplest confirmation is based on tracking of overall annual energy through utility bills. All electric buildings are easier to verify because if the total purchased energy over the course of a year is 0, then the building should be zero. Various entities offer programs to validate these results (IFLI 2017). Information on these emerging protocols can be found on the NREL/DOE Zero Energy Building Resource Hub, Zero Energy Schools Accelerator Page (NREL n.d.).

QUALITY ASSURANCE AND COMMISSIONING

A strong QA approach begins with designating roles to help manage the QA process. A school district should consider creating a QA team made up of their own in-house technical experts, as well as any external expertise needed. At a minimum, the QA team should include those responsible for the operation and maintenance of HVAC systems, building automation systems, lighting systems, building envelopes, audio/visual, information technology, security, and kitchen operations.

One critical role on the QA team, typically served by an external party, is that of the commissioning authority (CxA). The commissioning process encompasses the review, testing, and validation of a designated system to ensure that it performs as expected. In a high-performance building, commissioning of the following components is a critical part of the QA process:

- **Building enclosure.** Walls, roof, fenestration, slab
- **Building systems.** Heating, ventilation, air conditioning (HVAC), lighting and lighting controls, plug load management, renewable energy systems
- **Indoor environmental quality.** Air quality, light quality, acoustical performance

In most cases, the CxA is directly contracted with the owner, so engaging a CxA is often done by way of a separate RFQ/P process. There are good reasons to consider engaging a CxA as early, if not earlier, than the design team itself. Typically, a CxA will contribute their technical expertise to the creation of the OPR.

The CxA 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 quality assurance.

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

COMMISSIONING DURING CONSTRUCTION

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

If issues are found, the contractor is required to resolve the issue.

Specific and detailed commissioning tasks are found in documents published by ASHRAE (ASHRAE 2013b, 2015) and ASTM (ASTM 2012, 2016). However, a basic descriptions of each category follows.

Building Envelope

The building envelope includes walls, roofs, windows, doors, slabs, and foundations. At various points in the construction process, assembly testing or whole-building testing may be performed on these components.

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

A mockup 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. Mockups are constructed early in the construction process by the contractor, and inspected by the CxA, 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 mockup testing has been performed, more expensive assembly testing can often be deferred. However, complicated facades such as large curtain wall assemblies, or heavily articulated wall extrusions may warrant further testing to assure performance.

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

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

Building Systems

Building systems include HVAC, lighting, and renewable energy. 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 will undergo a series of tests, called 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 commissioning process attempts to replicate these conditions prior to occupancy, but it is not uncommon for follow-up commissioning work to occur as the seasons change. For example, the FPT of a school may occur during the late summer. Therefore, additional FPT during the winter seasons would be advised to ensure that the heating systems are performing as required.

Indoor Environmental Quality

Indoor Environmental Quality (IEQ) includes indoor air quality, lighting quality, acoustical performance, and thermal comfort. Commissioning of the indoor environmental quality (IEQ) is less common than enclosure or systems commissioning, but it is important to ensure that the zero energy school meets the environmental needs of the students, teachers and administrators.

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

- *Indoor air quality*: CO_2, particulate matter, volatile organic compounds, formaldehyde, carbon monoxide, ozone, and radon.
- *Lighting quality*: brightness levels, contrast ratios, glare control, color quality, daylight efficacy
- *Acoustical performance*: HVAC noise criteria, reverberation time, sound transmission, sound amplification devices.
- *Thermal comfort*: air temperature, radiant temperature, thermal stratification, humidity, individual thermal comfort surveys.

MEASUREMENT AND VERIFICATION

The measurement and verification (M&V) period typically spans 12 to 24 months after substantial completion of the building. During this time, the CxA, 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, these should be identified and resolved.

Normal 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 of time to study if the building performed as expected.

The scope associated with measurement and verification is vital, but is often missed during the selection process. It's 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 present a number of lessons learned. With zero energy projects in particular, it becomes important to document these. Many school districts have a set of technical specifications or standards that govern over design and construction projects in the district. It is helpful to capture lessons learned and best practices from the zero energy school design and use them to improve these standards.

Additionally, a number of publications and resources exist to support the greater adoption of zero energy practices and are always looking for excellent case studies. Development of case studies and lessons learned not only helps draw attention to the good work happening in your district, but it also provides valuable information to those districts that might seek to incorporate similar principles into their project.

POSTOCCUPANCY PERFORMANCE

Only after the project achieves a 12-month period of performance can it call itself a zero energy school. However, most districts find it important to continue to maintain the level of efficiency, if not improve on it. As a result, successful districts often incorporate the following strategies:

- **Energy manager.** Larger school districts will frequently employ an energy manager to manage the performance of the district's energy portfolio. Smaller districts may not be able to justify a dedicated position focused solely on energy, so cross-training of personnel may be required. New software and tools can help bridge the knowledge gap.
- **Monitoring-based commissioning.** This type of commissioning leverages software and connected devices to automate the diagnostic process during operations. These systems can identify anomalies in components or systems operating outside of their expected

parameters. For example, if a pump that is supposed to vary its speed continuously runs at full speed for a few days, the system would identify it and notify the facility operator. This allows for the operator or CxA to address the issue quickly with minimal impact to the school's energy performance.

ONGOING COMMISSIONING

Securing sufficient funds to maintain and operate buildings at optimal performance is often a challenge for school districts, especially in years when funds are tight and difficult budget decisions must be made. Sustaining zero energy performance and reducing energy consumption in the long term should be more important than saving money in the short term by reducing expenditures on maintenance.

When annual budgets are challenged, it can also be difficult for school districts to recruit and retain maintenance personnel, secure adequate maintenance contracts, or sustain an effective balance between the two. It can be particularly difficult for school districts to recruit and retain highly qualified HVAC technicians with experience in complex automated building control systems, especially when salaries are typically higher in the private sector. Consequently, the use of relatively straightforward HVAC and control systems address this problem directly because they can be maintained and controlled by less highly qualified and less highly paid technicians.

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DISCOVERY ELEMENTARY SCHOOL

Discovery Elementary School was designed to provide seamless integration between teaching, learning, design, and sustainability. Zero energy creates a culture in which students, teachers, and parents understand how their actions contribute to maintaining zero energy each year. Open, programmable space is preserved by stepping the building down an existing slope. The south-facing slope allows the school to be oriented north-south on an east-west axis for optimal solar orientation.

Light and the energy are an architectural focus—from the entry plaza, where an oculus in the canopy creates a solar calendar, to the rooftop solar laboratory, where students conduct real-time experiments. An energy dashboard, accessible through the school's website, tracks the building's energy consumption and production, data from student experiments, modes of transportation to school, recycled materials, and even the quantity of uneaten food sent to the local food bank.

CLIMATE ZONE 4A

EUI 15.8

Arlington, VA

Arlington Public Schools School District

School Webpage: https://discovery.apsva.us
Energy Dashboard: http://158.59.355.83

KEY ENERGY EFFICIENCY AND SUSTAINABLE FEATURES

- Ground source heat pumps, dedicated outdoor air delivery, CO_2 sampling, and energy recovery
- Dedicated outdoor air delivery with CO_2 sampling
- Insulated concrete form walls, high efficiency glazing, and exterior window shades
- Energy-efficient laptops
- Daylight switching zones with dimmable LED lighting
- Dimming controls in classrooms and offices
- Thermostats per heat pump zone
- Roof-mounted photovoltaics (PV)
- Type 2 cooking hoods and water-source refrigerators
- Custom energy dashboard and educational solar lab
- Low-flow fixtures and site stormwater retention strategies
- Low/no-VOC-emitting materials

Discovery Elementary School aerial view.
Photo reprinted with permission of Digital Design & Imaging Service,

School floor plan
Image courtesy VDMO Architects

Project Data
Site area: 2.5 acres
Conditioned gross area: 97,588 ft^2
Building footprint: 63,838 ft^2
No. of floors: 2
Grade levels: Pre-K–5th grade
Occupancy: Year-round, extended day, summer school, community use
Context: Suburban
No. of occupants: 730
No. of students: 630
Year completed: 2015
Project delivery: Design/bid/build
Financing model: Bond sales, capital reserves
Construction cost: $33,516,195
Total project cost: $43,802,807

Energy Data
Predicted EUI: 21.1 $kBtu/ft^2 \cdot yr$
Predicted RE: 21.5 $kBtu/ft^2 \cdot yr$
Predicted net EUI: –0.4 $kBtu/ft^2 \cdot yr$
Actual EUI: 15.8 $kBtu/ft^2 \cdot yr$
Actual RE: 19.0 $kBtu/ft^2 \cdot yr$
Actual net EUI: –3.1 $kBtu/ft^2 \cdot yr$
Zero energy status: Zero Energy
RECS: Retained by district
Certifications: LEED Gold 2018

Building Envelope
Roof type: SBS with white reflective coating
Overall R-value: R-30.9
Wall construction: Insulated concrete forms (ICF)
Overall R-value: R-26.2
Slab edge insulation R-value: R-26.2 (ICF)
Under slab insulation R-value: R-10
Window type: Doubly thermal broken storefront and curtain wall with double-pane insulated glass
Window assembly U-factor: 0.29
Solar heat gain coefficient: 0.29
Visible transmittance: 64%
Glazing percentage: 39%
Modeled airtightness: 0.15 cfm/ft^2
Measured airtightness: 0.11 cfm/ft^2

Building Systems
HVAC systems: Ground-source heat pump (GSHP) with dedicated outdoor air system (DOAS), desiccant wheel, and staggered startup
RE type and size: 497 kW roof-mounted PV

Project Team
Architect: VMDO Architects
Engineers: CMTA, Inc., and 2RW
Construction manager: Heery International
Contractor: Sigal Construction Corporation
Other: Reynolds Consulting Engineers

Building Performance Simulation

4

INTRODUCTION

Technological advancements have given designers the capability to access feedback regarding the performance of their design almost instantly. Within the context of a zero energy building, incorporating building performance simulation as a process is critical to optimizing the project design.

As a 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 the energy performance of a building. However, high-performance buildings typically require other analyses to optimize the design. Some of the more common simulations cover lighting, daylighting, and natural ventilation strategies. While the energy impact of these design strategies is certainly of interest, particularly in a zero energy building, it is not the only criteria that defines success. Lighting quality, thermal comfort, and indoor air quality are examples that should be modeled while meeting the energy goals. As a result, “building performance simulation” is a more accurate description for the process advocated in this chapter.

SIMULATION TEAM

Building performance simulation may be provided by engineering firms, architecture firms, or by dedicated specialists. Rather than focusing 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. A school should require analysis related to the following:

- Climate
- Building Massing
- Energy
- Daylighting
- Lighting
- Mechanical systems sizing and selection
- Air movement

- Acoustics
- Heat and moisture migration
- Thermal comfort

The responsibility for modeling and evaluating the performance of the project in these areas will often be distributed among several team members as it is challenging for one person to be an expert in all areas. All of 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.

SIMULATION TYPES

This chapter contains descriptions of simulations types used to evaluate and enhance design strategies that may be developed in response to performance targets set for the project. If the project is supported by a team capable of providing the capabilities noted in this chapter, then these performance targets represent the ideal outcomes that an iterative analysis should seek to achieve.

Analysis for zero energy schools requires multiple instances of the energy model. Like a set of plans, the model follows the entire design process from conception through operations. These instances may include:

- **Baseline model.** Typically used for comparison purposes. It represents a theoretical benchmark against which the proposed design can be studied. It can be used to calculate percent energy savings from "typical" design. As zero energy defines an absolute energy goal, baseline models are not necessary unless energy savings is needed for some other reason. It can also serve as a starting point for analysis, as the code-compliant building is the worst energy performing building that can be legally constructed.
- **Design model.** Intended to weigh trade-offs and evaluate strategies and features. These strategies are tested to determine the impact and progress towards meeting the goal. Ideally, this model is started at conceptual design and informs the form of the building. This model may not represent the final design as it may need to satisfy rules associated with showing code compliance.
- **Predictive model.** While most modelers will try to satisfy the project needs with only the design models, the standards and codes to which they must adhere may require that they simulate aspects of the building that are not necessarily reflective of the actual project design. This model needs to meet the zero energy design goals, including those for renewable generation. It also includes passive strategies that are used to eliminate or reduce mechanical cooling requirements, or when the design team plans to use plug load reduction by selecting efficient equipment. The predictive model should match the final set of plans used for construction.
- **Calibrated model.** Created to reflect the most accurate set of conditions following construction and during the occupancy of the building. This should reflect as-installed equipment, as-tested performance information (such as enclosure leakage), and include actual weather and occupancy information. The calibrated model is ultimately used in the measurement and verification process to tune the building and ensure that it is operating properly. When deviations from actual performance exist, they can be compared against the calibrated model looking for issues to correct.

While the baseline and design models are common for most projects that incorporate building performance simulation, a predictive and calibrated model are critical for a zero energy project. As such, the inclusion of these models should be in the scope of the design. The model is a valuable tool to guide design and operational decisions for the entire life of the building and not just a code-compliance tool.

SIMULATION PROCESS AND STRATEGIES

The value and appropriateness of simulation types varies based on the stage of the project. Simulations can provide data to make 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 simulation, these early decisions can streamline the design and operation of the building saving the project time as it unfolds.

Decisions from simulation, such as Form/Shape analysis are highly valuable at the early stages of a project. If left until later in the design process, such an analysis is unlikely to change 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. These analysis should be done before HVAC is designed as it may inform the sizing and type of HVAC equipment.

Whereas Figure 3-1 describes when certain analyses should be performed, the following section provides greater detail describing what is being analyzed, as well as where some opportunities may exist for a modeler to help provide valuable feedback to the design team.

CLIMATE

The location of the project dictates what climatic conditions represent opportunities or challenges. It is easier to achieve zero energy goals if the building uses the climate as a benefit, rather than working against the climate; therefore, thorough understanding of the site climate is a fundamental first step. Obtaining data from a weather station that reflects the local climate is a key starting point. If long-term weather data is available from the building site, it can also be used. 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 are examples of influences on microclimates.

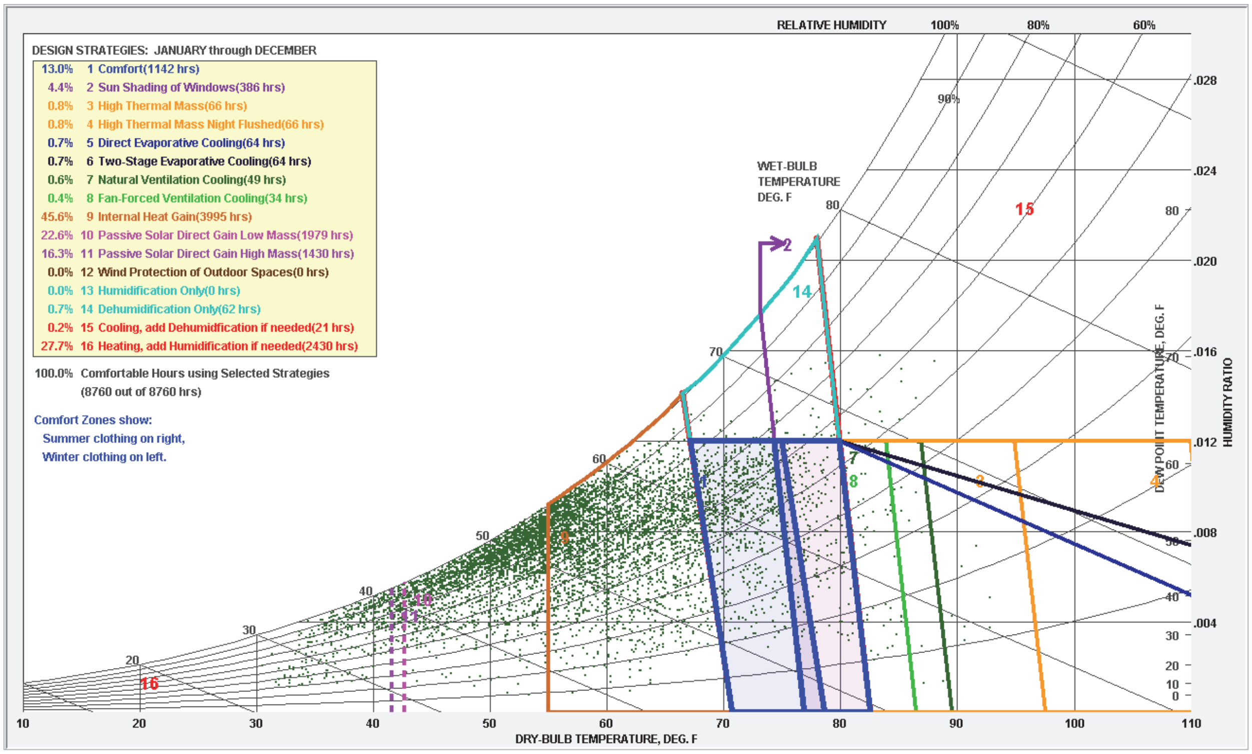
Data generated from these weather files requires analysis and interpretation. This analysis should help inform early design thinking by generating climate-specific strategies. Temperature and humidity data (Figure 4-1a) provide early indications about using natural ventilation during the school calendar, while a wind wheel (Figure 4-1b) would provide insight into wind direction and velocity during those periods. Combined, the information could influence the orientation of the building to benefit natural ventilation. It also will provide insights as to whether sufficient wind resource exists for on-site wind turbines. Annual weather volatility can affect also energy consumption and the production of renewable energy, which together can affect the overall energy profile of a project.

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 file(s) to determine if it is appropriately representative of the actual site conditions (Olgyay 2015; DeKay and Brown 2014).

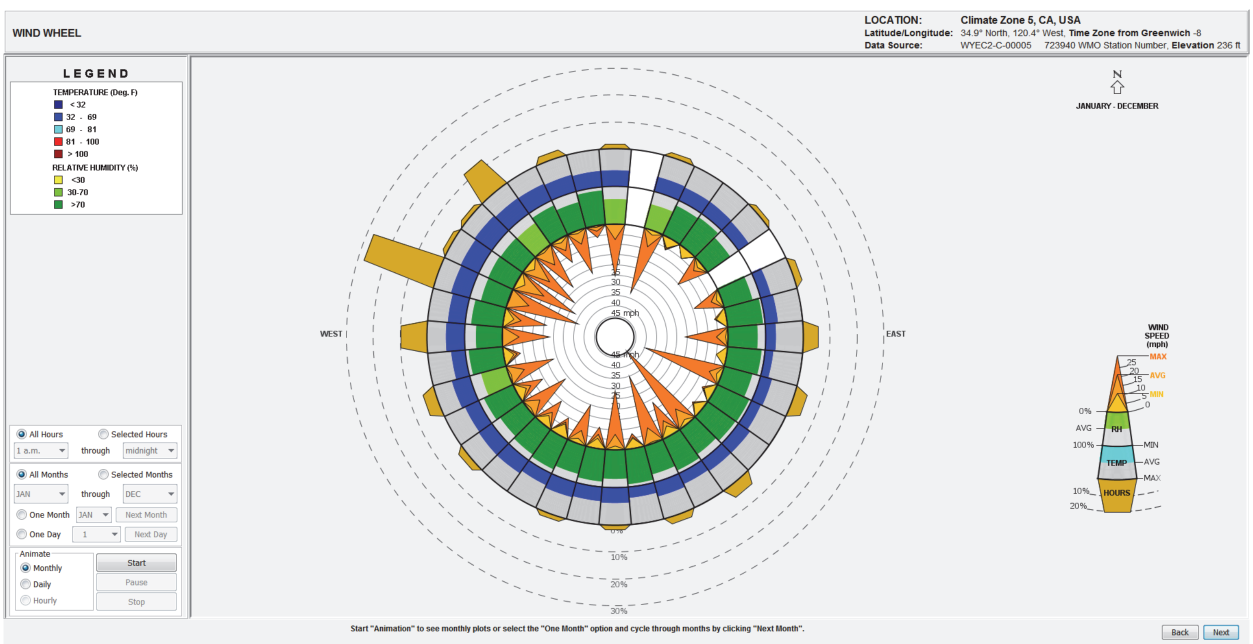
Lastly, because the weather files use historical data, it may be worth considering future weather changes. Weather data files can be altered to test the sensitivity of building design elements into the future. An example may be a natural ventilation strategy may work for additional hours in a northern climate with higher ambient temperatures.

FORM AND SHAPE

A form and shape analysis examines the impact of the building's geometry on the energy performance, including the building energy consumption and energy production from photovoltaic systems. The building design team is able to quantitatively understand 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.



(a)



(b)

Figure 4-1 (a) Annual temperature stress by month and (b) wind speed and direction.
Source: National Renewable Energy Laboratory

Figure 4-2 shows examples generated during the schematic design process of a school to test the impact and performance of three different schemes under consideration. Even at such an early level, this analysis helps determine the low energy and daylighting potential for each concept.

WINDOW-TO-WALL RATIO

Window-to-wall ratios can be analyzed by applying increments in percentage of windows to the entire model, different facade orientations, or selected rooms. When applying the windows, the option to select the height, width, and spacing for the windows is available to create an accurate model. Windows can also be segregated into those that primary provide daylighting to offset electric lighting loads and view glass.

This study should reveal the optimum point between the increasing window to wall area ratio versus the change in energy usage and peak loads. 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 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 window-to wall ratios, see EN42 and DL6 in Chapter 5.

SHADING

Closely coupled to the window-to-wall ratio 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 glass can help with this problem, overhangs 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 length of the overhang can be determined such that it benefits the energy use as well as managing glare from the sun.

Figure 4-3 is a solar analysis of a school in early design. The base analysis shows significant solar radiation (colored red and orange) on the roof and south facades. As expected, the east facade in this image (colored green) receives far less solar radiation. Because this project is in a hot/humid climate, manipulating the form and adding exterior shading systems may be an appropriate design response. Further iterations of this analysis would visually demonstrate the impact of these strategies.

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 an occupied zone, occupant comfort could be compromised or shading systems could reduce the heat gain.

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. Sometimes, alternate technologies can help, such as Trombe walls.

Strategies related to shading techniques are discussed in Chapter 5. (See BP2, BP4, BP9, EN52, DL2, DL5, DL6, DL8.)

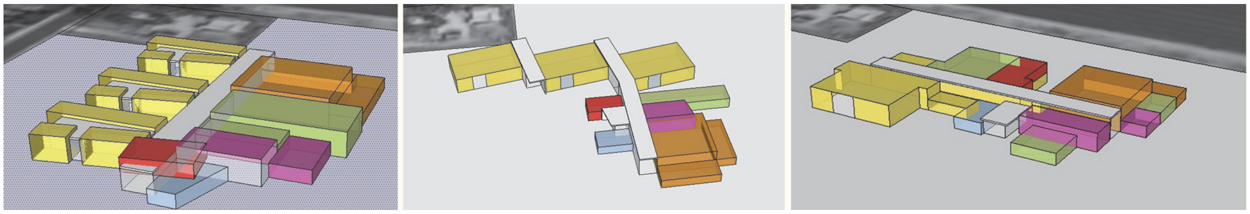


Figure 4-2 Varying geometries to analyze impact of form/shape.
Images courtesy of M.E. Group

Chapter 4

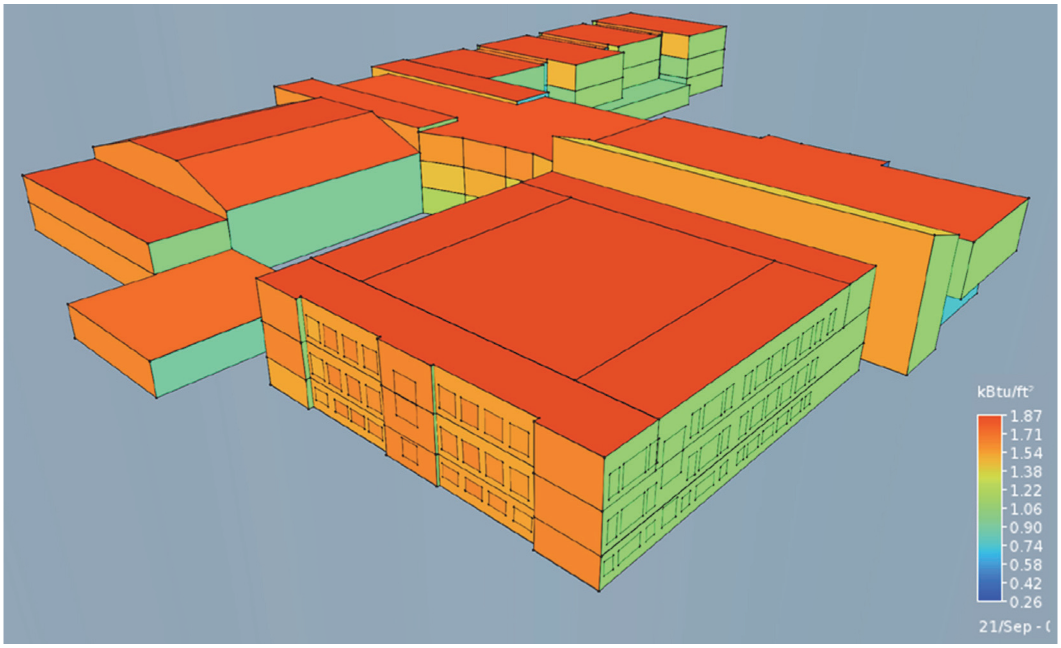


Figure 4-3 Solar analysis.
Image generated by M.E. Group using IES-VE

ENVELOPE

The barrier between the outdoor 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. However, there is generally a point of diminishing returns between improvements to the building envelope reduction in energy use and peak loads. Since each building is impacted by many factors including form, climate, internal usage, and glazing; each building's point of diminishing returns differs. However, the point of diminishing returns for each building can be found through careful analysis.

Figure 4-4 is a simple comparison of overall building energy use intensity (EUI) versus exterior wall insulation. 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.

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 leakage.

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

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

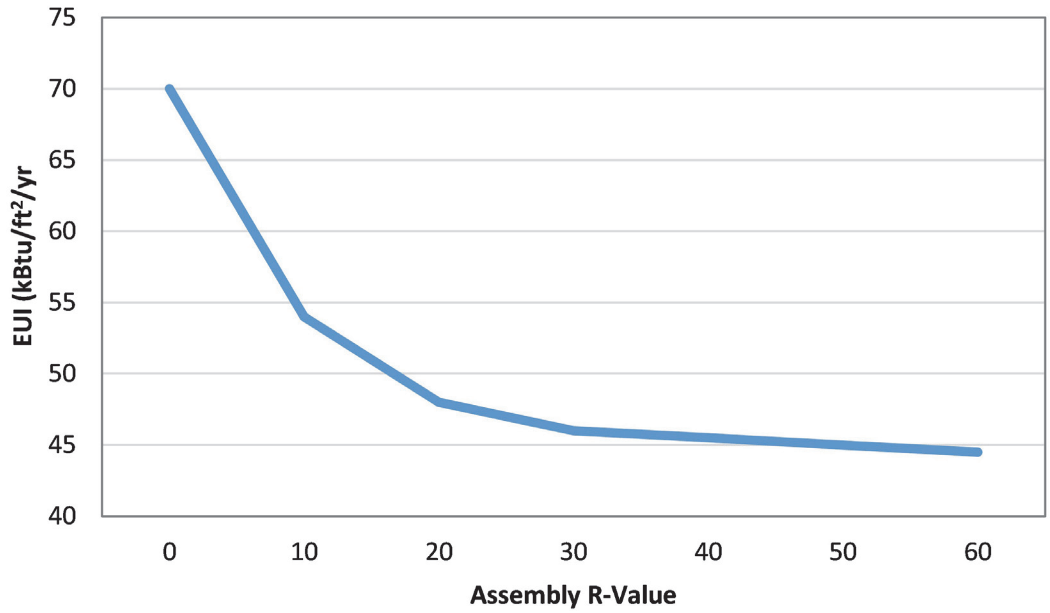


Figure 4-4 Exterior wall insulation versus EUI.

USER BEHAVIOR

Estimating user behavior is an attempt to understand how a building occupant both react to their environment and also influence it with their active and passive behaviors. The objective is to mimic the occupant with operational schedules such that lights and HVAC are operated during occupied hours. It is a common fault of models that occupancy is underestimated, which shows up in actual building operations as a building that uses too much energy. In addition, the number of occupants changes during the day and week and this must be accounted for to properly model internal heat generated from the occupants.

Surveys and interviews with district operations staff, as well as data collection from existing district schools, can be used to determine the actual building occupancy and schedules of use. Actual usage can vary substantially from the official operating hours for the school, which affects the accuracy of the model. Activities such as after school tutoring, sports, clubs, and community events may be regular occurrences that should be accounted for within the energy model.

In addition to hours of operation, the way a school district's maintenance staff operates a building has an impact on the energy use. The model should be aligned with the school district's specific operations policies as closely as possible.

Specific links to occupant engagement relative to building performance are discussed further in Chapters 2 and 3.

EQUIPMENT SCHEDULES AND LOADS

Equipment schedules and loads are assumptions which help estimate the thermal gain and energy consumption. These includes plug loads, information technology, process loads, and any other load that is connected to an energy supply that is 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 the building.

Estimated equipment loads and schedules are provided in the ASHRAE Standard 90.1 User's Manual (ASHRAE 2017b) for different building types. When actual equipment loads are not available, these 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.

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 right size mechanical systems within the design schedule. For additional information on rightsizing HVAC equipment, see HV21 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, illuminance levels, daylight harvesting, and other controls options. For more information on these metrics, see the electric lighting section in Chapter 5.

NATURAL VENTILATION

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

Modeling software has various levels of sophistication with regards to modeling natural ventilation. Determine the feasibility of using natural ventilation with the fastest, most reasonably accurate simulation methodologies first. to. Only after the strategy has been deemed feasible and worth pursuing should more sophisticated analyses, such as computational fluid dynamics (CFD) be considered. A CFD analysis is typically time consuming, and is a better strategy for optimizing the ventilation scheme, such as opening locations and sizes, rather than determining the feasibility of natural ventilation itself. Strategies related to natural ventilation are covered in Chapter 5. (See BP1-BP3, BP7, BP14, EN42, EN43, EN57, DL2, DL5, HV1, HV34, HV35.)

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 agent, and model strategies against conventional approaches to determine the value of pursuing these strategies.

Actual, tested air leakage rates should be obtained from the commissioning agent and updated in the model to reflect the as-constructed conditions. See EN1 and EN2 in Chapter 5 for more information on infiltration and air leakage control strategies. Additional information on air leakage testing is provided in the Commissioning during Construction section of Chapter 3. For design purposes, using leakage rates from previous buildings is a good start. See EN1 and EN2 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 AUTONOMY AND GLARE ANALYSIS

An effective daylighting system is one in which the occupants don't want the lights on. To achieve this level of effectiveness, detailed daylighting must be performed. Improvements in the efficiency of lighting technologies can reduce the impact of daylighting such that a balance of electric lighting and daylighting should be evaluated. This balance of lighting technologies, thermal performance of glass, and providing views may not fall within the capability of the simulation software utilized; but it is vital to the successful experience of the occupant.

Spatial daylight autonomy (sDA) is the desired metric to determine the accessibility occupants have to daylight on an annual basis. Additional information on these metrics is provided in DL3 in Chapter 5.

Glare analysis is the study of how the light levels impacting the space can have an effect on occupant comfort and ability to work. The data can be analyzed so that adjustments can be made to the building form, or shading in order to reduce glare levels, and increasing comfort for users.

Figure 4-5 is an example of a spatial daylight autonomy study conducted on an early building form. It indicates areas that do not have enough daylight, as well as those that have too much daylight that could cause glare problems. This information is used to refine the daylighting strategies to increase daylight in underlighted areas, and reduce or provide better controllability of daylight in areas that are overlighted.

Shading and occupant controllability of shading are critical considerations. Where occupants are able to control the use of shades, the modeler must take care to include expected occupant behavior within the energy results.

RAY TRACE ANALYSIS

Ray tracing analysis is a daylighting analysis method which allows the user to see daylight levels over a period of time.

Ray tracing is done in a modeling program which allows designers to visually see how daylight changes over time in a space. This allows building designers to see how natural daylight levels will affect the users of the space, and when the space will need to be supplemented with artificial light. This allows the designer to alter the space to allow for more, or less, daylight levels to satisfy the occupant while using less energy.

HEATING AND COOLING LOADS

Heating and cooling loads, and the corresponding equipment sizing may be used as a proxy for energy performance. Larger heating and cooling plants will generally require more energy. Strategies that yield smaller plant sizes will also be found to reduce energy consumption. Therefore, analyses used to evaluate load reduction strategies should be included in the process.

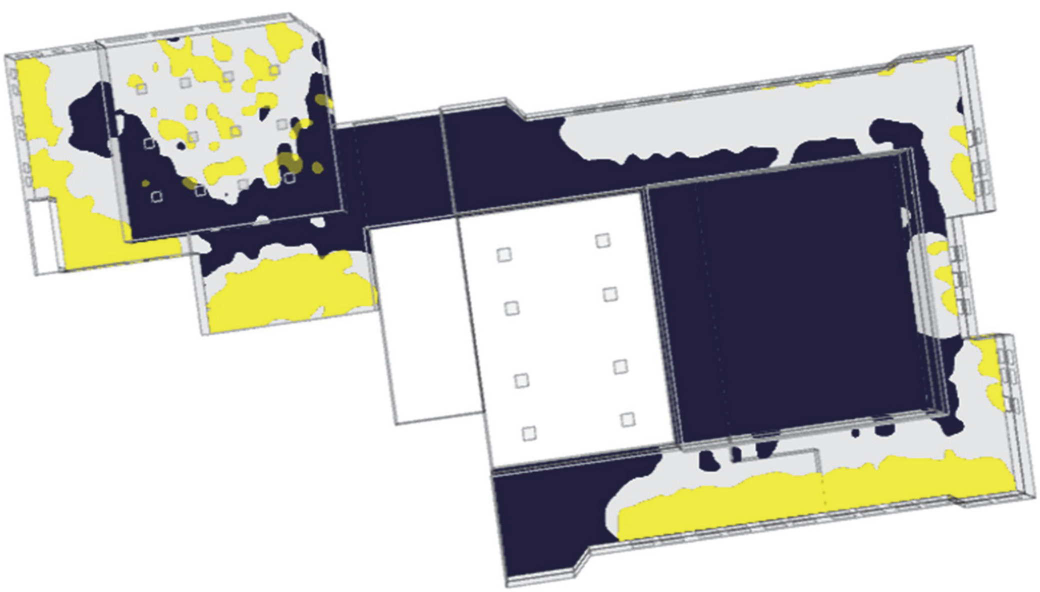
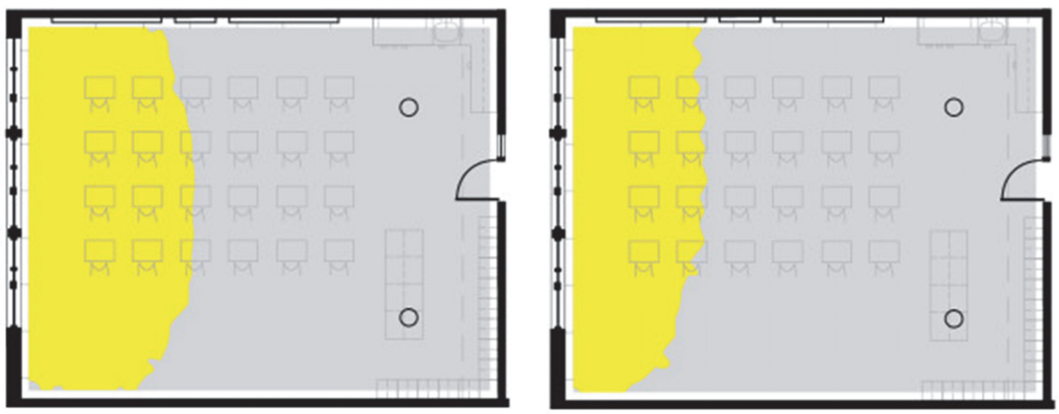


Figure 4-5 Spatial daylighting autonomy (sDA) analysis.
Image generated using Sefaira

Evaluating Daylighting Performance

A well daylighted classroom would have a high spatial daylight autonomy (sDA) and low annual sunlight exposure (ASE). (See dynamic daylight metrics and DL3 in Chapter 5 for additional discussion on these metrics.) A daylighting analysis of the initial design might yield the results shown in the initial design figures.



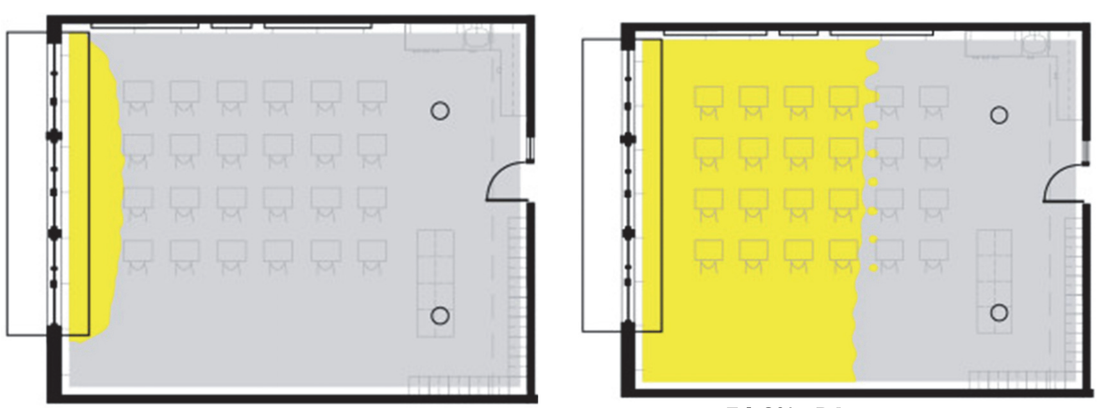
31.3% $ASE_{1000\ lux,\ 250\ hours}$
669 average hours

28.1% $sDA_{300\ lux,\ 50\%}$

Daylighting illumination levels—initial design.

This analysis reveals that the proposed design falls short of the performance targets for sDA and ASE. This would result in increased artificial lighting use. Additionally, the percentage floor area subject to visually uncomfortable amounts of glare is too high.

Based on these results, the design team might consider incorporating an exterior shading element to reduce the glare, and an interior light shelf designed to reflect light deeper into the space. Modeling this scenario yields the following results:



10.1% $ASE_{1000\ lux,\ 250\ hours}$
604 average hours

54.3% $sDA_{300\ lux,\ 50\%}$

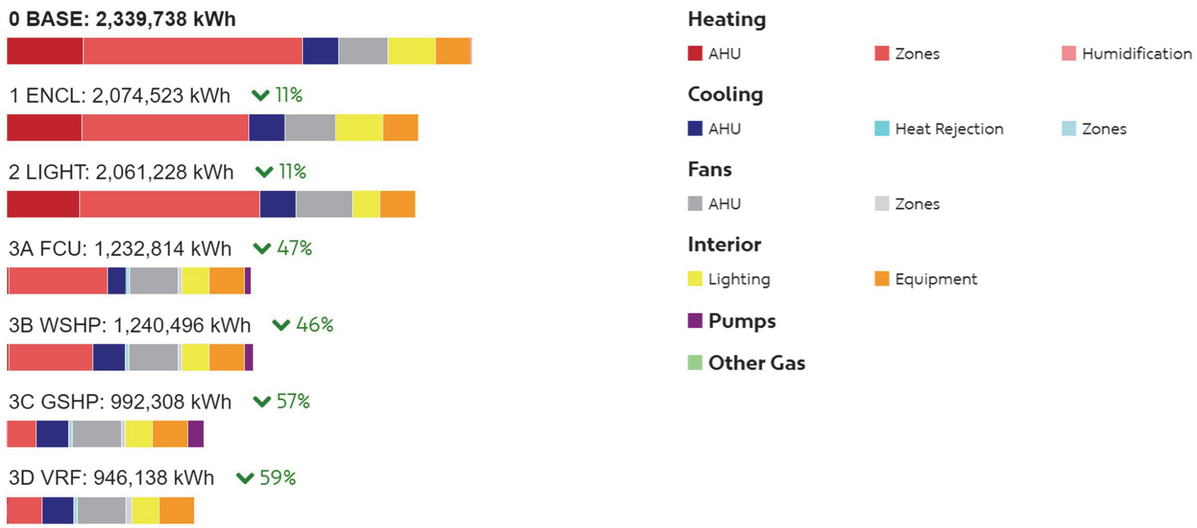
Daylighting illumination levels—with easier shading element.

Both the sDA and ASE results were greatly improved. A greater percentage of floor area achieves spatial daylight autonomy, while a lower percentage of floor area was subjected to excessive glare. The design team would continue to work collaboratively with the modeler to evaluate how greater daylight penetration could be accomplished without negatively impacting the ASE results. Next steps to consider might incorporate the modeling of tubular daylighting devices or perhaps a reflective louver system. EUI should be incorporated into the results, and an optimal scenario would yield a high sDA, low ASE, and low EUI.

Parametric analysis defines the ideal outcome—in this case, balancing sDA, ASE, and EUI and running numerous models runs hundreds of iterations to find the optimal result. These results yield recommended strategies for the design team.

Comparing Mechanical Systems

The figure below illustrates a comparison of mechanical systems performed early in the design process. In this analysis, basic enclosure and lighting improvements were made prior to conducting the analysis of four HVAC systems, denoted as FCU (fan coil unit), WSHP (water source heat pump, GSHP (ground source heat pump), and VRF (variable refrigerant flow). In addition to providing an overall assessment of the energy use for each system, the analysis provides details about the relative energy consumption of the system end uses (heating, cooling, pumps, fans, etc.). This type of macro analysis is typically done in schematic design to allow for system selection, but smaller micro decisions may be required during subsequent design development stages. Examples of these smaller decisions include comparing various equipment efficiencies and controls strategies.



Analysis of energy-efficiency measures.
Image generated by Sefaira

A fundamental energy savings strategy is right sizing of mechanical equipment. Oversized equipment is responsible for energy waste. 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 HV3, HV8, and HV2

MECHANICAL SYSTEMS COMPARISONS

A mechanical systems plant consists of the equipment that produce and distribute the heating and cooling such as: chillers, boilers, cooling towers, fans, and pumps. In this comparison process, multiple heating and cooling options are evaluated to determine the most effective solution for the project.

Plant comparisons help with effective decision making regarding the HVAC systems. The HVAC system components are the primary consumers of energy to create a conditioned space, however, they use energy in part because of plug loads, lighting loads, outdoor air requirements, and the building envelope.

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ODYSSEY ELEMENTARY SCHOOL

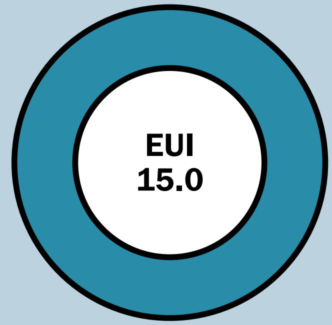
As a prototype for the district, the design of Odyssey Elementary had to work on any site and still use daylighting in the classrooms. It was designed so that the four classroom wings can be properly oriented even if the building is flipped to accommodate different sites.

The school uses a number of automated systems that allowed the size of systems equipment to be reduced, which lowered both energy use and first costs. To ensure proper operation, the school employed an extensive commissioning and training process.

The school did not initially expect to reach a zero energy level, although it was designed to be zero energy ready. Once the design EUI was brought down below 22 kBtu/ft^2·yr, it was an easy decision to go for zero energy. Because the building is so cost effective (it functions as energy positive), summer activities throughout the district are funneled to the school.

For more information about this school, visit the U.S. Department of Energy Commercial Buildings Resource Database: https://building-data.energy.gov/cbrd/search/resources/k12casestudy.

CLIMATE ZONE 5B



Woods Cross, UT

Davis School District

Odyssey Elementary School. **Commons area.**

Images courtesy of VCBO Architecture, photography by Dana Sohm

Project Data	Building Envelope
Site area: 12 acres	Overall roof R-value: R-30
Conditioned gross area: 84,758 ft^2	Wall insulation type: 3 in. continuous polyisocyanurate
No. of floors: 2	Overall R-value: R-20
Grade levels: Pre-K–6th grade	Window type: Double glazed
Occupancy: Standard and summer programs	Window assembly U-factor: 0.27
Context: Suburban	Solar heat gain coefficient: 0.25
No. of occupants: 725	**Building Systems**
No. of students: 650	HVAC systems: ground-source heat pump (GSHP) heat exchange loops, evaporative cooling, water-to-water pumps, gas boiler
Year completed: 2014	Ventilation: Thermal displacement
Financing model: Bond	RE type and size: 320 kW photovoltaic (PV) (1100 panels)
Construction cost: $13,021,600	**Project Team**
Energy Data	Architect: VCBO
Predicted EUI: 21.8 kBtu/ft^2·yr	Engineers: Bsumek Mu and Associates, Ensign Engineering and Land Surveying, Van Boerum & Frank Associates, Envision Engineering
Actual EUI: 15.0 kBtu/ft^2·yr	Contractor: Hughes General Contractors
Actual RE: 31.2 kBtu/ft^2·yr	
Actual net EUI: –16.2 kBtu/ft^2·yr	
Certifications: LEED Gold 2016	

HOLLIS MONTESSORI SCHOOL

The Hollis Montessori School exemplifies zero energy ready in institutional buildings. The project successfully balances multiple goals, including education, Montessori principles (such as independence, freedom, and respect), and the institutional goals of healthy indoor air, durability and longevity, cost effectiveness, and exceptional energy performance. The solution for the school was a high-performance building enclosure, very high-efficiency HVAC systems, design that maximizes daylighting, and orientation for passive solar gain.

KEY ENERGY EFFICIENCY AND SUSTAINABLE FEATURES

- Multiple lighting zones per classroom, photosensors, and occupancy sensors
- Designed for future PV, including roof structure for wind loading and conduits to roof for wiring
- All electric systems with PV to be installed
- Individual controls for each classroom for heating/cooling/ventilation systems
- Demand-controlled ventilation via CO_2 monitoring
- Superinsulated and airtight building envelope
- Triple-paned windows
- Low-flow fixtures and waterless urinals
- Low- and no-VOC material
- Rainwater collection for garden irrigation

CLIMATE ZONE 5A

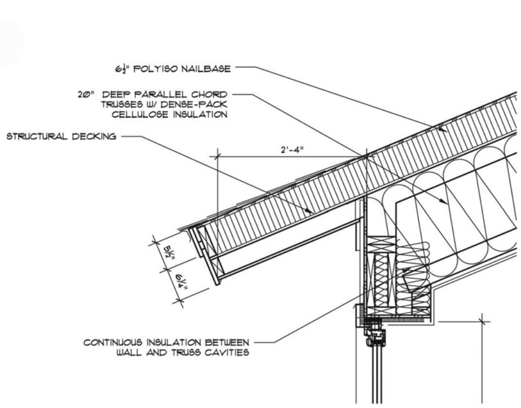
EUI
9.6

Hollis, NH

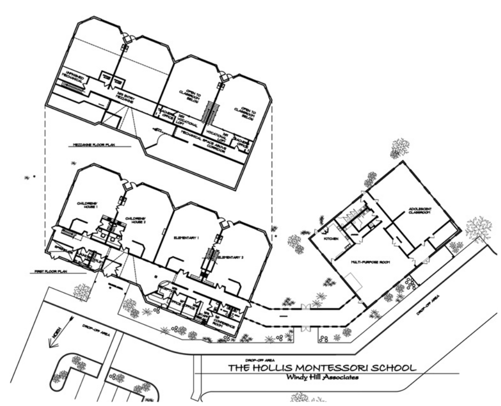
Hollis Montessori
School District

Webpages:
http://hollismontessori.org/
http://zeroenergy.com/hollis-montessori

Hollis Montessori School.
Photo © Eric Roth Photography, reprinted with permission



Roof/wall section.



School floor plan.

Images courtesy of Windy Hill Associates

Project Data	Building Envelope
Site area: 9.5 acres Conditioned gross area: 11,000 ft^2 Building footprint: 9066 ft^2 No. of floors: 2 Grade levels: Age 3–9th grade	Roof type: Parallel chord truss Insulation type: Dense-packed cellulose plus 6 in. continuous rigid polyisocyanurate Overall R-value: R-111
Occupancy: Standard Context: Rural No. of occupants: 125 No. of students: 113	Wall construction: Double-stud wood framed Insulation type: Dense packed cellulose Overall R-value: R-41
Year completed: 2013 Financing model: Loan + donation (10%) Construction cost: \$200/ft^2	Slab edge insulation R-value: R-8.8 Under slab insulation R-value: R-54
Energy Data	Window type: PVC triple glazed tilt/turn (argon gas) Window assembly U-factor: 0.15 Solar heat gain coefficient: 0.33 Visible transmittance: 0.46 Glazing percentage: 14%
Predicted EUI: 10.3 kBtu/ft^2·yr Predicted net EUI: 10.3 kBtu/ft^2·yr	Modeled airtightness: 0.60 ACH50 Measured airtightness: 0.30 ACH50
Actual EUI: 9.6 kBtu/ft^2·yr Actual net EUI: 9.6 kBtu/ft^2·yr Zero energy status: Zero energy ready (27 kW system needed	**Project Team**
Certifications: Passive House	Architect: Windy Hill Associates Engineers: Hayner/Swanson, Inc.; Trexler Engineering, Reno Engineering and Light Design; Zero Energy Design Energy consultant: Zero Energy Design Construction manager/contractor: TJ Dang
Building Systems	
HVAC system: Air-source heat pump (HP) with heat recovery ventilator	
	Note: *ACH50 = air changes per hour at 50 Pa pressure*

How-To Strategies

5

There are many pathways to achieve a zero energy school, and more are becoming available as new technologies are developed. Both renewable energy and existing energy-efficiency technologies are also advancing rapidly. This chapter outlines strategies to move a project toward zero energy. Success will come by finding synergies through the integrated design of all components that affect the energy consumption of the building. The objective is to achieve a low energy use intensity (EUI) target as specified in this guide (see Tables 3-1 and 3-2) and balance that with renewable energy. Even if renewable energy is only planned into a project, the decisions about energy efficiency will create a building ready for the future. Technologies are changing fast enough that prescribing a list of technologies will quickly become out of date and will not produce an economically competitive building. 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 part in determining which technologies to use.

The differences between school size, construction classification, climate sensitivities, and regional practices make it impossible to address all the conditions that will be encountered in a typical school project. The how-to information in this chapter is intended to provide guidance on strategies and good practices for achieving a zero energy school. 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 a starting point 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 building design is following (✓column) and components that the building design doesn't contain (**X** column).

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

Table 5-1 Summary of Strategies and Recommendations

	Component	How-To Tips	✓	X
Building and Site	Site design strategies	BP1–BP2		
	Building design strategies	BP3–BP8, BP11–BP16		
	Building orientation	BP9–BP10		
	Planning for renewable energy	BP17–BP23		
	PV as percentage of gross floor area by climate zone	Table 5-2		
Envelope	Construction strategies	EN1–EN5		
	Opaque components	EN6–EN17		
	Recommended envelope construction factors	Table 5-3		
	Thermal bridging	EN18–EN41		
	Building fenestration	EN42		
	Recommended fenestration criteria	Table 5-5		
Daylighting	Design strategies	DL1–DL13		
	Recommended SHGC multipliers for permanent projections	Table 5-6		
	Recommended design criteria by space type	Table 5-7		
	Recommended DFA by climate zone	Table 5-8		
	Minimum interior surface reflectance	Table 5-9		
	Space specific strategies	DL14–DL18		
Electric Lighting	Luminaire and design strategies	EL1–EL10		
	Luminaire recommendations	Table 5-10		
	Control strategies	EL11–EL22		
	Recommended LPDs by space type	Table 5-11		
	Space specific strategies	EL23–EL27		
	Exterior lighting	EL28–EL31		
PL	Plug load management	PL1–PL6		
	Power distribution systems	PL7–PL8		
Kitchen Equipment	Equipment and design strategies	KE1–KE9		
	Equipment performance specifications	Tables 5-13 to 5-19		
	Refrigerator and freezer recommendations	Table 5-20		
	Walk-in coolers and freezers	KE9–KE20		
	Walk-in freezer floor insulation levels	Table 5-21		
	Walk-in refrigerator recommendations	Table 5-22 to 5-23		
	Heat recovery	KE21–KE22		
SWH	System types	WH1–WH2		
	Gas water heater recommendations	Table 5-24		
	Electric resistance water heater recommendations	Table 5-25		
	Heat pump water heater recommendations	Table 5-26		
	Piping insulation recommendations	Table 5-27		
	Design strategies	WH3–WH8		
HVAC Systems	Design strategies	HV1–HV3, HV21–HV37		
	Equipment recommendations	Table 5-28		
	Chilled/hot-water system with single-zone AHU	HV4–HV6		
	Air-source variable-refrigerant-flow (VRF) multi-split heat pump	HV7–HV10		
	Ground source heat pump (GSHP)	HV11–HV14		
	DOAS	HV15–HV20		
RE	Terminology	RE1		
	Design strategies	RE2–RE9		
	Implementation strategies	RE10–RE13		

building energy usage by making smart and informed decisions that establish a solid framework for subsequent decisions and conservation measures.

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

SITE DESIGN STRATEGIES

BP1 Select Appropriate Building Site(s)

There are many factors that affect the viability and sustainability 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.

Building sites that are level or southward-facing are preferred to sites on slopes facing in other directions. It can be difficult finding adequate sites for new schools in congested or built-out cities and suburbs. Likewise, in rural areas, be cognizant of the need to conserve and maintain forests, farmland, and other undeveloped land parcels. As many schools are located in residential areas, utility power constraints, especially for renewable energy production, may impact the ability to achieve zero energy.

Where natural ventilation or wind power is desirable, site assessments for each site should include a comparison of solar orientation and solar access, followed by wind speed and wind quality. Ideally, the local climate, solar access, potential shading issues would be studied as part of the site selection. Chapter 4 discusses modeling for climate analysis. Additional information on evaluating building sites for complete solar access is covered in BP17.

BP2 Optimize Building Siting Combined with Landscaping and Site Features

Site features that should be considered or developed into an energy-efficient school include the following:

- Use of dense evergreen trees and landscaping to reduce undesirable winter winds, which will reduce building infiltration
- Use of trees and landscaping to funnel desirable breezes toward a building for cooling or ventilation
- Use of deciduous trees to provide beneficial shading of the sun in summer. But, be careful not to shade solar panels as trees grow to full height
- Even when trees lose their leaves, shading from branches will impact passive solar gains as well as shade solar panels
- Proximity of water bodies to provide beneficial changes in temperature or humidity to the immediate microclimate
- Effect of landforms and plant forms on wind speed and wind quality, relative to natural ventilation and wind power
- Effect of landforms and plant forms on solar access and daylighting
- Beneficial effects of plant-based evapotranspiration on thermal comfort
- Beneficial effects of earth-berming on reduced cooling loads
- Thermal conductivity of the soil as it relates to the potential of ground-source heating and cooling systems
- Proximity of water bodies for discharging heat

Figure 5-1 shows a site analysis plan used to analyze the effect of these features on the Poquoson Elementary School.

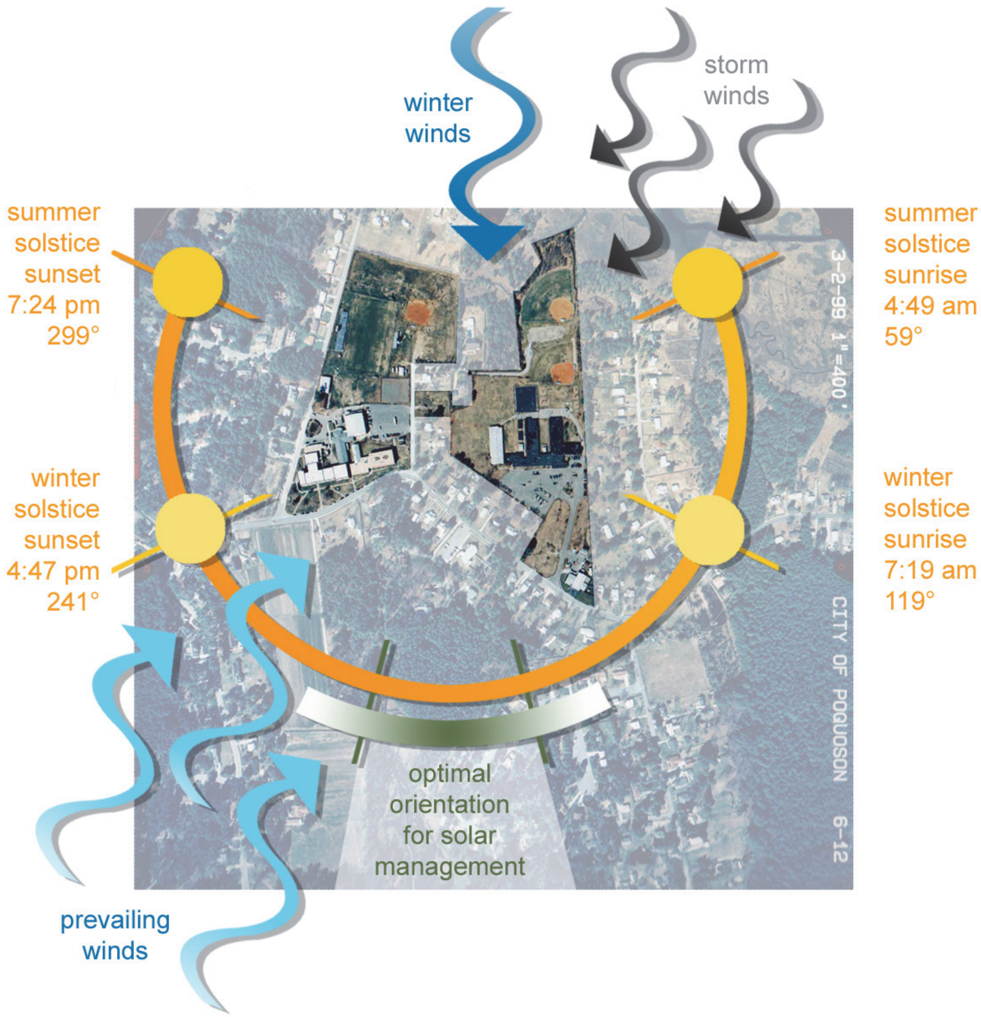


Figure 5-1 (BP2) Site analysis plan—Poquoson Elementary School.
Reproduced by permission VDMO Architects

BUILDING MASSING

The articulation of a building's physical form can affect energy use in many different ways

BP3 Minimize Surface Area to Volume Ratio

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

A sphere has the most efficient ratio of surface area to volume. In more practical building terms, a cube has the most efficient ratio and would minimize thermal losses through the building envelope, though the compact shape poses some challenges to other goals such as maximizing daylighting and providing natural ventilation. Looking at just energy, appropriately sized windows used for daylighting save more lighting energy than the heat loss or gain through these windows. This is maximized by appropriate orientation (See BP9 and BP10).The massing of the building must support this function even if it results in additional opaque insulated exterior surfaces.

Shape factor is known to have a more pronounced effect on building energy usage in the coldest climates. In climate zones 7 and 8, rely on very simple and compact shapes. Give preference to massing strategies that stack program elements vertically to create multistory buildings. In many communities, three and four story school buildings are a common trend based on land resource considerations.

BP4 Optimize Building Shape

Where a climate-responsive approach dictates, configure buildings as elongated rectangles, or as a series of such rectangles. This specific shape, when properly oriented (see BP9), can reduce energy use, ease solar shading strategies, and help to mitigate unwanted glare. The optimal shape allows for daylighting of indoor spaces and quality views from indoors to outdoors.

BP5 Minimize Surfaces Receiving Direct Solar Radiation

Minimize the incident angle of solar radiation, especially during the cooling season. In general, it is difficult to shade east and west facades that are susceptible to overheating (see BP9). South facades typically have high incident solar angles as the sun is high in the sky. Even so, appropriately sized overhangs will minimize solar gains. Avoid reliance on glass that has a low solar heat gain coefficient (SHGC) to correct an overglazing issue.

BP6 Avoid Reflected Solar Glare

Unwanted solar reflection can come from many different sources and is often unavoidable. Building massing strategies that effectively reflect radiation from one part of a building to another should be avoided. In addition, avoid creating a situation where the new building causes a reflection problem on another building.

As an example, where a lower building volume is located on the southern side of a higher building volume, reflective roof or terrace surfaces below will reflect radiation into the higher portions of the building—likely giving rise to overheating, uncontrollable glare, and visual discomfort. Reflected light can be beneficial for interior daylighting if effectively managed. Ensure that the reflecting surface is not generally visible to the building occupant.

BP7 Optimize the Building for Natural Ventilation

Design building massing to make beneficial use of the wind for natural ventilation. In many climates there are significant time periods during which natural ventilation can play a role in bringing fresh air to the classrooms and other spaces. See HV35 for additional information on natural ventilation.

The most important factor in the effectiveness of natural ventilation is cross-ventilating the space. Place openings lower on the side facing the summer prevailing breezes (windward side), and higher on the leeward side, to take advantage of the stack effect of exhausting the warmer air. A solar chimney with operable vents at the top can also be used on the leeward side to help pull the warm air out of the building.

If the conditions are right to use natural ventilation, a computational fluid dynamics simulation should be run to test the airflow through the space. A roof shape that may appear to be conducive to effective flows may in fact prove ineffective in the simulation run; for instance, by creating turbulence that disrupts the flow.

> ***Caution:*** Ambient noise conditions should be verified, and the following items should be considered: the attainment of National Ambient Air Quality standards (EPA 2015), solar gains at the start of any natural ventilation strategy, and solar orientation (see BP5)

Other considerations include humidity, pests, and allergens. In most cases, innovative forms can be developed to enhance natural ventilation, such as using the breeze to pull air out of a chimney on the windward side rather than to push it into the building.

BP8 Configure the Building Massing to Provide Shelter from Wind

Where prevailing or seasonal winds are detrimental to a building's energy performance (e.g., cold winter winds), practitioners should consider configuring the building to minimize windward surface area, minimize the extent of windward windows, and minimize wind turbulence around the building perimeter. While landscaping can assist, considerations need to be made until landscaping is mature.

BUILDING ORIENTATION

BP9 Optimize Orientation

Building energy use varies directly with building orientation, and orientation should be optimized during the early design process. Strategies for orientation relative to the solar path are well-understood; however, a comprehensive optimization also considers the effects of prevailing and seasonal winds relative to energy consumption without neglecting concerns relative to acoustics and reverberation time. Figure 5-2 illustrates the effect of solar path on a building.

For optimal solar orientation in all climate zones, select building sites and orient the building such that a rectangular footprint is elongated along an east-west axis. This orientation achieves the following:

- Minimizes unwanted and difficult-to-control radiation on the 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 in other building components to achieve energy goals.

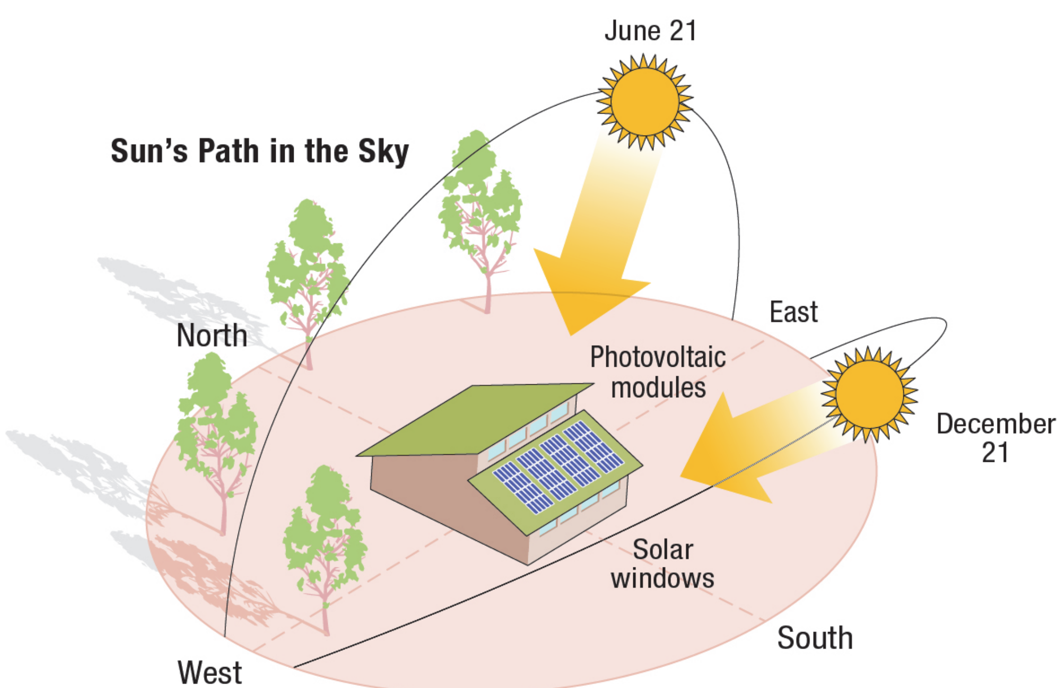


Figure 5-2 (BP9) Solar path illustration.
Source: National Renewable Energy Laboratory

BP10 Fenestration Orientation

In most climate zones, windows should be located in south-facing surfaces, where solar radiation is readily controlled with proper overhangs; however, low-angle winter light may be a problem in northern climate zones with glare concerns. Openings in east- and west-facing walls should be optimized through iterative energy simulation as this radiation is very difficult to manage. Glare and summer heat gains are the predominant issues, and the typical solar control measure of overhangs are limited in their value. (See also DL2, DL5, and DL6.)

North-facing fenestration can be used in all climate zones, but glazing specifications should be optimized and differentiated from glazing facing other directions. North-facing fenestration is ideal for daylighting and avoids solar heat gains. For information on glazing specification see the building fenestration section later in this chapter, specifically EN44–EN46.

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

> ***Caution:*** The potential for environmental noise should also be considered. For example, orienting "C" shaped buildings with the open side toward environmental noise sources should be avoided due to expected reverberation within the open volume.

BUILDING DESIGN STRATEGIES

BP11 Integrate Programmatic Elements for Minimal Energy Use

The manner in which building programmatic elements are arrayed, stacked, or otherwise aggregated can affect building energy usage. Strategies can vary greatly by climate zone, so early phase energy modeling is critical to understanding how zoning actually affects energy use.

Nonregularly occupied spaces such as corridors can be located along exterior walls to buffer envelope-induced temperature swings in the regularly occupied spaces. Corridors can also experience glare and provide a conduit for daylighting to enter classrooms, minimizing glare. These transitional spaces can also be easily naturally ventilated. Brainstorming on how the use of the space can be enhanced by energy-efficiency strategies is critical.

BP12 Zone the Building for Multiple Use and Shutdown

More so than many building types, a school's occupancy schedule and intensity of use can vary greatly over the course of a day, week, or year. Planning is required to anticipate and respond to the changing building loads and comfort needs and to achieve maximum efficiency. Underlying this assumption are two fundamental aspects of zero energy school operation: (1) school systems (lights, HVAC, etc.) should be shut down as soon as possible after the school day ends and (2) only occupied areas of a school should be conditioned. The following strategies can be used to minimize the operational time based on space planning during design:

- Anticipate that the building may be used differently in the future from what is currently programmed or modeled (for example, more community use or less summer occupancy).
- Zone the building and buildings systems to allow low or no energy usage in areas unoccupied during the summer. This could require having the school's administration area as a distinct conditioning zone.
- Zone the building to accommodate conditioning of just those areas occupied for after-school, evening, weekend, or community uses. In practice, anticipate that spaces such as the media center, gymnasium, or cafeteria could need conditioning for short periods of time during non-school activities.

BP13 Provide Exterior Circulation

Interior corridors generally require space conditioning and lighting, which together account for significant energy usage. In milder climates, use covered exterior circulation paths.

BP14 Optimize Classroom Configuration

While educational methodologies are rapidly changing, the fundamental and predominant program element in many schools remains the classroom. As such, smart configuration of the classroom unit can substantially reduce building energy use. The items detailed below are further discussed in the envelope and daylighting sections of this chapter as noted.

Orientation. Where sidelighting strategies are used, building planning efforts should give highest priority to the north-south orientation of classrooms and classroom wings. Give special care to solar control on east- and west-facing classrooms, as glazing in these locations are a source of solar gain and glare. (See also DL5.)

Classroom Height and Depth. Floor to floor heights of at least 14 ft are recommended to allow for daylighting, structure, and other infrastructure needs. For top floor classrooms, where toplighting is available, the depth constraint is less critical. (See also DL11.)

Classroom depths of 25 to 30 ft support an optimal balance of daylighting and energy efficiency, with careful consideration of the deepest portions of the room (see also DL2, DL6, and DL16). Deeper spaces can be adequately daylighted with sidelighting and daylighting reflecting devices (see also DL13 to DL17). For a given classroom area, shallower classrooms will generally entail longer corridors.

Classrooms with Natural Ventilation. In areas where natural ventilation is used, organize classrooms to maintain a ventilation pathway opposite the windows, or through the roof near the opposite wall (for example through a roof monitor). In many cases, this involves operable openings along a corridor wall. (See also EN57, HV30, and HV35.)

Caution: Openings along the corridor can exacerbate acoustic issues.

B15 Provide Entrance Vestibules

Entrance vestibules are a technique to reduce air infiltration from people entering and existing the building. Vestibules should be considered on any doorway that is frequently used. For example, a playground that is directly accessible from a classroom should have a vestibule. Consider the following strategies for vestibules:

Orientation and Configuration. Orient vestibule openings to avoid unwanted infiltration by prevailing winds. The inner and outer doors in school 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 as they increase the walk-off surface available and in turn reduce the amount of dirt and moisture introduced to the school interior. Deeper vestibules also offer the co-benefit of limiting the instances of simultaneous opening of inner and outer doors during passage. Vestibules that are 10 ft or more in clear inside depth are recommended.

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

Vestibule Conditioning. The vestibule should be a semiheated space and not mechanically heated to above 45°F.

BP16 Use Automatic Doors Appropriately

Automatically operating doors (including "ADA doors" with push-button actuators) can be of great functional benefit when used appropriately. Automatic doors use additional energy, add construction costs, and can prove an impediment to daily use when not properly maintained or adjusted for non-automatic use. For these reasons, automatic doors should be selected and deployed with discretion, and the number of automatic doors provided should be limited to the quantity that is functionally necessary. Where automatic doors are specified, low-energy options are available in the marketplace. Capabilities of full-powered versus low-energy options should be examined to ensure the right choice is made with respect to end usage.

Be aware of applicable accessibility requirements and evaluate the energy use of automatic doors in relation to their use as component of a universal design (universally accessible) approach.

Where automatic doors are used in series at an exterior vestibule, ensure that the doors are controlled separately, or are otherwise programmed for asynchronous opening.

Vestibule doors should not be propped open as this defeats the purpose of the vestibule.

PLANNING FOR RENEWABLE ENERGY

BP17 General Guidance

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, the PV arrays are located on the roof to minimize the overall footprint. Planning for the array must begin with project conceptualization to ensure that an adequate roof area is reserved for renewable energy generation. A more detailed discussion on the use of PV is provided in the renewable energy section later in Chapter 5.

Other renewable technologies such as, but not limited to, wind power and micro-hydroelectric generation, may make sense in some regions or on some specific sites. Wind power should be evaluated for noise considerations. Wind power can be attached to the building, but structural and vibration considerations must be designed into the system.

BP18 Roof Form

PV panels may be mounted on flat roofs or pitched roofs. For pitched roofs, the slope should be within 30° of south to maximize the solar production. Building orientation impacts the system functionality. The ideal building orientation would be significantly closer to south and siting the PV system on the south-facing segment will optimize performance.

Single-sloping shed roofs are preferable to gable roofs since large portions of gable roof will have limited or no solar access. As panels will likely be mounted directly to the pitched roof, the pitch of the roof is critical. As a rule of thumb, the pitch should be approximately equal to the latitude. While there is an optimal angle for solar production, variations in roof pitch are not significant. In general, pitches should be maintained between 10° and 50°. Solar calculators can be used to estimate the production.

For additional information on roof construction strategies see EN4, EN5, and EN6.

BP19 Determine Required Roof Area

Based on the modeled data developed by NREL, the approximate roof area needed for PV panel installation can be calculated in each climate zone (Torcellini et al. 2017). This area should be confirmed during the planning stages for the specific goals, project, and climate zone.

Table 5-2 indicates the required area for the two modeled school types in each climate zone. The area indicated in Table 5-2 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 school project. The table demonstrates that in most climate zones, for schools over two stories, it will be exceedingly difficult to achieve zero energy with only rooftop solar.

> ***Caution:*** Individual projects may need to adjust the upgrade factor to account for the elements on the roof and how they are configured.

Early in the project, verify the goals relative to the PV area required for a zero energy school. Recognize that a building roof is never 100% available for PV; space is required for

Table 5-2 (BP19) PV Area as Percent of Gross Floor Area

Climate Zone	Primary School*	Secondary School*
0A	27%	27%
0B	19%	19%
1A	20%	20%
1B	21%	21%
2A	21%	21%
2B	17%	18%
3A	20%	20%
3B	16%	16%
3C	16%	16%
4A	23%	23%
4B	16%	16%
4C	24%	24%
5A	25%	24%
5B	20%	20%
5C	23%	24%
6A	27%	26%
6B	24%	23%
7	31%	29%
8	45%	44%

* Note: Table percentages are for the PV only and do not include the upgrade factor for aisles and other elements on the roof.

roof access, toplighting, plumbing vents, rooftop equipment that cannot be located elsewhere, and other miscellaneous elements. It is possible to arrange these elements to maximize the PV area, sometimes approaching 80% of the roof area. (See BP20.)

Using Table 5-2, the required percent of roof area required for PV can be calculated as follows:

Gross floor area × PV area % (Table 5-2) × upgrade factor = roof area required for PV

Roof area required for PV / gross roof area = percentage of roof area needed

The calculations for a 2-story, secondary school in climate zone 5A, are as follows:

$$\text{Gross floor area} = 227{,}700 \text{ ft}^2$$

$$\text{Gross roof area} = \text{gross floor area / stories} = 113{,}850 \text{ ft}^2$$

PV area % (from Table 5-2) = 24%

Upgrade factor = 1.25

$$\text{Roof area required for PV} = 227{,}700 \text{ ft}^2 \times 0.24 \times 1.25 = 38{,}310 \text{ ft}^2$$

$$\text{Percentage of roof area needed} = 54{,}648 \text{ ft}^2 / 113{,}850 \text{ ft}^2 = 60\%$$

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In this simple example, which does not account for double-height spaces such as gymnasiums, the PV array would require approximately 84% of the gross roof area; however, it is unlikely that 84% of the gross roof area would be available for the installation. 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 ground-mounted array or other form of on-site renewable energy.
- 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)
- Perform a more detailed analysis that looks at available roof area and production needs

Additional information on specifying PV systems is provided in the renewable energy section, including tools to fine-tune the PV output based on orientation and module selection

BP20 Maximize Available Roof Area

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

Consider the following strategies for maximizing available roof area:

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

BP21 Roof Durability

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

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

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

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

BP22 Roof Safety

Be aware of applicable code requirements, fire department access requirements, and worker safety regulations. Any required guardrails or guarding parapets will cast shade and thus directly affect the location and placement of PV collectors. Conversely, roofs without guards or parapets will need to maintain significant clear areas around roof edges and will thus sacrifice roof area that could be otherwise used for solar-electric generation.

The renewable energy section later in this chapter provides technical recommendations for PV planning and installation.

BP23 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 to be 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, or other appurtenances on the building that would impede solar access
- Avoid shade thrown by parapets, monitors, stairwells, mechanical equipment, and other rooftop items.

REFERENCES AND RESOURCES

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.

Torcellini, P., D. Goldwasser, A. Honnekeri, E. Bonnema. 2017. Technical Support Document for Zero Energy K–12 Schools. NREL-!P-550-70513. Golden, CO: National Renewable Energy Laboratory. www.NREL.gov/docs/fy18osti/70513.pdf.

ENVELOPE

OVERVIEW

The building enclosure, or envelope, serves many functions, both aesthetic and performative. Architects and engineers rely on the envelope to provide a durable and visually appealing exterior while also managing the migration or transmission of water, water vapor, air, and thermal energy. This section provides strategies that ensure an airtight and well-insulated building envelope (ASHRAE 2017).

Installation and commissioning are critical to the success of a high-performing building envelope and by extension the success of a zero energy building. Further discussion of building envelope commissioning and other quality control efforts is provided in Chapter 3, Quality Assurance and Commissioning.

Figure 5-3 presents heating-dominant and cooling-dominant school buildings by climate zone. This information can be quite useful as an intuitive starting point as one starts to evaluate appropriate building strategies for a specific project and, more specifically, how climate in which a building is located changes the HVAC heating and cooling loads.

Caution: Additional considerations include the following:

- Existing recommendations and warranties from manufacturers and manufacturer trade organizations may be tested. In many instances, dialogue with manufacturers and trade organizations will yield useful new understandings and opportunities.
- Adhere to applicable building codes and the underlying reference standards. These standards impose limits on the extents and application of combustible materials, and in particular on foam plastic insulation products.

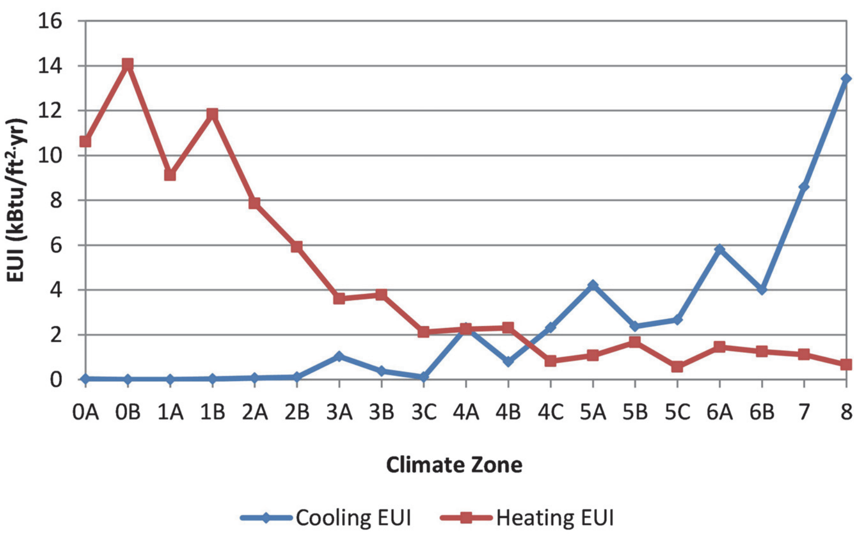

Figure 5-3 Heating and cooling loads by climate zone.

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- In many cases, specific tested assemblies may be required and slight variances may require engineering judgments from manufacturers to satisfy the authorities having jurisdiction (AHJ).

AIR BARRIER SYSTEM

EN1 Provide Continuous Air Leakage Control

An airtight envelope minimizes energy loads especially when the building is unoccupied. Even when it is occupied, an airtight building will allow for mechanical ventilation to provide the correct amount of ventilation based on occupancy rather than relying on external weather conditions through infiltration to provide fresh air. In addition, mechanical ventilation allows for heat recovery, which more than accounts for the fan energy (see HV20).

The air barrier system should be continuous over all surfaces of the building envelope including at the lowest floor, exterior walls, and the roof (see Figure 5-4). An air barrier system should also be provided for interior separations between conditioned spaces and semiconditioned spaces. Semiconditioned spaces maintain temperature or humidity levels that vary significantly from those in conditioned space.

Various methods for durable sealing of penetrations are available, including high performance tapes and liquid applied products. (Nordbye 2011a, 2011b, 2013)

To maintain complete continuity, pay attention to those areas known to pose obstacles to continuity, notably wall to roof transitions, wall to foundation transitions, wall to fenestration

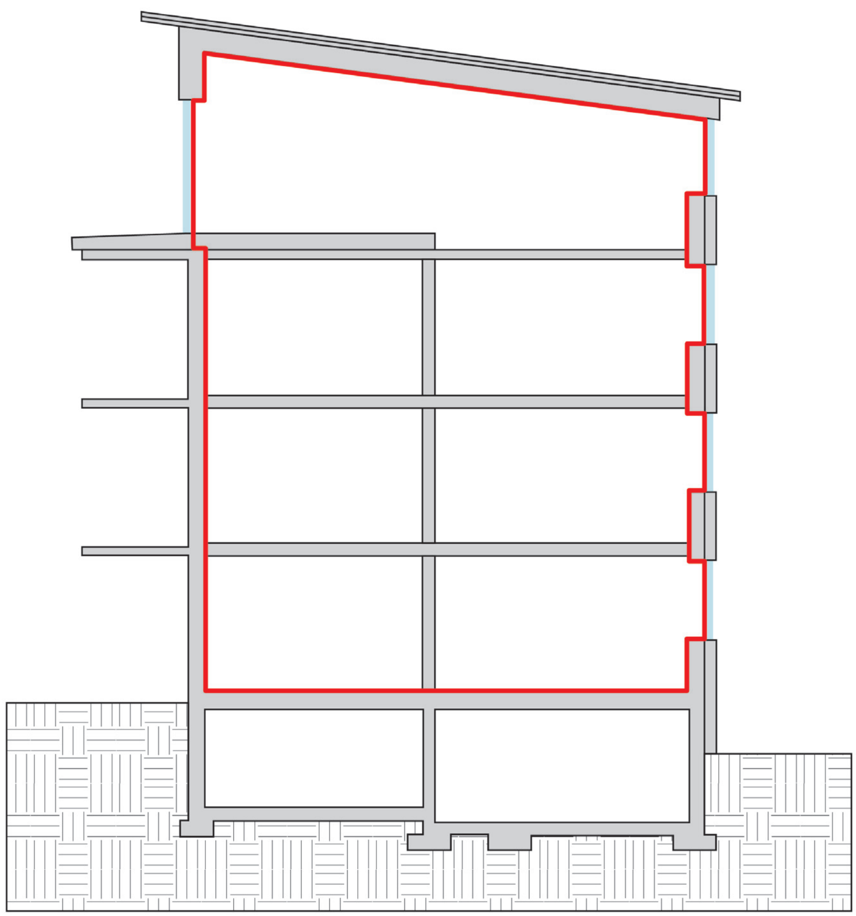

Figure 5-4 (EN1) Continuous air barrier.

transitions, and the perimeter of all air barrier penetrations. A useful technique during the project development is to draw a continuous red line along the entire air barrier in the building sections to trace its location within each assembly and to identify areas of critical intersections.

The location of the air barrier within the assembly should be driven by climate conditions to avoid condensation within the assembly or on the interior surface. A hygrothermic analysis is recommended to confirm a proper placement of the air barrier. In many cases, the air barrier is coincident or coplanar with the insulating layers of the envelope. Recommendations on continuous insulation are shown in the building thermal insulation section that follows.

EN2 Establish an Infiltration Goal

The recommended target air leakage rate is 0.25 cfm/ft^2 of total envelope surface area at 75 Pa. Lower values are achievable, and should be considered in colder climates. The leakage goal should be established at a level that is as tight as can be expected given the anticipated construction.

THERMAL MASS

EN3 Include Mass Veneers Outside of Building Insulation

In warm and hot climates, mass veneers can be employed outboard of building thermal insulation to mitigate extreme swings caused by envelope gains. Conventional masonry cavity walls are examples of this construction and offer the cobenefit of a very durable exterior finish. Exterior mass does not create the same types of complications as interior thermal mass and therefore is more appropriate for schools and school operations staff. For additional information on building massing, see BP3 to BP8. For additional strategies relating to thermal mass, see HV22 and HV34.

ROOF CONSTRUCTION

EN4 Select Appropriate Roofing Materials

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

The effects on a school's IEQ should also be evaluated, particularly for flat roofs, as adhesives inside the building envelope (i.e., inboard of the membrane) can adversely affect the indoor environment and in turn occupant health and achievement.

Rooftop PV arrays can complicate roof maintenance and future roof replacement. See BP21 for strategies on designing a long-lasting roof.

EN5 Cool Roofs and Warm Roofs

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 at the Cool Roof Rating Council at www.coolroofs.org.

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 Cool Roof Rating Council or the U.S. Department of Energy's *Guidelines for Selecting Cool Roofs* (DOE 2010).

Cool roofs provide energy reductions in climate zones 0–4. Warm roofs, in contrast, reduce energy use modestly in climate zones 7 and 8. Differences in modeled energy usage

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between cool roofs and warm roofs are negligible in the remaining climate zones. Project teams should always model both roof types (or multiple types) to confirm the results for a specific building. Consider evaluating some roof areas separately, based on occupancy and scheduling.

It would seem intuitive that PV panels shade the roof and preclude the need for cool roofing, but the modeling that was done for this guide actually contradicts this perspective. While energy differences were more modest, the installation of PV panels did not change the relative difference in any climate zone. Also consider the roof's effect on the productivity of the PVs. Elevated temperatures adversely affect solar production, so in many cases, cool roofs will improve the efficiency of the system and increase the amount of energy produced.

The urban heat island effect should also be considered when selecting a roofing material. Individual project goals that favor a reduction in the heat island effect may warrant a slight energy penalty in the heating-dominated zones.

BUILDING INSULATION—OPAQUE COMPONENTS

EN6 General Guidance

There are numerous insulation products available. There are many factors that are used to evaluate insulation including recycled content, recyclability, combustibility, outgassing, and R-value. Insulation should be installed according to manufacturer's specifications, and in some cases, provide an airtight wall construction. Structural components 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 meet the recommended U-factor for the envelope while considering all the other criteria for a successful envelope.

While increasing insulation beyond recommended levels will save energy, this reduction may be minimal and efforts should be placed on other efficiency gains. Project teams should start with the recommended insulation levels (EN2) and increase to see if additional insulation is effective at reducing the EUI. In addition, additional insulation can be compared to alternative electronically commutated motors (ECMs) to provide the best energy savings strategy for the project budget. For most schools, increased roof insulation is more effective than increased insulation of other building elements.

The prescriptive climate zone recommendations provided in Table 5-3 represent one pathway for upgrading the thermal performance of the envelope. Alternative constructions that are less than or equal to the U-factor or F-factor for the appropriate climate zone construction are better. U-factors and F-factors that correspond to all recommendations are presented in Appendix A. For information on doors, see EN15 to EN17.

EN7 Maintain Insulation Effectiveness

To a certain extent, the effectiveness of any thermal envelope is a function of the installation quality, and designers, owners, and contractors must be vigilant in the proper installation referring to the manufacturer's best practices. All insulation types can be susceptible to poor installation that impacts energy performance, condensation, and comfort. Insulation installations should be visibly inspected. Evaluate first cost, life-cycle costs, construction sequencing, and scheduling effects before finalizing the selection of any insulation system.

Table 5-3 (EN6) Envelope Construction Factors

	Recommendations by Climate Zone								
Component	0	1	2	3	4	5	6	7	8
Roof U-factor	0.039	0.048	0.039	0.039	0.030	0.030	0.030	0.027	0.027
Walls above ground U-factor	0.124	0.077	0.077	0.064	0.061	0.052	0.047	0.047	0.035
Slab F-factor	0.730	0.730	0.730	0.730	0.494	0.494	0.485	0.400	0.400
Doors U-factor	0.370	0.370	0.370	0.370	0.352	0.352	0.352	0.352	0.352

Two insulation types warrant special consideration relative to installation quality, and in turn insulation effectiveness:

- *Rigid board insulation* used in wall construction requires diligence to keep boards, level and square. Insulation must be cut neatly around openings and penetrations. Any gaps and edges must be thoroughly sealed with detailing foam or other appropriate insulating gap filler.
- *Batt insulation* is popular because of its low initial cost and ready availability. Thermal batt insulation should be combined with continuous insulation outboard of the framing cavities.

EN8 Roof Insulation

Insulation entirely above deck is recommended. When relying on insulation installed entirely above the structural deck, carefully consider the consequences of the specified installation method. Mechanically attached 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 and can reduce an assembly's ability to resist a given uplift pressure.

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 increased VOCs inside the building envelope, the potentially degraded recyclability, and the more limited ability to disassemble the roof. In addition, ensure that the adhered installation meets related technical requirements defined by the building codes and third party stakeholders (such as insurers).

To minimize thermal losses and infiltration, board insulation should be installed in at least two layers staggering the joints.

If PV panels will be mounted to the roof, the roofing system must be able to handle uplift from the panels. Attachments for PV panels need to minimize thermal bridging (see EN35). Often, ballasted PV systems are used as they do not penetrate the roofing membrane.

EN9 Mass Walls—Concrete and Masonry

A mass wall is a wall with a heat capacity exceeding (1) 7 Btu/ft^2·°F or (2) 5 Btu/ft^2·°F, provided that the wall has a material unit weight not greater than 120 lb/ft^3 (ASHRAE 2016). Continuous exterior insulation is preferred over interior insulation as it limits moisture management issues, makes air barrier and insulation continuity easier, and better accommodates the use of the thermal mass for energy efficiency. Rigid board or sprayed-in-place insulations are suitable for this application. All exterior walls should meet the U-factor recommendations in Table 5-2.

For additional strategies relating to thermal mass see EN3, HV22, and HV34.

Option: In addition to the wall insulation options discussed in EN6 and EN7, alternative or hybrid structures, such as insulated concrete forms (ICF's) may also be used as long as the actual U-factor complies with the values in EN-1.

EN10 Steel-Framed Walls and Wood-Framed Walls

Cold-formed steel framing members can be thermal bridges. Continuous insulation is the recommended method for insulating steel-framed stud walls to minimize thermal bridges. 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. Rigid board (suitable for exposure to moisture) or sprayed-in-place closed-cell polyurethane foam insulations are effective.

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 Appendix A, and provided that analysis demonstrates that vapor will not condense in the wall. Wall sheathing with integral insulation can provide exterior continuous insulation that simplifies wall construction.

Be sure to follow the manufacturer's specifications to insure a quality installation for insulation used in stud wall cavities.

EN11 Below-Grade Walls

Continuous exterior insulation is recommended for below-grade walls. Certain closed-cell foam insulations are suitable for this application. Continuous exterior insulation can reduce moisture management issues, makes air barrier and insulation continuity easier (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 depth.

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.

Foam products are susceptible to termite damage. In this case, use products that are termite resistant.

EN12 Mass Floors

Mass floors should be insulated continuously beneath the floor slab. As columns provide thermal bridges, the insulation should be turned down the column to grade. Note that this is in reference to supported mass floors. Slab-on-grade floors are addressed in EN14.

EN13 Framed Floors

Insulation should be installed between the framing members and in intimate contact with the flooring system supported by the framing member in order to avoid the potential thermal short circuiting associated with open or exposed air spaces. Nonrigid insulation should be supported from below, in accordance with manufacturer's recommendations, or in the absence thereof, no less frequently than 24 in. on center. Sprayed polyurethane insulation is also a suitable insulation type.

EN14 Slab-on-Grade Floors—Unheated and Heated

Where slab edges or the enclosing stem walls are exposed to the exterior, rigid insulation should be used around the perimeter of the slab and should reach the footing. See Figure 5-5.

For heated slabs, continuous insulation should be placed below the slab as well.

To ensure thermal comfort requirements are met, always evaluate slab surface temperatures and adjust insulation levels and other variables until interior surface temperatures are within 9°F of the indoor air temperature. In schools where students may spend significant time on the floor, this is an even more critical design-phase activity.

Use termite-resistant products and strategies where below-grade insulation is recommended and where termite infestation poses a problem.

EN15 Evaluate Doors

Maximum U-factor values for doors are shown in Table 5-2. While there are no additional recommendations on U-factor and air leakage of doors, they do need to comply with ANSI/ASHRAE/IES 90.1-2016 as a minimum requirement. This includes opaque nonswinging doors, opaque swinging doors, entrance doors (vertical fenestration).

> ***Caution:*** Some thermally broken door assemblies have been known to show decreased durability compared to conventional product options. All doors should be carefully inspected prior to final acceptance to ensure that all weatherstripping is tightly sealed to the door and to ensure that all sweeps and bottom seals are tightly contacting the threshold or sill. Consider using double sweeps to ensure an airtight installation.

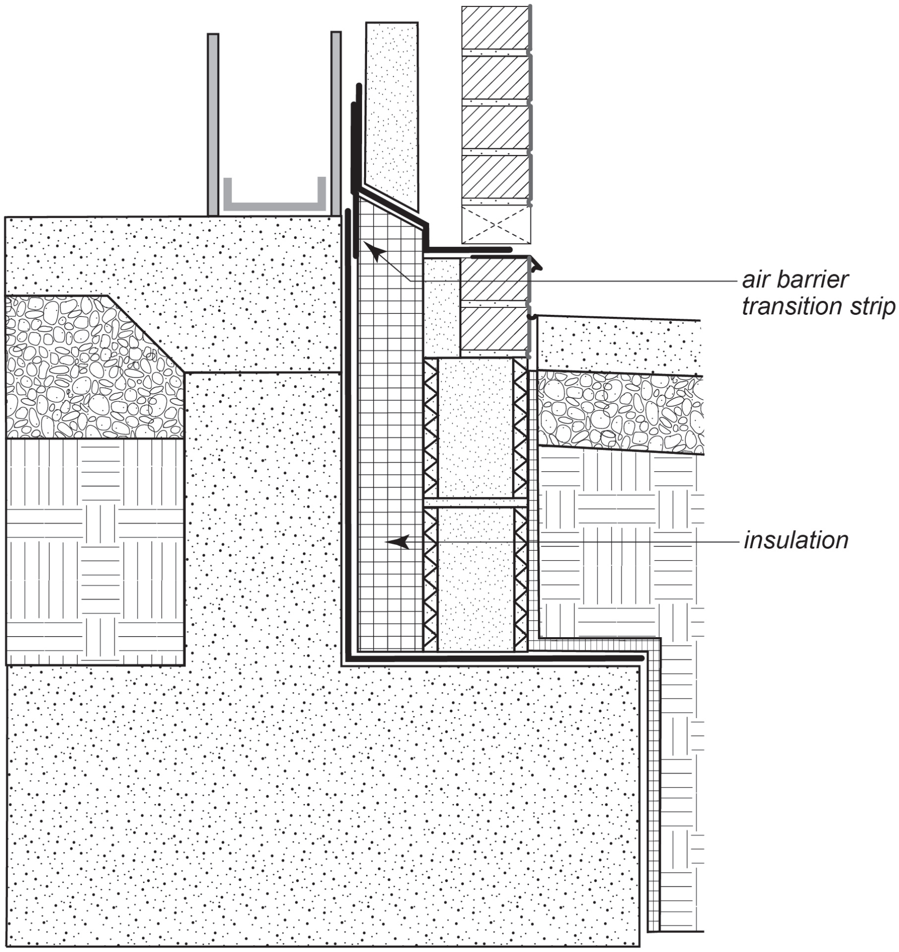

Figure 5-5 (EN14) Slab insulation.

EN16 Person-Doors

Where exterior swinging doors are provided, single doors should be specified. Double swinging doors without a center post should be minimized and limited to areas where width is important, typically for moving large equipment. In that situation, consider removable center mullions, which can be more tightly sealed than door astragals.

EN17 Doors—Opaque, Non-Swinging

When nonswinging doors are functionally required, use doors that have a U-factor of less than 0.10, including edge effects and joints. A tight seal at the edges is critical to minimize infiltration.

Metal doors pose more challenges because they can have poor emissivity, resulting in a hot exterior surface from solar gains, which are transmitted through the door, increasing cooling loads and magnifying thermal comfort issues. Where steel doors are functionally required and are exposed to solar radiation, a high emissivity/reflectivity coating should be specified and proper solar shading should be provided. Specify insulated curtain slats and ensure that the installed unit has seals contacting the curtain slats.

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

BUILDING INSULATION—THERMAL BRIDGING

EN18 General Guidance

The design and construction of an effective building envelope requires a consistency in building assembles and construction sequencing that necessarily focuses on the continuous air barrier system and continuous insulation strategies. Continuous insulation is easily defeated or compromised by thermal bridging through the building envelope, so potential thermal bridges must be identified in advance of construction and in an integrated manner to eliminate, or at least mitigate, all bridging.

Thermal bridging occurs when highly conductive elements connect internal and external surfaces. In general this most often happens because of fastening systems, changes of construction types, or at corners. The types of bridging encountered varies considerably with construction type. The thermal conductivities of various materials are outlined in the chart shown in Table 5-4.

Thermal modeling at the detail level can be used to compare approaches and optimize solutions for thermal bridges. Fourier's Law can also be used to compare conductive losses through simple bridges.

$$q = k\,A\,dT / s$$

where

q = heat transfer, Btu/h
k = thermal conductivity of a material, Btu/(h·ft·°F)
A = heat transfer area, ft^2
dT = temperature gradient, °F
s = material thickness, ft

Material densities are provided to help define the actual building material. In some cases, the density has an impact on the thermal conductivity. See *ASHRAE Handbook—Fundamentals* for more information (ASHRAE 2017).

Table 5-4 Envelope Material Conductivity

Material	Density, lb/ft^2	Thermal Conductivity, Btu·in./h·ft^2·°F
Polyisocyanurate	1.6–2.3	0.15–0.16
Extruded polystyrene	1.4–3.6	0.20
Expanded polystyrene	1.0–1.5	0.24–0.26
Cellulose	1.2–1.6	0.27–0.28
Polyurethane foam	0.45–0.65	0.26–0.29
Glass fiber batts	0.47–0.57	0.32–0.33
Wood	25	0.74–0.85
Gypsum sheathing	40	1.1
Brick—common	120	5.0
Brick—face	130	9.0
Concrete—sand/gravel	150	10–20
Stainless steel	494	96
Carbon steel (mild)	489	314
Aluminum (alloy 1100)	171	1536

Strategies for minimizing thermal bridges can be categorized as follows:

- Avoid possible thermal bridges by careful building planning and analysis of alternate construction methods.
- When bridges are unavoidable, use fewer, larger bridges. This might include further spacing for structural or stud elements. Use modeling to compare scenarios.
- 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 5-4 for comparing materials.
- 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.
- Mitigate thermal bridges to the greatest extent possible, which generally entails the provision of additional insulation inboard and/or outboard of the bridging component including incorporating a layer of continuous insulation.

Thermal bridging is generally more problematic in areas with wider differences between indoor and outdoor temperatures. Thermal bridging should be evaluated as minimizing bridge-induced condensation leads to envelope degradation.

EN19 Supporting Columns Below Floors

Exposed exterior columns as a result of supported elevated floors should be minimized as the exposed floors and thermal bridging from the columns is difficult to insulate. Where this detail is necessary, the column should be insulated continuously from the elevated floor insulation to grade, or in the event of an extraordinarily tall column, to a minimum of 1 ft per required R-value to meet the necessary U-factor for the floor. For example, if R-20 is required, the column should be insulated to a minimum of 20 ft.

EN20 Wall Type Transitions

Transitions in the construction of exterior walls can pose special challenges to the continuity of the air and thermal barrier. Conventionally, such transitions have frequently occurred at or near finished grade. A true continuous thermal barrier is only achievable by installing below-grade insulation outboard of the basement wall directly connecting to the continuous wall insulation above.

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 cavity can be extended below grade to the same depth, or alternately an at-grade shelf angle may be used to minimize the extents of below-grade masonry. Figures 5-6 through 5-8 detail the wall transition under various circumstances. Figure 5-6 illustrates continuous insulation to the foundation. Figure 5-7 illustrates continuous insulation to the foundation with masonry veneer. Figure 5-8 illustrates the wall transition where a shelf angle carries brick above grade.

EN21 Cladding Attachment and Rainscreens

Thin building skins and rainscreens require attachment to the structure of the building. These attachment points can be sources of thermal bridging. Attachment systems should be evaluated based on their ability to meet the load requirements without compromising the thermal integrity of the envelope.

Where project circumstances cannot support the integration of proprietary attachment systems, 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.

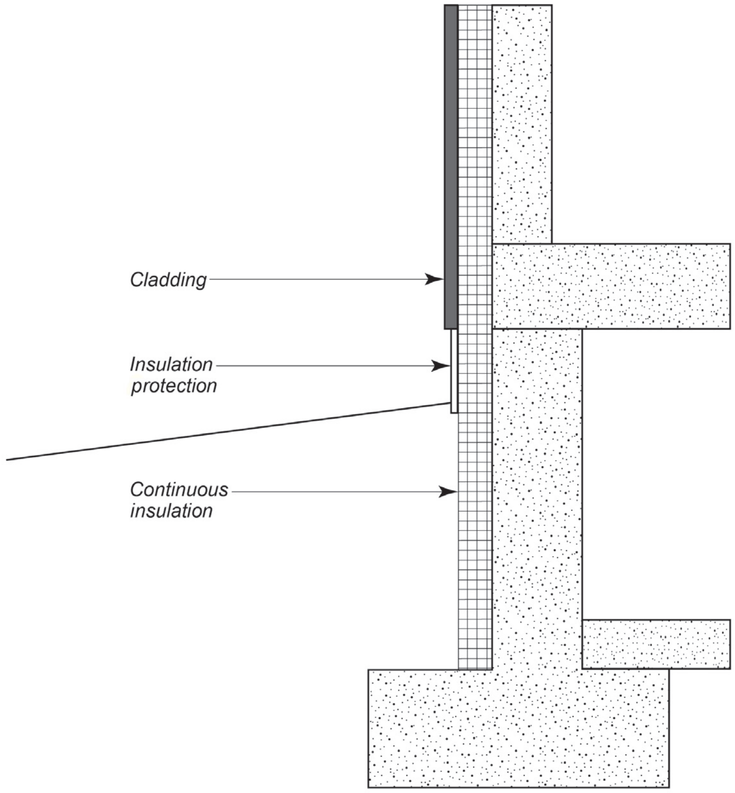

Figure 5-6 (EN20) Wall transition with insulation continuous to foundation.

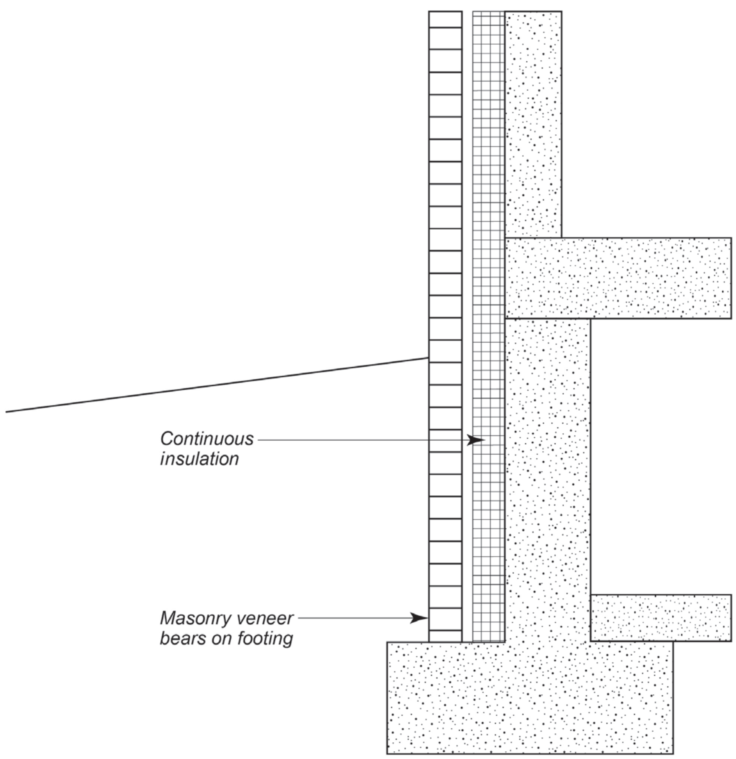

Figure 5-7 (EN20) Wall transition with insulation.

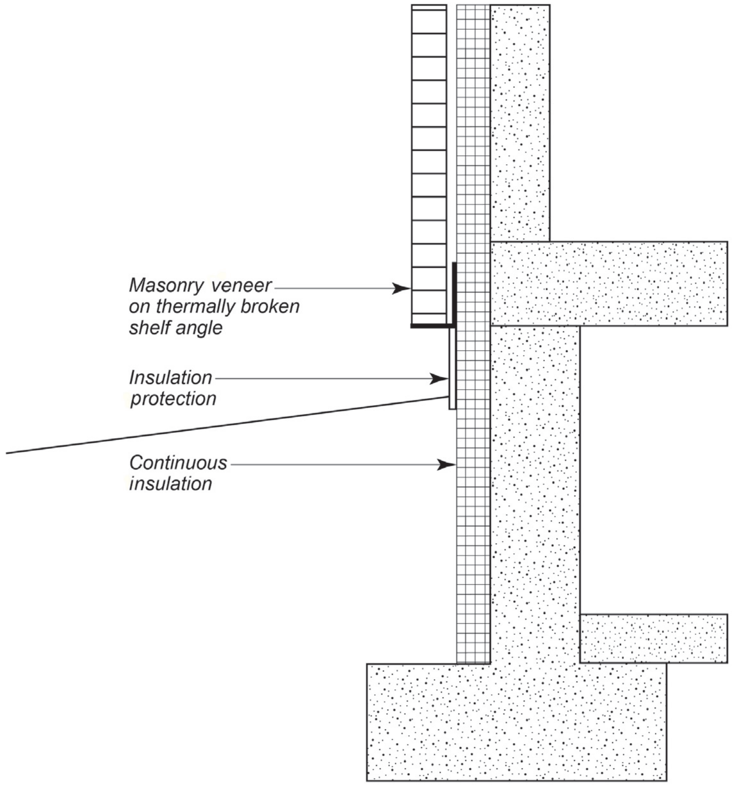

Figure 5-8 (EN20) Wall transition where shelf angle carries brick above grade.

- Design attachment systems to minimize the number of attachment points and thermal bridges. Use calculations to compare the energy conducted through various attachment scenarios (unless thermal bridges are being comprehensively modeled and tested).
- Use nonconductive clips at all penetrations. Where nonconductive clips are not an option, use the least conductive option available (such as stainless steel in lieu of carbon steel).
- Ensure that all attachment points are thermally broken. Exterior sheathing is typically an adequate insulator in metal stud construction.
- Ensure that all cladding attachment systems are structurally sound.

As part of the design, it is important to integrate the architectural finishes with the energy features. If the facade treatment compromises the thermal integrity of the envelope, alternate treatments should be considered. Cross sections should be carefully examined to prevent these thermal bridges.

EN22 Cavity Walls Above Roofs

Upper story exterior walls that intersect lower roof planes are commonly encountered. Where the higher wall is a masonry cavity wall, conventional practice would allow 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, as illustrated in Figure 5-9.

EN23 Shelf Angles

Shelf angles are an especially problematic source of potential energy transfer through the building envelope. Conventionally, shelf angles are attached directly to the building structural

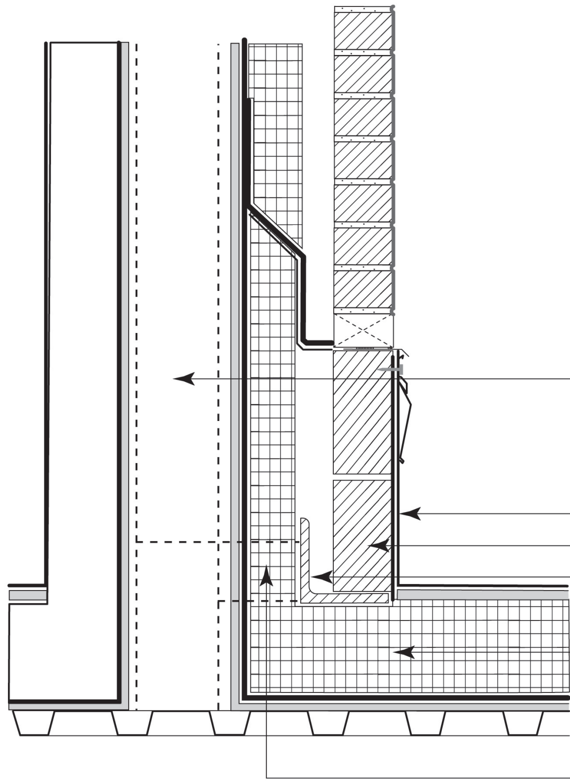

Figure 5-9 (EN22) Cavity wall insulation.

frame or floor edge. In such an installation, a 3/8 in. steel angle can be responsible for as much heat loss as the entire story of insulated opaque envelope above.

Minimize the number and extents of shelf angles. Investigate strategies to avoid a shelf angle at each floor.

Where provided, 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 frame or floor edge by clips or proprietary structural components that allow insulation to pass between the shelf angle and the frame or floor edge as illustrated in Figure 5-10. Structural engineers should be retained that can help provide appropriate structural integrity without compromising the thermal envelope.

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.

EN24 Balconies

Projecting or cantilevered balconies and walkways represent serious thermal breaks. Conventional engineering practice has relied on a cantilevered extension of the primary structural floor to support the balcony

Envelopes must 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.

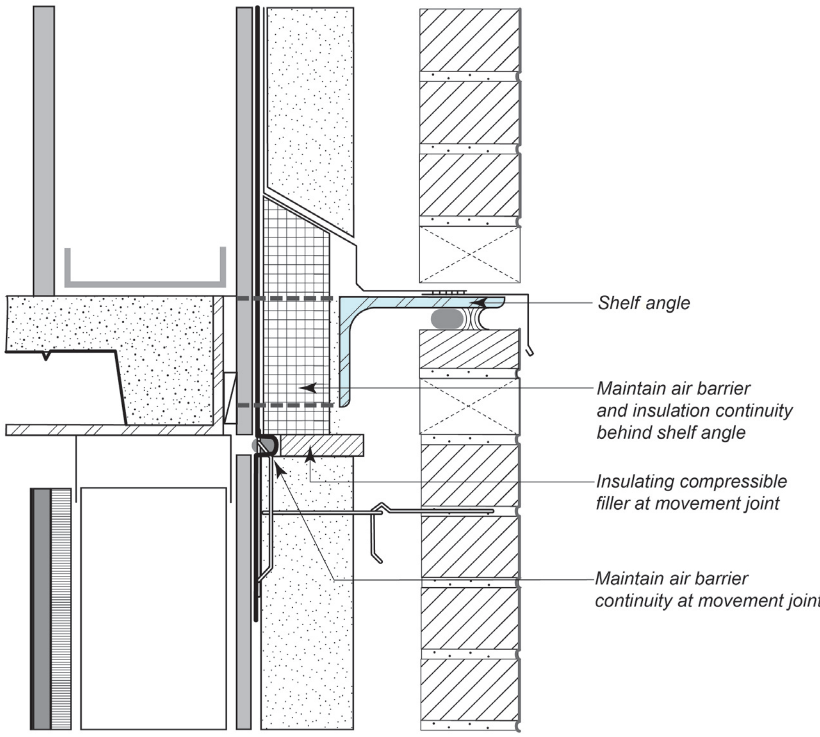

Figure 5-10 (EN23) Shelf angle installation.

EN25 Canopies and Overhangs

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. To maximize building energy saving, consider the following:

- Evaluate if 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, for example, 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.

EN26 Other Structural Penetrations in Walls

A school building is likely to have multiple instances of structural penetrations in the building envelope. In practice, zero energy schools often require many penetrations to accommodate various types of exterior shading devices. All such penetrations should be evaluated 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, nonconductive plates should be placed between the interior and exterior structural members and located in the plane of the wall insulation.

Where decoupling is not possible, penetrating elements should be insulated to the greatest degree possible, both inboard and outboard.

EN27 Louvers

Penetrations in the envelope for exterior louvers and the associated ductwork are compromises in the thermal envelope. Consider the following when detailing louvered penetrations:

- Consider a thermally broken louver
- Tie-in the building air barrier system to the duct.
- Use a flexible duct sleeve for a thermal break in the ductwork
- Insulate the duct all the way to the building thermal envelope and ensure complete tie-in with detailing foam

EN28 Through Wall Overflow Drains/Lambs Tongues

Roof drains frequently break the building thermal barrier compromising building energy efficiency and providing a potential source for condensation within concealed areas of the building. Heat loss from such conditions can be clearly seen in thermographic imaging during the cold season.

When possible, designers should consider a roof water removal system that does not require internal drain leaders. Where internally routed roof drains are unavoidable, energy losses can be mitigated by using plastic pipes and by insulating the pipe inboard of the point where it exits the building envelope.

Like any penetration in the envelope, all gaps at the penetration should be insulated and sealed to the building air barrier system.

EN29 Parapets

Continuous air barriers and continuous insulation must be applied to parapets. 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 5-11. In practical terms, this can involve up to three or four insulation types to meet the individual requirements for the various surfaces. For tall parapet walls, consult with building envelope experts to ensure that air barrier and insulation layers are continuous without sacrificing other technical aspects of the design.

Continuous parapet insulation poses several challenges, including the following:

- Where an air barrier or vapor retarder is used beneath the roof insulation, the multiple tie-ins can pose additional complexity
- High-performance assemblies may not be tested to specific NFPA requirements, and engineering judgments from product manufacturers may need to be solicited
- Wind uplift requirements in the building codes need to be considered

EN30 Roof Edges

Insulation (as well as air, water, and vapor control) must be continuous at roof edges, gravel stops, and similar conditions. Where wood cleating or nailers are necessary for anchorage, cleats should be attached outboard of the continuous insulation and fastened with oversize screws to the parapet structure. Where a nailer must be embedded in the thickness of the insulation, minimize compromises of the envelope by installing nailers in a discontinuous fashion only where required for structural integrity.

EN31 Through-Wall Scuppers

Roof design often uses through-wall parapet scuppers, in part to avoid interior roof drains (see EN30). Such scuppers may 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 5-12.

EN32 Plumbing Vents

Plumbing vents penetrating the roof are often thermal bridges. Plumbing vent penetrations should be sealed and all gaps around the penetration should be filled, as illustrated in Figure 5-13. Where nonconductive (plastic) pipe is used, additional pipe insulation is not necessary. When metal pipe is used, the pipe should be insulated to the top of the vent before being flashed. On the inboard side, metal pipe should be insulated for a minimum of 10 ft.

EN33 Roof Drains

Roof drains are a unique source of energy loss (and internal building condensation) that can compromise the building envelope. These drain assemblies and the substantial connecting pipes can represent very large energy losses in flat-roofed buildings. 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).

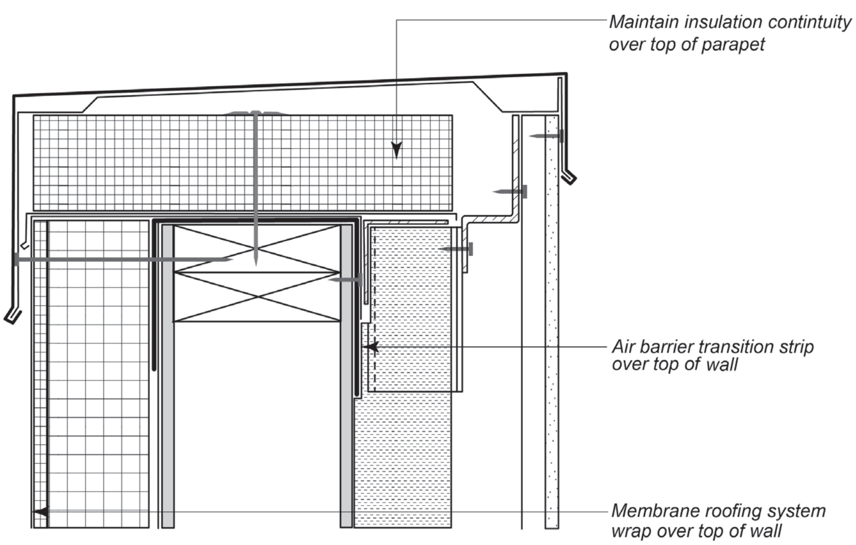

Figure 5-11 (EN29) Parapet insulation.

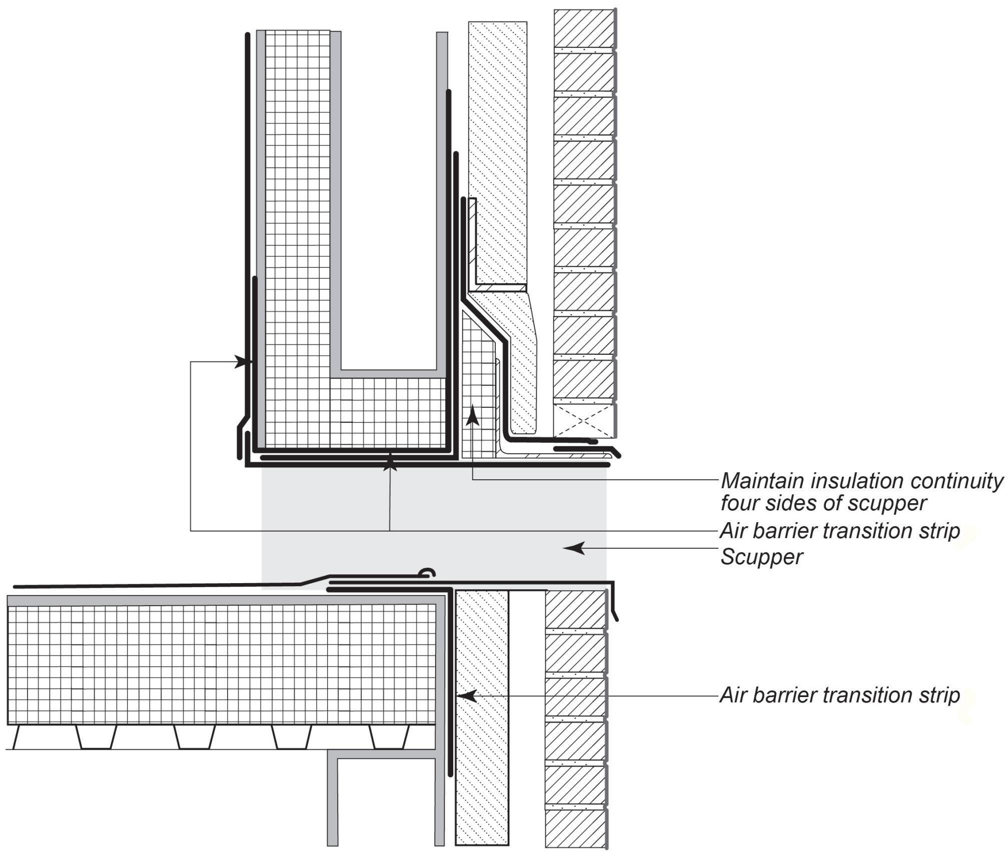

Figure 5-12 (EN31) Through-wall scupper insulation.

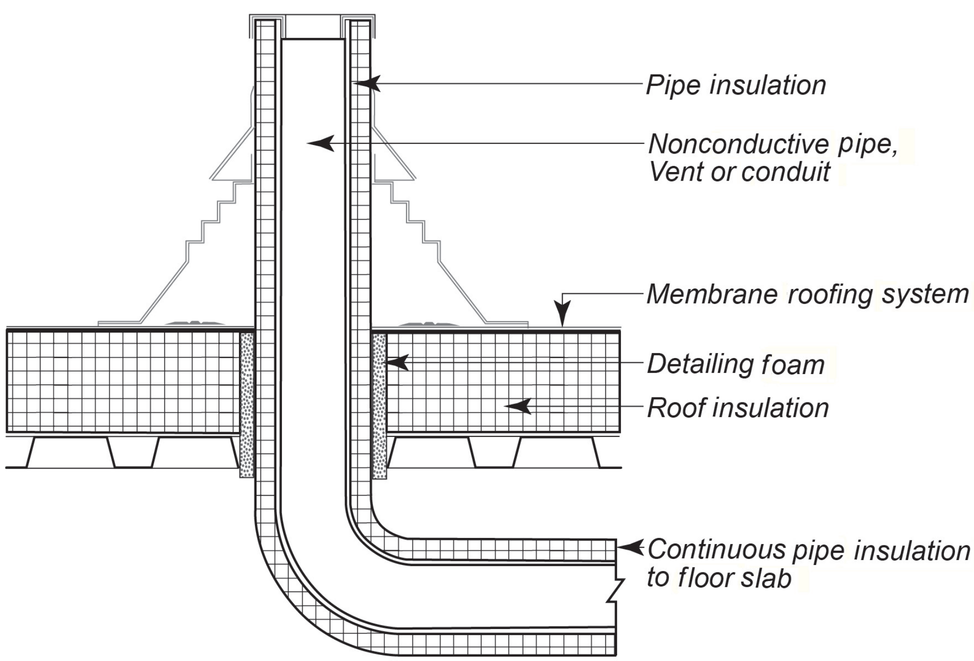

Figure 5-13 (EN32) Plumbing vent insulation.

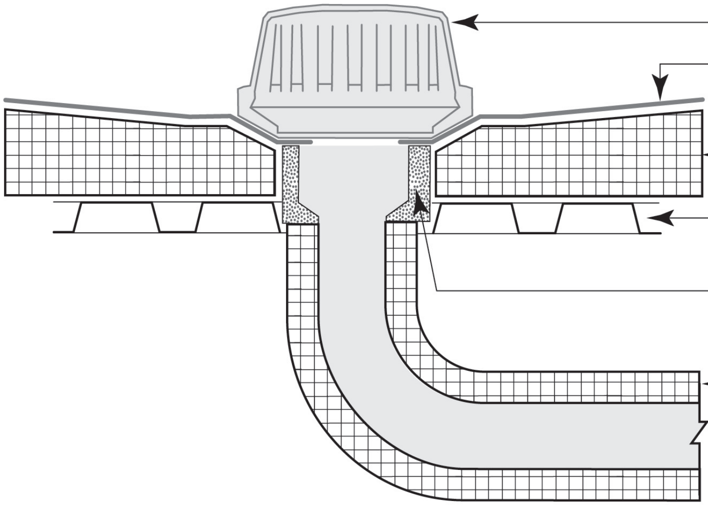

Figure 5-14 (EN33) Roof drain insulation.

EN34 Roof Hatches

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. Consider roof access that does not require roof hatches or follow the following recommendations:

- Select hatch covers with the maximum available insulation. Covers with at least R-18 are 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 available.
- Select thermally broken curb mounts.
- Consider whether supplemental insulation can be added to the outside of the curb and whether such an application affects the manufacturer's warranty.
- Consider the quality of the hatch cover weather-stripping (airseal) and compare manufacturer's infiltration data.

EN35 Equipment Pedestals and Other Structural Penetrations in Roofs

Commercial construction projects frequently have structural components penetrating the roof and the roof insulation. 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.

EN36 Mechanical Curbs

Apply the principles outlined in EN34 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.

Chapter 5
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EN37 Skylight Curbs

Skylights are conventionally mounted on premanufactured curbs. Premanufactured curbs generally offer limited insulation levels, few insulation material choices, and few thermally broken options. 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.

See also BP17-BP23 regarding information on PV roof layout.

EN38 Below Grade Piping and Conduit

All penetrations should be sealed. Depending on local climate, bury depth, and ground temperatures, penetrations may warrant insulation for a reasonable distance in one or both directions from the penetration. In additions, when sleeves are used, the wire or piping in the sleeve should be sealed to prevent infiltration.

EN39 Duct Bank Entrances

Duct bank entrances create thermal bridges and can contribute to building energy losses. In most cases, duct banks enter the building at elevations shallow enough that the below-grade wall will be insulated. To mitigate thermal losses, duct bank casings should be held back from the below-grade wall so that the full thickness of wall insulation separates the casing from the building. Consider using plastic piping at the building penetration.

EN40 Miscellaneous Penetrations—Detailing Foam

In general, all penetrations need to be insulated and air-sealed. Follow manufacturer's recommendations, otherwise, seal gaps with expansive detailing foam and provide sealant at the exterior drainage plane and, if warranted, at the exterior skin.

EN41 Use Advanced Framing Techniques

Many conventional wood-framed buildings are overbuilt structurally. This results in the use of more wood than is structurally necessary and also creates additional thermal bridges because each framing member represents a thermal bridge in the envelope assembly.

Advanced framing techniques aim to maximize structural and thermal performance. An example is to reduce the number of wood members used to frame building corners. Advanced framing also integrates considerations for airtightness into the construction process. A complete discussion of advanced framing techniques is available in Building Science Corporation's Builder's Guide series of publications (BSC, n.d.). Building resources are also available from Passive House Institute US (PHIUS 2017).

Although advanced framing techniques reduce the number of thermal bridges in a wood stud wall, using a layer of continuous insulation outboard of the stud is also recommended, as discussed in EN7 and EN10.

BUILDING FENESTRATION

EN42 General Guidance

Fenestration includes the light transmitting areas within a wall or roof assembly, including windows, skylights and glass doors. Vertical fenestration (or windows) includes glazing with a slope equal to or greater than 60° from the horizontal. Other glazing (sloping less than 60° from the horizontal) is considered a skylight. Clerestories, roof monitors, and other such fenestration fall in the vertical category.

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 (see HV35). On the negative side, fenestration is a significant source of heat loss and gain through the building envelope. Designers should seek the right balance between the benefits of fenestration (views, daylighting, and natural ventilation) and the penalties (heat gain and loss) through iterative modeling and testing fenestration strategies. An effective window should provide more benefit from daylighting and natural ventilation than the adverse heat loss and gain from a weakened thermal envelope.

Additional guidance is provided in the daylighting section that follows (see DL1 through DL6).

In general, an optimized energy solution is to minimize the glass for daylighting and natural ventilation realizing that additional glazing is often desired for views. Balancing the amount of glass to meet architectural and energy goals requires careful energy simulations to evaluate the impact as it varies considerably by climate and fenestration orientation.

Glazing selection and fenestration sizing should be selected by varying these parameters with energy modeling to achieve the desired energy goals. Effectively designing the fenestration is one of the cornerstones of creating a zero energy school. See Chapter 4 for more modeling information.

EN43 Consider Fenestration Early in the Process

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

With integration, common architectural components may serve dual functions, which reduces first costs. For example, a cool roofing material can serve as a waterproofing membrane, reflect solar radiation to reduce cooling loads, reduce roof temperatures to improve PV performance, but also boost lighting through vertical glazing in roof monitors. Only a comprehensive, well thought out approach will provide a low-cost system that achieves the desired benefits.

The opposite is true of nonintegrated designs. If the daylighting system is designed and bid as an alternative to a design with no daylighting, the daylighting strategy probably will not be as cost effective or resource efficient. If the designer thinks that the daylighting components have a good chance of being eliminated, he or she will be less likely to risk designing a smaller mechanical cooling system for fear of having to pay to redo the design.

EN44 Install Fenestration Prior to Building Skin

A properly detailed building enclosure requires that building fenestration be installed prior to the building insulation and the building skin. This allows the wall air barrier system to be easily and thoroughly tied to the fenestration components minimizing infiltration issues. Critical issues that enable an early installation include an early start to fenestration submittals and shop drawings as well as adequate protection of the fenestration postinstallation and throughout the remainder of construction.

Always consult with the fenestration manufacturer to vet the sequencing early in the process to ensure that all stakeholders understand the goals of the envelope installation and the benefits of a potentially alternative construction sequencing.

EN45 Window to Wall Ratio

The window-to-wall ratio (WWR) should be defined early in the design process, as it can have a profound effect on building energy performance. Yet, the actual articulation of fenestration may not be developed until later in the design process. The WWR value generally references the area of above grade walls, excluding parapets.

The modeled early-phase WWR of the overall building should generally not exceed 30%. In practice, the WWR may be further defined by building elevation, such that north and south elevations have greater glazing extents and east and west elevations have less glazing as east and west facades are difficult to control solar gains and glare. Higher WWRs may be pursued while commensurate savings are achieved from other energy conservation measures.

In all instances, use the energy model and cost analyses to optimize the glazing percentage relative to project goals for energy efficiency, daylighting, and views.

When developing window placement and sizing, consider the use of the space. It is not efficient to design a building such that bookshelves are placed in front of windows or the shades are always drawn. The latter usually signals an issue with the fenestration, such as excessive glare.

See the daylighting section (DL1–DL6) for a detailed discussion of glazing for daylighting and views.

EN46 *Select the Right Fenestration*

The selection of window glazing should be considered separately for each orientation of the building. In addition, daylighting and view functions should be considered separately. The three main properties of fenestration assemblies that should be considered are as follows:

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

Table 5-5 shows the target values for U-factor, SHGC and VT. Fenestration products are available that exceed the minimum requirements in Table 5-5 and should be considered for zero energy schools. The interactions between the fenestration, other building components, and the energy goal require energy modeling to effectively make decisions (EN43).

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

EN47 *U-Factor*

The U-factor is the rate of heat loss or gain through the window—the lower the value the better. The U-factor of a window or skylight depends not only on the number of panes of glazing and any special coatings, but also on the construction of the window frame. The best frames are constructed of non-metallic materials or have a thermal break that separates the interior portion of the frame from the exterior portion.

Ensure that all models and specifications reflect the assembly U-factor and 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.

In colder climates, select a 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 is less likely for windows with low U-factors as the reduced heat loss translates to a higher glass surface temperature. This also translates to improved thermal comfort.

In high-performing buildings, glazing will almost certainly include multiple panes of glass. The most commonly specified spacers between glass panes are highly conductive aluminum; however, less conductive spacers are now available in the marketplace.

Additional improvements can be made with low conductivity window spacers as well as low conductivity window frames. The whole-window U-factor incorporates all these technologies and gives the best indication of window performance.

Table 5-5 (EN46) Fenestration Criteria

	Recommendations by Climate Zone								
	0	1	2	3	4	5	6	7	8
Maximum U-Factor	0.45	0.45	0.45	0.45	0.36	0.36	0.34	0.31	0.28
Maximum SHGC	0.21	0.24	0.24	0.24	0.34	0.36	0.38	0.43	0.43
Minimum Ratio of VT/SHGC	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10

Maintain Internal Surface Temperatures

A minimum R-value of insulation is required for each assembly of the exterior envelope, so as to maintain minimum internal surface temperatures. These are essential to maintain the thermal comfort of the interior. Where these minimum internal surface temperatures are not maintained, radiant and convective heat flows develop, causing drafts and variations in temperature throughout the space. These produce feelings of discomfort even if the average interior air temperature is adequate, which in turn can drive occupants to use additional energy.

The internal surface temperature can be calculated as follows:

$$Hi \cdot (Ti - Tg) = U(Ti - To)$$

where

Hi = interior film coefficient = 1.35 Btu/h·ft^2°F (horiz. flow) or 1.031 (vertical flow)

Ti = interior temperature (68)

Tg = interior glass surface temperature (min. = 68 – 4 = 64)

To = outdoor temperature

U = U-factor of component

EN48 Solar Heat Gain Coefficient (SHGC)

At a minimum, the SHGC of fenestrations should comply with the SHGC delineated in Table 5-5. While higher SHGCs are allowed in colder regions, continuous horizontal overhangs are still necessary to block the high summer sun angles.

Overhangs work to effectively reduce the SHGC of vertical fenestration on the east, south and west facades, 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 5-6 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 projection factor of 0.75, the effective SHGC would be 0.40 × 0.51 = 0.20.

While these reduce solar radiation on the east and west, there still may be a glare problem that can be assessed through the annual sunlight exposure (ASE) calculation (see DL3).

EN49 Visible Transmittance (VT)

The visible transmittance (VT) is the fraction of the visible spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight. As the VT is coupled to the SHGC, the ratio of VT to SHGC is often used. With advanced coatings, it is possible to block most of the radiation outside the visible spectrum while allowing visible light to pass through.

Table 5-6 (EN48) 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

Such glazing is known as spectrally selective, since it selectively allows some wave lengths to pass while blocking others.

The target value for VT/SHGC ratio as shown in Table 5-5 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 students and teachers can see out. The amount of daylighting that enters the building is directly proportional to the VT, so daylight apertures should have high VTs. The view windows below 7 ft do not require high light transmission glazing, so VT values between 0.25 and 0.75 are acceptable, depending on the orientation and climatic zone. Glazing for view windows should be selected so that views are not hampered.

EN50 Minimize Spandrel Panels

Glazing systems such as storefront and curtain wall accommodate a variety of building products that give designers aesthetic flexibility. Glazing systems, even with opaque or insulated panels, are significantly less energy efficient than conventional opaque wall assemblies. Glazing systems should be used only where transparency is required or desirable.

Where spandrel glass or opaque panels are used in these systems, the installations should follow the U-factor recommendations for opaque wall assemblies. In practice, this requires the use of oversize rabbet-edge panels (where insulated panels are glazed in) and supplemental insulation (where spandrel glass is used.) The latter approach poses technical challenges in terms of continuous insulation, and the condition is better addressed by an opaque wall system. When insulated panels are used, they must be sealed to the assembly to prevent airflow to the spandrel that would substantially reduce the U-factor.

EN51 Evaluate Glazing Frame Alignment

Installing the fenestration outside of the plane of the wall insulation defeats the thermal break in the window frame. Fenestration should be installed to align the frame thermal break with the wall thermal barrier as illustrated in Figure 5-15. This will minimize the thermal bridging of the frame due to fenestration projecting inboard or outboard of the insulating layers in the wall.

In the same way, insulated exterior doors need to fall entirely within the exterior building insulation plane as illustrated in Figure 5-16. 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.)

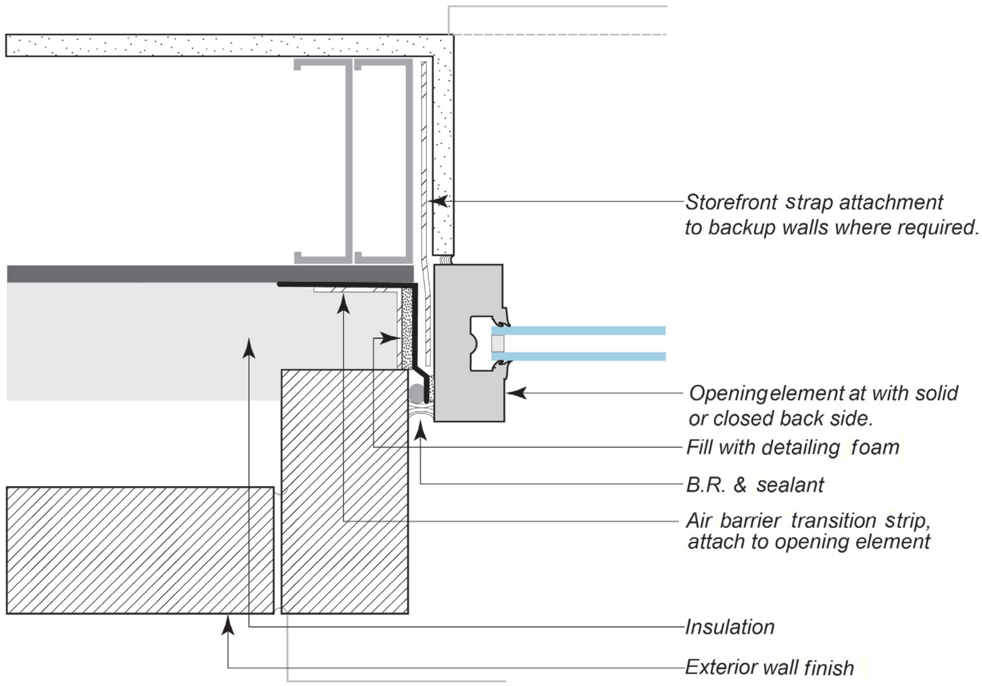

Figure 5-15 (EN51) Top view of a window system to opaque wall connection.

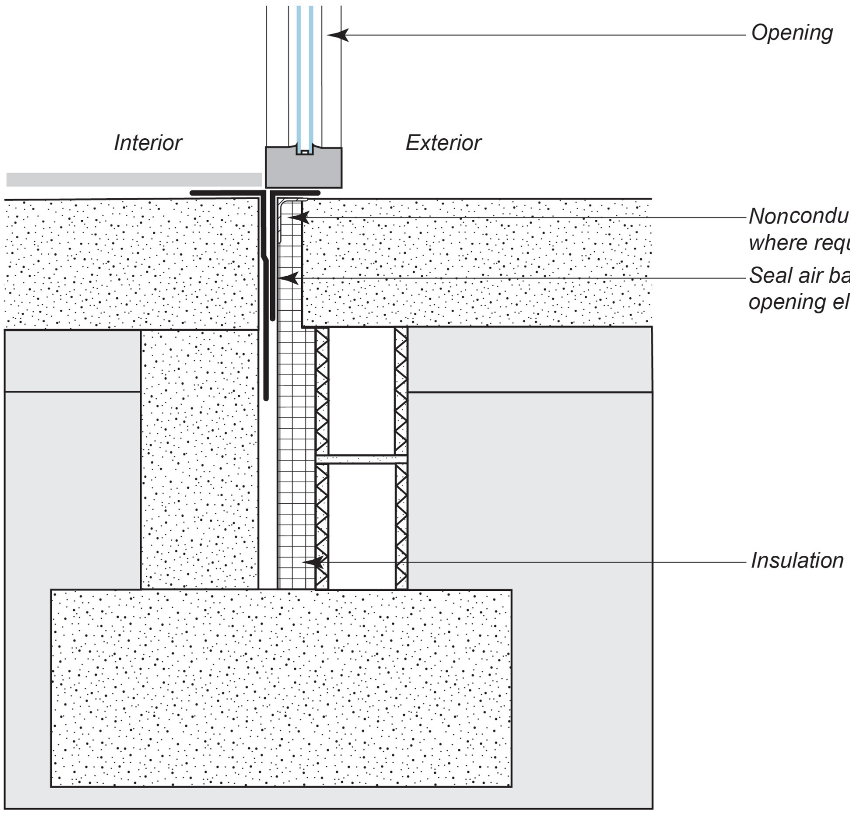

Figure 5-16 (EN51) Exterior door insulation installation.

EN52 Framing and Assembly U-Factors

The recommended fenestration U-factors in Table 5-5 are *assembly* U-factors that include the U-factor of the glass with the mullions and window frame including the edge-of-glass spacers.

It is typically easier to establish U-factors for factory-built window units than with storefront or curtain wall glazing systems. Sometimes modeling must be used to ensure that the window system selected can meet the recommended U-factors and will contribute effectively to meeting the overall energy performance of the building.

Product manufactures may also be able to provide assembly level U-factors. Manufacturer-provided online calculators can also be used.

The method of installation of the window system including factory-built windows, storefront, and curtain wall systems must be considered and accounted for in the overall energy modelling. 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 (See also EN18).

EN56 Framing and Assembly Infiltration Rates

Use frames and framing systems that, with glazing, meet infiltration recommendations. While the infiltration recommendations in this section include the entire envelope, windows are an important part of achieving the desired level of airtightness (EN2). Note that while storefront and curtain wall systems are frequently tested to the same level of airtightness, in practice, curtain wall is typically more airtight than storefront.

EN54 Mullion Penalties

Mullions often have more conductivity than the window glazing. That is, more energy is lost through the mullion than through an equivalent area of glazing (at the recommended U-factors). To maximize energy efficiency, intermediate mullions should generally be minimized. Note that mullions are helpful to separate daylighting glass from view glass and can be used as a mechanism to attach light shelves and blinds that can reduce glare without impacting the daylighting.

Mullions must be considered in the overall U-factor of the glazing system, as discussed in EN52.

EN55 Air Barrier and Thermal Break Continuity

Some fenestration types pose particular challenges or opportunities in regards to connectivity with the wall air barrier.

Conventional windows can be tied to the wall air barrier in a relatively straightforward way through the combination of self-adhering membranes, low-expansion foam insulation, and sealants.

Curtain wall is also well suited to air barrier continuity. Self-adhering membranes or silicone transition strips can be terminated directly in the glazing pocket and mechanically clamped by the pressure plate. Framing members generally have structural capacity and reinforcing is not required.

Storefront systems pose more challenges for air barrier continuity. Continuity is complicated by the nature of the extrusion, the method of bearing/attachment, and the method of draining and flashing the system. To maximize efficiency, consider the following strategies:

- Always specify continuous filler plates on the concealed portion of the extrusion (to receive the air barrier.) Filler plates should be thermally broken or nonconductive.
- Size storefronts such that all units can be carried by mounting brackets. Use thermally broken bearing plates. Where bottom bearing units are unavoidable, use noncontinuous bearing plates at the storefront shimming locations.

- Size storefronts such that steel reinforcement of mullions is not required. Steel reinforcement of jambs is typically not thermally broken and defeats framing systems that are otherwise thermally broken.
- Size storefront-mounted shading to avoid the need for steel reinforcing of the vertical mullions. Where shading devices would require mullion reinforcement, compare the energy penalty to that of other mounting strategies.
- Require secondary mechanical attachment of the self-adhering membrane or transition strip to the storefront filler plate (and ensure all parties understand the tight tolerances required to do so.)
- Never insulate inside the extrusion without the manufacturer's written endorsement.
- Ensure that all glazing units are air-sealed by the fabricator per the manufacturer's recommendations and can be represented by the manufacturer's infiltrations test reports.

EN56 Construction Sequencing

Air sealing to fenestration units is more effective when the fenestration units are installed prior to both the building exterior insulation and the building skin. This construction sequence is nonstandard for many contractors so understanding and appreciation of the new methodology needs to be strongly encouraged.

EN57 Operable Fenestration

Operable fenestration offers personal comfort control and connections to the environment. Therefore, there should be a high level of integration between operable windows, envelope, and HVAC system design to maximize the energy benefits of this strategy. The envelope should be designed to take advantage of natural ventilation with well-placed operable openings. See HV35 for guidance on interfacing operable windows with the HVAC system. See BP7 for guidance on building and site planning as it relates to natural ventilation.

Operable units should meet fenestration requirements discussed elsewhere in this document (see BP10, EN42–EN52, DL2–DL6). Note that casement, awning, hopper, and tilt-turn windows usually have less infiltration than hung windows or sliders.

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.

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DAYLIGHTING

OVERVIEW

Daylighting is an essential design strategy for zero energy schools. Properly designed daylighting uses sunlight to offset electrical lighting loads, save energy and reduce cooling loads. The benefits of daylighting are especially important for classrooms (particularly special-needs classrooms). Daylighting should provide lighting of better quality than electric lighting alone. Otherwise, occupants are motivated to turn on the electric lights even when they are not needed. Good daylighting design seeks the right balance between enough daylight and too much sunlight, which can be a source of glare and excessive heat gain. As electric lighting systems become more efficient, the energy savings from daylighting are reduced, but at the same time, the cost of daylighting controls is declining. On balance, energy savings from daylighting still justify the investment. When enhanced student performance, alertness, and attention are factored in along with other the nonenergy benefits, daylighting is still an excellent investment for school districts and should be an essential element of all zero energy schools.

DL1 General Guidance

To achieve energy savings, the electric lights must be automatically dimmed or turned off through the use of photo controls. Lighting control should be designed to not disrupt teaching or be a distraction, so continuous dimming systems are preferred. Information on electric lighting controls is provided in EL13 to EL22.

Lighting uniformity is an important design goal. The ratio between the areas of the classroom with the most illumination should be no greater than ten times the illumination in the areas with the least illumination (maximum ratio of less than 10:1). It is easier to achieve this balance if skylights are used in combination with sidelighting. Traditional skylights or tubular skylights located near the back wall (away from the window wall) brighten the back wall and greatly increase uniformity. Skylight placement must be coordinated with the design of the PV panels if they are located on the roof. (See BP20.)

Students learn quicker and teachers perform better in classrooms that have good daylighting, views, and acoustics. A recent study by Rensselaer Polytechnic Institute (RPI) concluded 8th grade students receiving daylighting were positively impacted (Figueiro and Rea 2010).

DESIGN STRATEGIES

DL2 Fenestration Functions

Daylighting apertures should be located as high in the space as possible while view windows should be located at eye level. Openings for natural ventilation need to be located both low and high in the space. For these reasons, fenestration should be designed to separately serve each function. See Figure 5-17 for an example of separated fenestration functions.

In general, daylighting fenestration should be located 7 ft or more above finished floor (AFF) and view fenestration should be located below 7 ft, although sometimes views up toward the sky are beneficial. View windows should be provided in classrooms, resource rooms, cafeterias, and administrative offices and should be strategically positioned and limited in size to minimize the energy loss and unwanted solar gain. View windows positioned in the corners of rooms reduce dark spots by washing the adjacent wall with light. North and south orientations are best because they are more easily shaded. View windows on the east and west should be minimized, as they are difficult to shade and can result in glare and excessive heat gain.

North-facing windows below 7 ft can be considered daylighting fenestrations if they are designed to reduce contrast (uniformity illuminance ratio less than 10:1 within the intended daylighted space). South-, east-, or west-facing windows can be considered daylighting apertures but an appropriate fenestration VT must be selected to minimize glare. (See EN43, EN46.)

The sill height should be low enough that views can be enjoyed from a seated position. In classrooms used for early grades and preschool, the appropriate sill height is about 18 in. from the floor. A sill height of about 30 in. is appropriate for other spaces, to enable book cases to be positioned underneath.

Figure 5-17 Fenestration example.
Photo by Paul Torcellini, NREL Image 49039

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Wall space is precious in classrooms. As a result, view windows often serve as display areas. Additionally, these windows are almost always accompanied by user-operated window treatments (blinds or shades) that can readily be closed by teachers and students. Even if they are not covered by artwork or blinds, they have limited daylight benefit, except for lighting spaces very close to the window. To avoid compromising daylighting postoccupancy, adequately address the requirements for display space and glare avoidance, and the ease of using shading controls.

Both view windows and daylighting apertures can provide natural ventilation. Apertures for natural ventilation should be located near the floor and high in the space when ventilation is to be driven by the stack effect. Fenestration for wind driven ventilation should be located where building form creates positive and negative pressure areas.

DL3: Daylighting Design Criteria

Daylighted spaces should provide a minimum of 300 lux for at least 50% of the operating hours. This illumination is then supplemented as needed by electric lighting. Based on these thresholds, the spatial daylighting autonomy (sDA) for classrooms should be greater than 75% and greater than 55% for other regularly occupied spaces in schools (see Table 5-6). The sDA criteria ensures that enough daylight is provided, but too much daylight is also a problem, because it introduces unnecessary heat gain and can be a source of glare. For this reason, a second criterion is provided, which is the maximum annual sunlight exposure ($ASE_{1000,\ 250}$). Direct sunlight should not exceed 1000 lux (over ambient) for more than 250 hours per year. The ASE should not exceed the values shown in Table 5-7.

DL4 Applicable Space Types

When designing a zero energy school, daylighting the majority of classrooms and other regularly occupied spaces should be a high priority. The top priority should be the classrooms and resource rooms, followed by media centers and administrative spaces. Daylighting in these spaces will have the greatest nonenergy benefits for students, teachers, and staff. Highly utilized gymnasiums and multipurpose spaces will often show the greatest energy savings from daylighting. Cafeterias are used by students and faculty only during lunch periods, but they are used by the cafeteria staff for a much longer portion of the day and should be designed for daylighting. If cafeterias are expected to be used for other purposes such as end-of-grade testing, they should be designed like classrooms and other regularly occupied spaces to limit direct sunlight and the ASE criterion should apply.

DL5 Orientation of Vertical Fenestration

Effective fenestration design starts with good orientation and good orientation begins with building siting (see BP1, BP2, BP9, and BP10). For classrooms and most other spaces, the vertical facades that provide daylighting and views ideally should be oriented within 15° of either north or south; a deviation from north or south of about 30° should be considered the maximum. Windows in this range of orientation can be more easily shaded with simple overhangs on the south and solar gain is minimal on the north. East and west glass is problematic from a solar heat gain perspective, is difficult to shade, and can provide nonuniform daylighting. East facing glazing is a special problem because classes are usually in session in the morning.

When positioning fenestration on the building, consider adjacent buildings, trees, terrain, and other elements. These can affect views and daylighting in a positive or negative way. On the east and west, trees can provide shading and can filter daylight. However, the primary daylighting apertures on the north and south should be as clear as possible from shading obstructions. See BP7 for additional considerations.

South-facing windows can be major source of glare in extreme northern latitudes as the sun is at a low altitude for much of the school year. In southern latitudes near the equator, there is less of a penalty for east and west oriented windows as they can be more effectively shaded with overhangs.

Dynamic Daylight Metrics

The most common metric is *daylight factor*, which is the ratio of the light level inside a space to the light level outside under overcast conditions. Point-in-time measurements or calculations (for example, illuminance on September 21st at 3:00 pm) can be useful for understanding best- or worst-case scenarios, but don't provide a good picture of whether a space or building is performing well overall.

Dynamic daylight metrics take local climate and sunlight conditions into account, as well as detailed information about the size, shape and color of the space and the daylighting apertures. Two metrics are of particular importance: spatial daylight autonomy (sDA) and annual sun exposure (ASE). Additional explanation on these metrics is available from IES (IES 2013a). Together, the metrics give a clear picture of daylight performance and can help architects make better design decisions (van den Wymelenberg and Mahic 2016).

- *Spatial daylight autonomy (sDA)* is the percent 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 level and for any percentage of time, but the most common threshold is an illumination level of 300 lux for 50% of the time. Subscripts are commonly attached to indicate the illuminance level and percent of operating hours. An $sDA_{300,\ 50\%}$ indicates that sDA is calculated for an illuminance of 300 lux and for 50% of the operating hours. If a daylighting design for a classroom has an $sDA_{300,\ 50\%} = 65$, this means that 65% of the floor area meets this condition. Calculation of sDA requires sophisticated software that can estimate the lighting level at different points within the space and for different times of the year; such software is offered by a number of vendors. Typically, lighting levels are calculated on an hourly basis for a 2 × 2 ft grid within the space.
- *Annual sunlight exposure (ASE)* is a metric that describes the potential for visual discomfort in interior work environments and classrooms. It is defined as the percent of an analysis area that exceeds a specified direct sunlight illuminance level more than a specified number of hours per year. Like sDA, subscripts are commonly used to indicate the thresholds. $ASE_{1000,\ 250}$ indicates that the thresholds are 1000 lux above ambient lighting levels and 250 hours per year.

A well daylighted classroom space would have a high sDA and a low ASE. Both dynamic metrics are needed evaluate daylighting in schools. sDA assures that there is enough daylight and ASE assures that there is not too much.

- sDA and ASE are now incorporated in common lighting analysis and design software packages, such as IESVE, Diva-for-Rhino, OpenStudio, Radiance, Daysim, Safairi, SPOT, and LightStanza. These tools are offered as examples and are not endorsed by ASHRAE or its AEDG partners. New tools are being offered each year so not all the available tools are included in the list. See Chapter 4 for additional information on building simulation and analysis.

Table 5-7 (DL3) Recommended Daylight Design Criteria

Space	Minimum sDA300,50%	Maximum $ASE_{1000,250}$
Classrooms	75%	15%
Gymnasiums/ Multipurpose Rooms	55%	25%
Library Reading Area	55%	25%
Administrative Offices	55%	15%
Cafeterias	55%	25%

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DL6 Fenestration Area

Recommendations on fenestration area depend on many factors including how the fenestration is used. Good design avoids fenestration areas that do not contribute to one of the principle functions: view from the building, daylighting of the space, or natural ventilation. Many prescriptive energy codes allow a WWR up to 40%, but this limit is not specific to schools. The average WWR for schools is about 22% and this is the baseline WWR for most energy modeling. For mid-latitudes, the best orientations are north and south and most of the fenestration should be located on these sides (see DL5). Figure 5-18 illustrates the various fenestration ratios used in this document as well as in codes.

Views. The recommended view fenestration area (VFA) for schools is expressed as a function of the conditioned floor area. The maximum net view area (the glass area) should be limited to 5% of the floor area for view windows that face east and west. Larger view windows are justified for north and south orientations. The recommended view fenestration on these facades is limited to 7% of the floor area. As an example, a 1000 ft^2 classroom would have view glass not to exceed 50 ft^2 if it faces east or west and 70 ft^2 if it faces north or south. Reducing view fenestration will save energy, especially on the east and west facades View windows should be located so that they frame interesting and visually stimulating views. If they are located in the corners of the room, they can also wash the side wall with light and reduce dark spots.

Daylighting. Classrooms should be designed to achieve an $sDA_{300,50\%}$ of at least 75%. Other regularly occupied spaces in schools should achieve an $sDA_{300,50\%}$ of at least 55%. For classrooms this means that three quarters of the classroom floor area should have at least 300 lux of daylight illumination for at least 50% of the occupied hours. The daylight fenestration area to achieve this criteria will depend on many factors, including its position in the space, the VT of the glazing (a higher VT means less area), the orientation of the fenestration, exterior and interior shading devices, surfaces reflectance both inside and out, and many other factors. As a starting point, Table 5-8 recommends the daylight fenestration area, expressed as a percentage of the floor area. This table assumes that all daylighting fenestration is located at least 7 ft AFF. Recommendations are given for different climate zones and for several daylighting systems. For visual connection to the outdoors, provide additional view windows below 7 ft from the floor. These rules assume a VT of the vertical daylighting fenestration ranging from 20% to 60%, depending upon strategy used. For horizontal daylighting fenestration, a 50% VT is assumed.

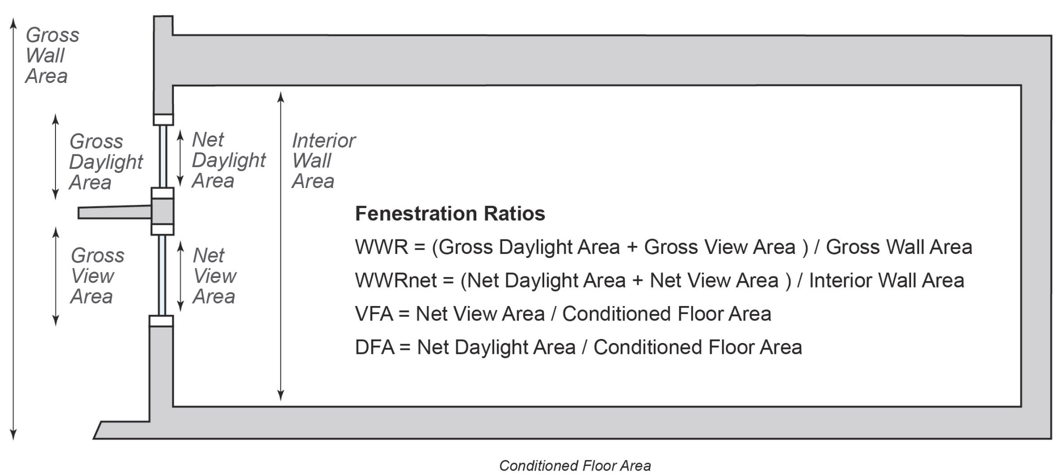

Figure 5-18 (DL6) Fenestration ratios.

Table 5-8 (DL6) Recommended Daylight Fenestration to Floor Area (DFA) Ratios

Orientation	Daylighting Strategy	VT[1]	CZ 0 to CZ 2	CZ 3 to CZ 5	CZ 6	CZ 7 and CZ 8
South	Overhang	0.60	7–8%	8–11%	8–12%	12–15%
	Light shelf	0.60	8–12%	8–13%	11–15%	13–17%
	Blinds between glass	0.50	7–9%	8–10%	9–11%	11–13%
	Roof monitor[2]	0.60	7–8%	8–11%	8–12%	12–15%
	Fiberfill	0.30	9–14%	10–15%	12–17%	14–18%
	Aerogel	0.20	11–15%	12–16%	14–17%	16–19%
North	High window	0.60	12–16%	13–17t%	15–18%	17–16%
	Roof monitor[2]	0.60	8–11%	8–12%	11–13%	13–16%
Horizontal	Tubular skylight[3]	N/A[3]	2–5%	3–5%	4–5%	4–5%
	Skylight	0.50	2–5%	3–5%	4–5%	4–5%

1. VT values are for center-of-glass.
2. DFRs on the lower end of the range for roof monitors should be used for gyms and high ceiling spaces while DFRs on the higher end of the range should be used for classrooms.
3. Tubular daylighting devices are optically complex to gather maximum light and to reflect and diffuse the light that makes it to the bottom glazing layer. For this reason, the peak VT method has been replaced by an "annual average VT" by NFRC. Consult manufacturers for daylighting layouts that achieve daylight goals.

DL7 Daylighting Analysis

While prescriptive guidelines can be used early in the design process, more comprehensive daylighting and whole-building energy simulations are recommended to achieve zero energy. To more accurately simulate daylighting contributions a detailed daylight analysis that considers daylighting across the entire space and for different times of the year is recommended. The analysis tool should be able to predict illumination and surface brightness for a grid of points within the space and to calculate performance during all hours of operation. These tools may be used to calculate both sDA and ASE for all typical classrooms and other regularly occupied spaces in schools. At a minimum, point-by-point daylighting levels should be calculated for multiple design conditions, including sunny and cloudy conditions, the summer and winter solstices, the peak cooling day, the equinox, and three times during the day: 9:00 a.m., noon, and 3:00 p.m. For an example, see Chapter 4, Evaluating Daylighting Analysis.

The best way to determine the optimum daylight fenestration area is through iterative modeling, where the variables described above (and others) are systematically varied within a range that works with other design goals until the desired result is achieved.

While, analyzing daylight options can be complicated, the Advanced Buildings Daylighting Pattern Guide (NBI 2017) is a resource that provides daylight performance information in a consistent format. To get started and to quickly understand the how area affects daylight, the Daylight Pattern Guide has precalculated the daylighting for classrooms, gyms, and administrative offices and for a variety of window and skylight configurations.

The online guide contains example daylight solutions for classrooms and other school spaces. When using the guide, performance information can be evaluated in a similar format for different window areas and fenestration configurations. Consulting this guide is useful to frame the problem and obtain some early guidance on the fenestration area needed to achieve good daylighting and to meet the sDA and ASE recommendations shown in Table 5-6. It is an easy way to understand the impact of design changes, short of a detailed daylighting analysis.

DL8 Shading

Uncontrolled solar heat gain is a major cause of energy use for cooling in warmer climates and of thermal discomfort for occupants. Appropriate configuration of windows according to the orientation of the wall on which they are placed can significantly reduce these problems while simultaneously reducing or eliminating direct beam radiation and unwanted glare. Unwanted solar heat gain is most effectively controlled on the outside of the building. Significantly greater energy savings are realized when sun penetration is blocked before it enters the windows. Horizontal overhangs at the top of the windows are most effective for south-facing facades and must continue beyond the width of the windows to adequately shade them. Table 5-6 (EN45) has factors to approximate the impact of various size overhangs.

An essential component of good fenestration design is to limit direct-beam radiation into regularly occupied spaces. This is critical for all classrooms, libraries, media centers, and administrative spaces, but less critical for gymnasiums, multipurpose rooms, and corridors. Use strategies that bounce, redirect, and filter sunlight so direct radiation does not directly enter space for any significant period of time.

With good shading, interior shades may not be necessary except to darken the space for audio-visual (AV) purposes. Shades should not be used on daylighting apertures as it negatively impacts energy performance. Interior shades are typically closed to reduce solar heat gain and glare and not reopened. With advances in AV technology, including flat screens, high-lumen LCD projectors, and the incorporation of intentionally shaded projection screen areas within the classroom, it is now possible to allow the seating area within the classroom to benefit from daylighting with reduced darkening requirements.

As shown in Table 5-8, the ASE for all classrooms and administrative offices should be less than 15%. The ASE for gyms, multipurpose rooms, cafeterias, and library/media centers should not exceed 25%. This means that for classrooms, 85% of the floor area should NOT have sunlight exposure of 1000 lux greater than the ambient daylight in the space for more than 250 hours per year. If ASE calculations are not possible, evaluate sun angles at 9:00 a.m., noon, and 3:00 p.m. on the equinox and at the summer solar peak and make sure that there is no direct solar radiation on the work plane (typically a surface 30 in. above the floor) inside a band of 4 ft from the edges of the walls.

Limiting direct solar penetration into the space can be achieved through proper orientation as well as shading, filtering, baffling, and reflecting solar radiation at each daylighting aperture. The following are some example strategies. See also Figure 5-19.

- **Exterior shading strategies.** These include major building and architectural elements, such as overhangs, soffits, trellises, awnings, and external light shelves. This strategy can be most effective, as it prevents excess solar heat gain and glare.
- **Special glazing.** Shading, filtering, or reflecting materials can be integrated into the glazing to reject unwanted, excessive solar gain. These include glazing that employ special coatings with selective transmission, as well as opaque elements integral to the glazing, such as fritted patterns, fiber-fill, aerogel or blinds-between-glazing panels.
- **Interior shading.** These include baffles, louvers, rolling shades, blinds, and internal light shelves. Some interior shading devices can bounce light deeper into the space.

The success of daylighted schools depends on how occupants interact with the daylighting system. This is particularly true for blinds or shades on the daylighting glass that are available for adjustment. If blinds are left closed, the daylighting potential will not be realized. If temporary darkening of a specific space is not functionally required, do not install shades or blinds on the daylighting glass. Unnecessary blinds results in reduced daylight performance, increased first costs, and higher long-term maintenance expenses.

DL9 Light Shelves and Redirection Devices

Daylight from windows can be more effective on the south side with light shelves or other light redirection devices that bounce daylight off the ceiling. See DL16 for examples. Select durable materials for interior and exterior light shelves. Aluminum exterior light shelves are a compromise between good reflectance with little or no maintenance and cost. Incorporate white finishes on the top of interior light shelves. Aluminized acrylic sheets applied to the top of the interior shelf allows light to bounce further back into spaces and can improve performance in rooms without toplighting.

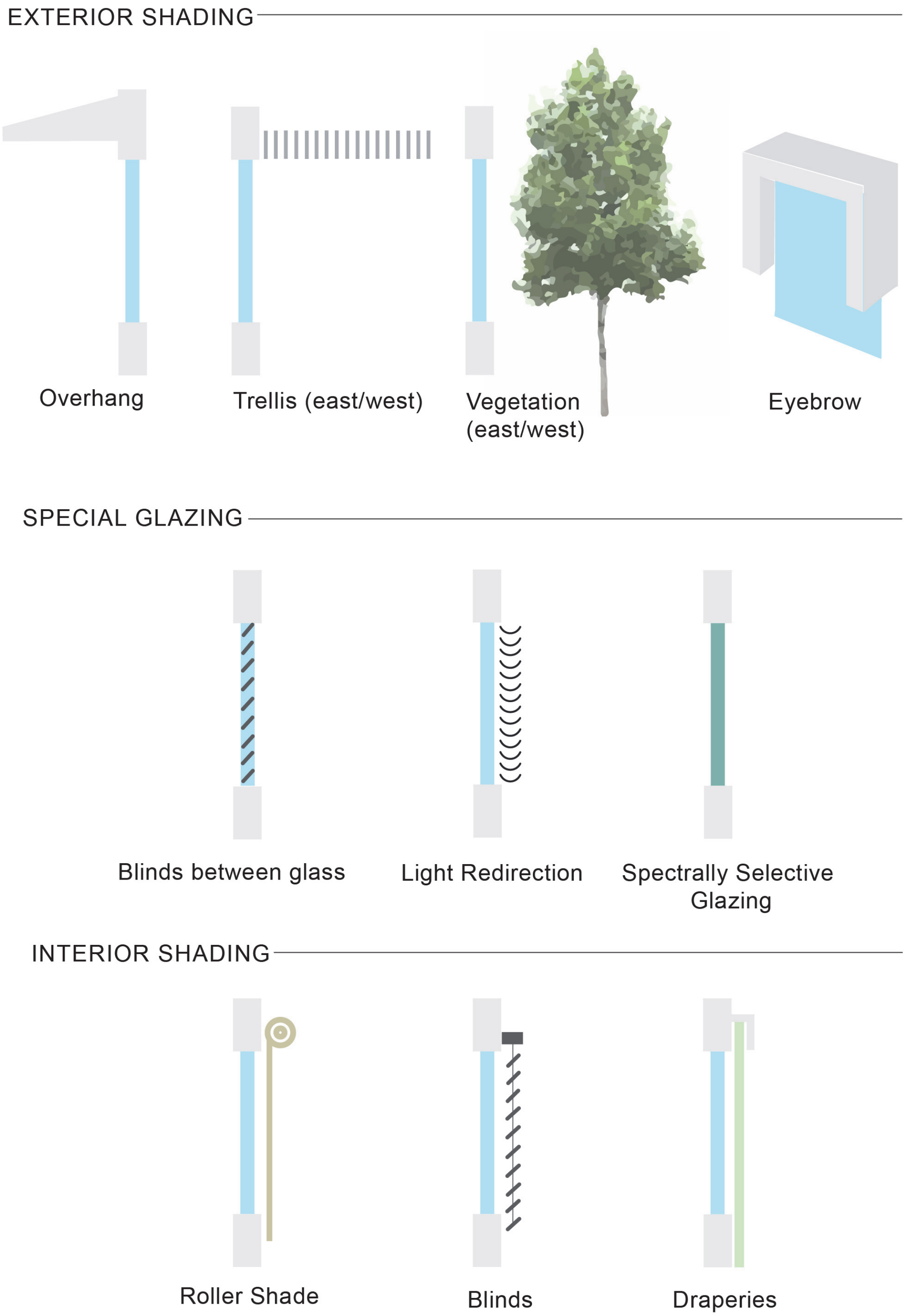

Figure 5-19 (DL8) Fenestration shading examples.

DL10 Ceiling Height

The height of the ceiling affects where fenestration can be positioned in the wall. A minimum 10 ft ceiling height is recommended for all classrooms and other spaces that are daylighted. When daylighting must be provided entirely from sidelighting, a higher ceiling is recommended at the perimeter wall. The ceiling should be sloped when possible with the highest ceiling near the window sloping down toward the back wall. (See DL14.)

DL11 Outdoor Surface Reflectance

Consider the reflectance of the roofs, sidewalks, and other surfaces in front of the glazing areas. The use of lighter colors can increase daylighting intensity and, in some cases, reduce the glass area needed for roof monitors or clerestories. Note that a light-colored walkway in front of view windows may cause unwanted reflections and glare.

DL12 Interior Finishes

The color of the ceiling, walls, floor, and furniture has a major impact on the effectiveness of the daylighting and electric lighting strategy. Select light colors for interior walls and ceilings to increase light reflectance and increase the effectiveness of the lighting and daylighting systems. Recommended surface reflectance is given in Table 5-9 for walls, ceilings, and other surfaces. When considering finish surfaces, install light colors to ensure daylight is reflected throughout the space.

Consider a ceiling tile or surface that has a high reflectance. Make sure that the ceiling tile light reflectance includes the fissures within the acoustical tiles, as these irregularities affect the amount of light absorbed. Do not assume that the color of a tile alone dictates its reflectance. When selecting a tile, specify a minimum reflectivity. Most manufactures will list the reflectance as if it were the paint color reflectance.

Dark colors absorb light, making the space feel darker. However, uniform higher reflectance on the walls and ceiling may not provide the preferred visual aesthetic for all spaces. To maximize inter reflections and maintain higher light levels, color should be used as an accent and large colored surfaces should be avoided.

DL13 Teaching Surface and Audio-Visual Activities

Whiteboard teaching surfaces have a specular surface and should be carefully located so there is no reflected glare from either daylighting apertures or lighting fixtures. Since the teaching surface is typically near the projection screen, separate control of the teaching surface light is essential. The recommended place for the teaching surface is perpendicular to the window wall to minimize reflected glare from the windows wall.

If a classroom or multipurpose room requires darkening for AV or other functions, consider motorized roller shades or motorized vertical blinds for apertures that are out of reach. This may seem to result in higher maintenance costs, but such controls can have the opposite effect. The mechanical stress placed on manual operators by students and teachers (because of

Table 5-9 (DL12) Minimum Interior Surface Reflectance

Location	Minimum Reflectance
Walls above 7 ft	70%
Ceiling	80%
Light wells	80%
Floors	30%
Furniture	50%
Walls below 7 ft	50%

uneven cranking) limits the effective life of these devices. The inconvenience associated with the process also results in a number of shades being left closed. Motorized shades, which cost more up front, will provide greater ease of operation and result in a better-performing daylighting design. Some motorized devices can also be programmed to reset in the open position at the beginning of each day.

Most new schools use TV monitors or liquid crystal display (LCD) projectors. These teaching tools often require that the light level at the specific location of the screen wall be as low as 70 lux for optimum contrast. Slightly higher levels (70 to 150 lux) should still provide acceptable light levels for the visual aids, but the reduced contrast will make them slightly harder for the students to read. If the light levels on the projection screen area are to exceed 150 lux, high-lumen projectors (3000+ lumens) and intentionally shaded screen areas should be used, and screens should be selected that are intended for use in daylighted spaces.

Visual comfort from both daylight and electric light sources is a must and must meet the dynamic needs of classrooms including multiple teaching surfaces and electronic devices. The lighting control system must walk the fine line of flexibility while being simple to use and meeting long-term maintenance objectives.

CLASSROOM SIDELIGHTING

DL14 Sloped Ceilings

When daylight can be provided only from the side, the ceiling should be sloped down to the back wall. A sloped ceiling can achieve a higher window head, which will result in greater daylighting penetration into the space. The slope will also provide a brighter ceiling. By sloping the ceiling from the outside wall to the back of the space, it is often possible to maintain the same floor-to-floor height while at the same time increasing ceiling height near the window. See Figure 5-20.

DL15 South-Facing Classrooms

The choice of fenestration and the placement of the apertures are critical. As discussed in DL8, all apertures should be shaded and oriented to avoid direct beam radiation entering the classroom. Direct sun can create glare and the teacher will simply close the blinds, which will negate the benefits of daylighting.

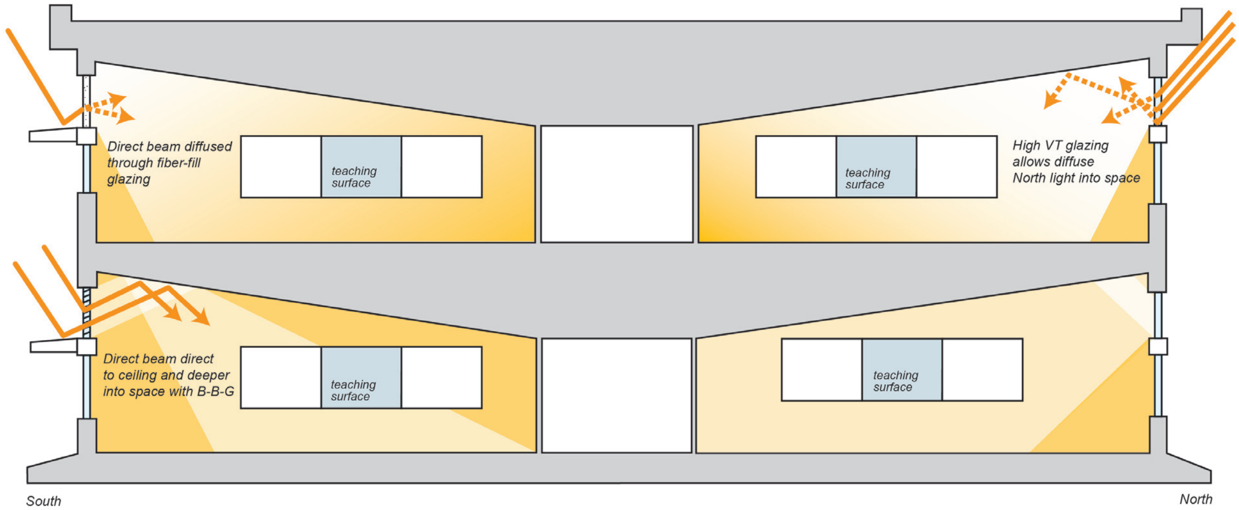

Figure 5-20 (DL14) Example classroom sidelighting strategies for both north and south orientations.

A light shelf is a design option that should be considered for south-facing walls. The daylighting fenestration above the light shelf should be as continuous as possible with a height of 3 to 5 ft. The daylighting aperture should be positioned as close to the ceiling as possible within structural constraints. As shown in Figure 5-21 (lower floor south), louvers can be positioned to block all radiation and reflect sunlight up to the ceiling during typical class hours. At the top floor, an overhang should be positioned over the daylighting aperture on the south and sized with the light shelf to prevent direct sun from entering the space. Set the cutoff angle of the light shelf or louvers to eliminate direct sun penetration during normal school hours.

Alternatives to interior light shelves include fiber-filled glazing to diffuse incoming sunlight (Figure 5-22) or the addition of mini blinds between panes of glass (Figure 5-23) to redirect sunlight up to the ceiling, with the addition of a third pane in cold climates. For these alternatives, the interior portion of the light shelf may be eliminated, but the outer portion is still needed to shade view glass.

The area of the daylighting aperture for a south-facing light shelf application should be in the range of 70 to 120 ft^2 for a typical 1000 ft^2 classroom, but this varies by climate (see Table 5-7) This recommendation is based on glazing with a center-of-glass VT of 60%. Glazing with a higher or lower visible transmittance may be used, but the aperture should be adjusted to maintain the same visible aperture. If the daylighting fenestration incorporates blinds-between-glass, the VT is typically 50%, while fiberfill applications are 30% and aerogel-filled glazing is 20%. Where windows are used specifically for daylighting, consider the use of low-e coated clear glass with a high VT. A larger daylighting aperture with a lower VT has the advantage of providing the same amount of daylight but with less glare and contrast, but costs are higher. (See also, EN46, EN49.)

Also consider horizontal blinds located between glazing or special louvers designed to reflect light to the ceiling. (See www.LightLouver.com, for example) As shown in Figure 5-23, blinds between glass both block all direct beam radiation and reflect incoming sunlight up to ceiling. The horizontal blinds should be highly reflective and have either flat or slightly curved

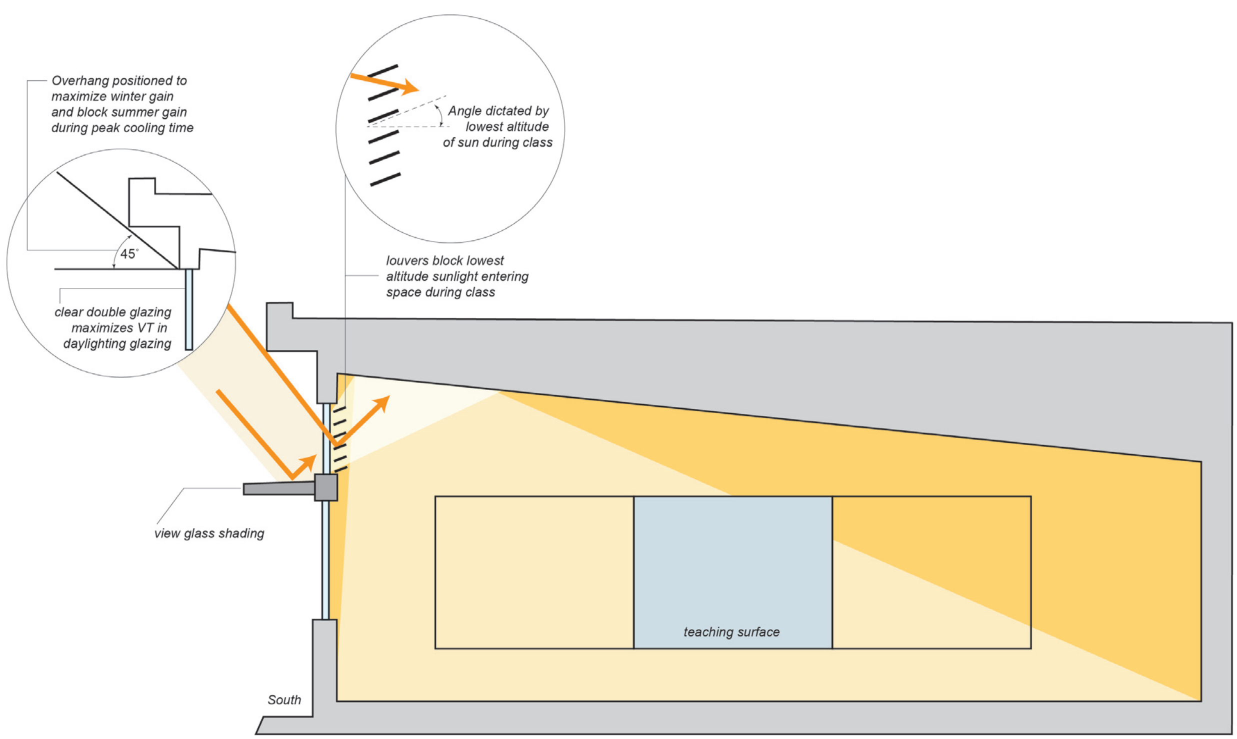

Figure 5-21 (DL15) Louvers blocking direct beam radiation.

blades. Because of potential dirt buildup and maintenance, the blinds should be placed between panes of glazing. If this option is used, consider the transmission of the blinds and increase the glazing area accordingly.

Most shades that are available today are operable and can be closed. However, if the space does not need to be temporarily darkened, the internal blinds should be directed up to the ceiling and fixed at the recommended cutoff angle for light shelves. By fixing the angle and not

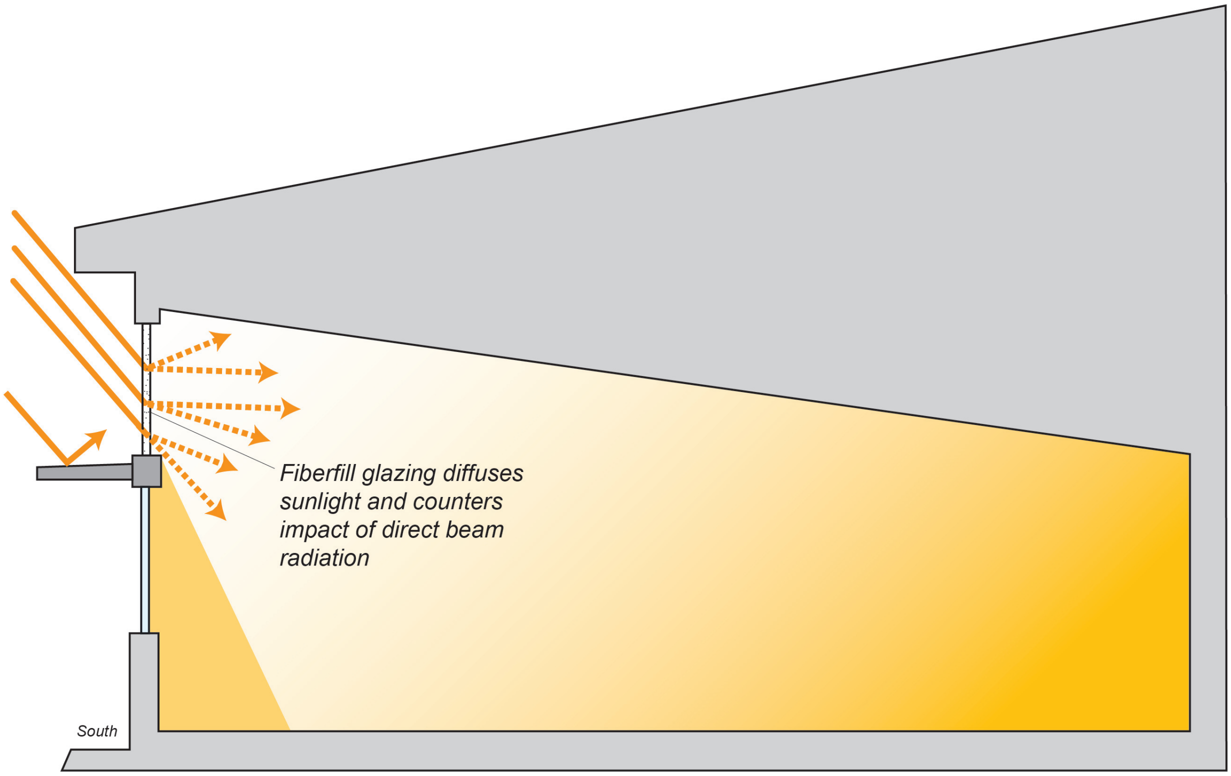

Figure 5-22 (DL15) Fiber-filled glazing diffuses sunlight.

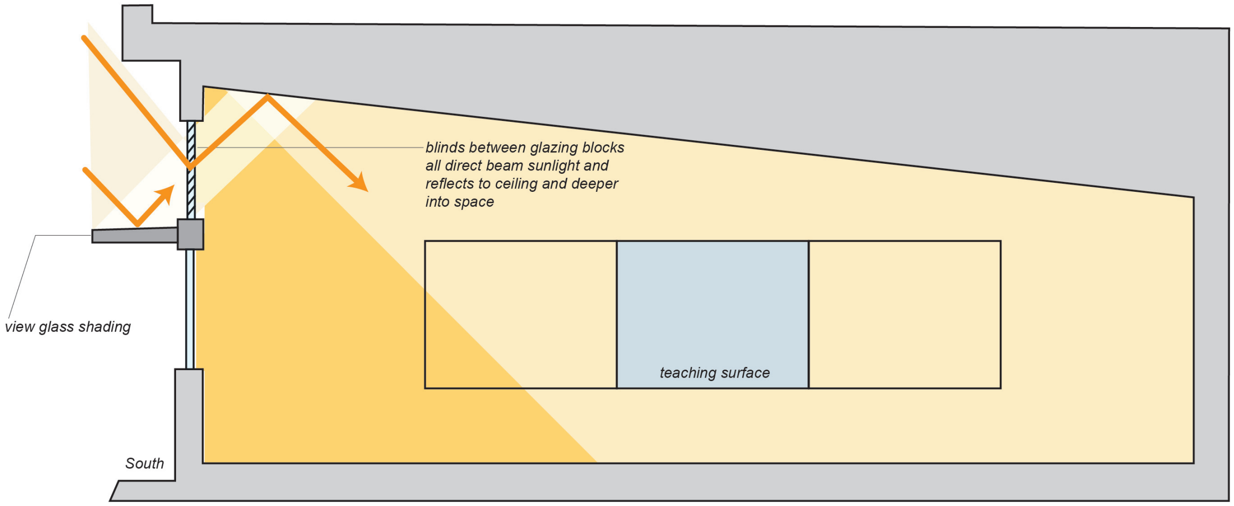

Figure 5-23 (DL15) Light shelf using blinds between panes of glazing.

allowing the occupants to operate the blinds, there will be less opportunity to override the daylighting benefits. If the internal blinds do need to be operated for darkening purposes, provide two fixed positions: the one just described and a second "closed" position.

The desirable color qualities of daylighting are best transmitted by neutral-colored fenestrations that alter the color spectrum to the smallest extent

An example of a classroom with light-directing louvers, Manassas Park Elementary School has continuous daylighting glass above the view glass as shown in the upper right corner of Figure 5-24. Note the sloped ceiling to assist in the distribution of light and the teaching surface perpendicular to the windows.

DL16 North-Facing Classrooms

For north-facing classrooms, a light shelf is not needed because its benefits are related to the reflection of direct solar radiation, and north facades experience little direct solar gain.

For north-facing classrooms, the daylight glazing should also extend as close as possible to the ceiling. Window area below floor height of about 7 ft should be considered as view glazing and not considered as a significant contributor to daylight. The daylighting glazing should be as continuous as possible along the facade. If continuous fenestration cannot be provided for structural or other reasons, the windows should be placed in the corners of the space with the opaque wall for shear or structure located in the center of the wall. This will light the walls perpendicular to the daylighting wall and provide better illuminance ratio and surface brightness.

From a daylighting perspective, high north glazing can be a good option into spaces up to a distance of 1.5 to 2.0 times the height of the top of the window. As with north-facing roof monitors, more glazing is required than for a south light shelf to achieve the same annual daylighting contribution, so the energy performance is not quite as good. The most significant advantage is that controlling any direct beam radiation is typically easy.

Figure 5-24 (DL15) Light redirection in a classroom.
Photo © Sam Kittner/Kittner.com, provided courtesy of LightLouver LLC

CLASSROOM SIDELIGHTING WITH TOPLIGHTING

DL17 General Recommendations

When necessary, adding skylights or roof monitors can improve daylighting and improve uniformity when implemented with vertical fenestration. Sometimes tubular skylights can be used on two-story buildings to deliver light to the first level. This strategy combines the sidelighting recommendations previously discussed, with small interior skylights, tubular daylighting devices, or roof monitors to balance daylighting across the space. Figure 5-25 shows a typical cross section.

GYMNASIUM/MULTIPURPOSE ROOM TOPLIGHTING

DL18 General Recommendations

For spaces with high ceilings, such as gymnasiums, or for larger spaces, such as multipurpose rooms, cafeterias, and commons, a basic daylighting design that uses toplighting is recommended. Toplighting has the distinct advantage of providing useful daylight under most conditions and allows for almost any orientation of the space. A minimum sDA of 55% is recommended for these spaces with a maximum ASE of 15%. (See Table 5-6.) Toplighting must be integrated with solar panels when they are located on the roof.

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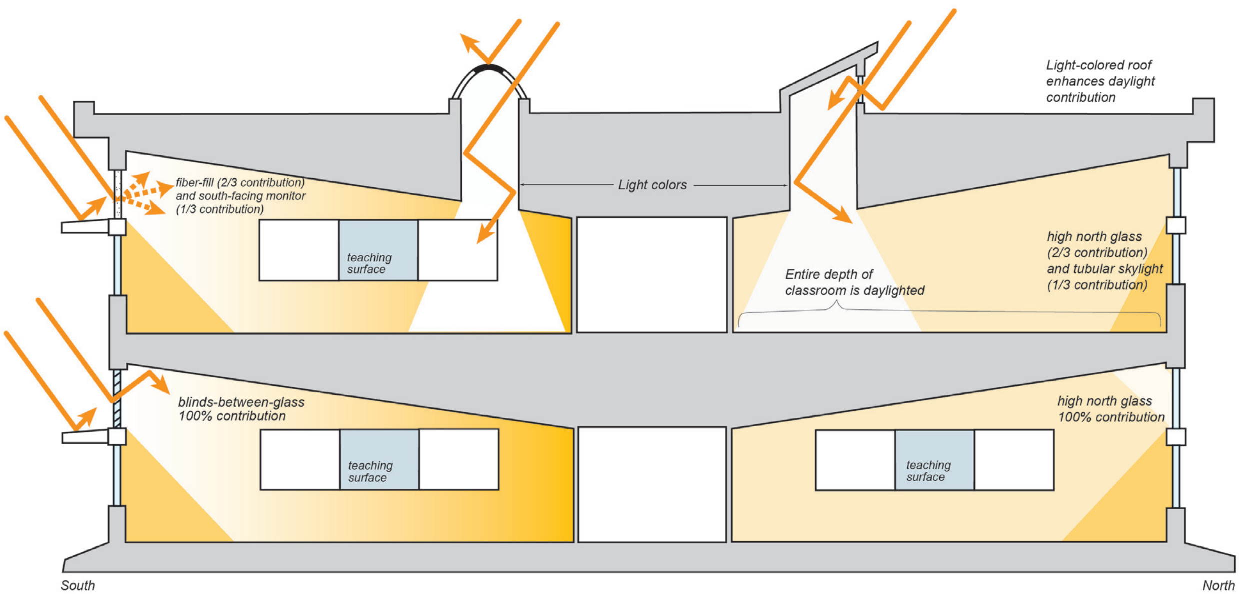

Figure 5-25 (DL17) Sidelighting enhanced with toplighting or roof monitors.

Chapter 5

DL

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ELECTRIC LIGHTING

OVERVIEW

Effective daylighting in schools provides high-quality lighting without compromising lighting quality or illumination levels. Energy savings are achieved through reduced lighting power densities (LPD) based on the lighting and control systems employed. The development of rapidly evolving technologies including efficacious sources, more efficient luminaires, and intelligent control systems have created opportunities to reduce the LPD of a school. This section explores critical luminaire metrics, design elements, and control strategies that impact energy use and maintenance as well as functionality, user comfort, and aesthetics. Lighting design for classrooms and other common space types are discussed in the space specific strategies section. Lighting layouts in conjunction with recommended illuminance targets and controls strategies show examples of how to significantly reduce energy while maintaining visual acuity.

LUMINAIRE STRATEGIES

EL1 Light-Emitting Diode (LED) / Solid-State Lighting (SSL)

A light emitting diode (LED) is a solid-state semiconductor device that produces a wide range of saturated, colored light and can be manipulated with color mixing or phosphors to produce white light. Products are available that allow the adjustment of the correlated color temperature (CCT), providing what is known as *dynamic* or *tunable* white. LED luminaires (also called fixtures) are also available in color changing plus white, dynamic white, or amber. These options are important when a luminaire needs to provide both color changing lighting as well as white only. A typical RGB (red, green, blue) color-changing luminaire produces a muddy white with poor fidelity. However, an RGB+W provides a separate channel of white. (IES 2008, IES 2014a, IES 2014b, IES 2015a). LED efficacy or the efficiency of the lamp continues to rise providing more options to save energy on the lighting system. Additionally, fidelity and particularly color consistency have greatly improved in the last several years. (See also EL3 and EL4.) Additional informative about fidelity and color specifications for solid-state lighting systems (SSL) is available from a number of sources (DOE 2015, DOE 2016, Wood 2015, Grabher-Meyer 2016).

Additionally, enhancements to diodes, circuit boards, and optics have improved glare control (EL7) and distribution options. They have also allowed luminaires to break out of their traditional shapes, scales, and configurations to add another layer of visual interest to the space. These are appropriate for spaces such as conference rooms or other areas where an improved aesthetic is preferred.

The life of LED luminaires and how the life span is documented continues to evolve. LEDs gradually produce less light output over their life, and with the exception of catastrophic failures they don't typically “burn out.” Therefore, end of life is when an LED luminaire’s light output, or lumen maintenance, has diminished by a determined percentage; currently, 70% lumen maintenance, known as L70. When specifying an LED luminaire, look for a manufacturer who uses the TM-21 standard for their life expectancy testing protocol (IES 2011a)

Factors to consider when selecting LED fixtures include the following:

- **Life Expectancy.** Heat limits the life of an LED, and while there have been numerous enhancements to improve their ability to dissipate heat, be cautious about locating luminaires to minimize excessive heat. One element to consider is color shift and its impact on what is considered end of life. The correlated color temperature (CCT) on LED luminaires may shift to either warm or cool in later stages in life (see EL3). Aged LED luminaires may end up looking like legacy metal halide systems, with a wide variance in color temperature. Additionally, even though it is less frequently discussed, LED drivers are often the first thing to fail on an LED luminaire.

  Look for a life expectancy of 10 years or higher (i.e., 50,000 hours or more). Look for LED modules with a failure rate of less than 1 in 2000 units along with excellent color rendering and dimming properties (see Table 5-10). LED fixtures warrantied for 10 years are recommended. Drivers and LED modules with five year warranties that cover color shift and light output are recommended

- **Dimming.** Unlike fluorescent switching, frequently turning an LED on and off does not hinder its expected life. 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% 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 (see also EL11, EL14).

- **Replacement.** Not all LED luminaires are able to be relamped. Even when possible, the cost to relamp may exceed the cost of purchasing a new luminaire. Drivers and LED modules should be plug-in and removable. These quick disconnect boards provide an easy means of accessing and replacing drivers. This significantly increases the likelihood of relamping and salvaging the luminaire. Luminaire types should be minimized to reduce the amount of replacement stock required for different driver sizes, types, and LED light engines. Because of the potential increased cost of changing LED boards, the likelihood of color shift, the decrease in lumen output, and the potential for low availability of luminaire parts, providing for group replacement is advisable. Furthermore, providing for additional attic stock of boards, drivers, or even spare luminaires may be useful. (IES 2017)

- **Thermal Capacity.** Heat is a well-known factor in limiting the life of an LED. Be cautious about where luminaires are located to minimize excessive heat. LED fixtures can reach 95°F ambient temperature at the ceilings. LED fixtures should be tested and rated at these higher temperatures.

- **Phosphor Location.** Some LED modules use remote phosphor technology that separates the phosphor disk from the LED emitters via an air space. By decoupling them, the phosphors stay cooler over life and there is substantially reduced degradation from heat. Heat

Table 5-10 (EL1) Recommendations for LED Luminaires

Metric	Fundamental	Tip
Efficacy	120 LPW	EL3
End of life	TM-21 L80 50,000 hrs +	EL3
MacAdam steps	3 for continuous luminaires, 4 for individual	EL4
Fidelity	CRI 85+ / TM-30-15 R_f above 85, R_g 90-110	Sidebar
Maintenance	Ensure LED board and driver are both easily accessible from below and that quick disconnects are provided	EL3
Glare	Minimize glare and eliminate direct view of diodes	EL7

degradation in LED fixtures is visible as color shift, meaning the modules are less prone to color shift over life than regular LEDs.

Table 5-10 shows the recommended metrics and fundamentals for selecting a linear static white LED luminaire for general ambient illumination, along with the tip number where that metric is discussed.

If possible, see a sample of the luminaire prior to specification and create a mockup prior to release of the order. When running LED photometric calculations, ensure appropriate light loss factors are taken into account. When photometrics are provided from a luminaire manufacturer, make sure the light loss factor is documented.

EL2 Linear Fluorescent Lamps and Ballast

Although they are now a legacy product for new construction projects, linear fluorescent luminaires are still widely available and being used in existing facilities.

DESIGN METRICS

EL3 Correlated Color Temperature and Spectral Power Distribution

Correlated color temperature (CCT) describes the tone of light from a static white lamp source. CCT should be combined with the desired spectral power distribution (SPD), to ensure that adequate energy is available in the visible light spectrum. LED solid-state lighting (SSL) sources with the same CCT may vary widely in appearance because of their individual SPDs. Select the lamp source's CCT and SPD for perception, availability, efficacy, circadian stimulus, and acuity.

Warmer color temperatures (2700 K) are often perceived as comfortable and soothing. Cooler color temperatures (5000 K) may feel institutional and unpleasant. All LED sources, regardless of CCT, contain a strong spike at about 480 nm, corresponding to “blue” light. To a certain extent, a space illuminated with a cooler color temperature lamp source is also perceived to be at a higher light level (Clear and Berman 1981), and people within the space may perceive greater visual acuity. However, an extremely high color temperature may cause eye strain or headaches. The use of a balanced source with strong power content across the visible spectrum can mitigate the potential negative effects of any CCT LED source. For an appropriate balance of visual impact, perception, acuity and energy savings, select a range of 3000 K to 4000 K CCT SSL systems with an SPD containing significant power in wavelengths across the visible light spectrum. A color temperature chart is shown Figure 5-26.

Most LED luminaires are available in a variety of color temperatures, although the most common are 3000 K or 4000 K. For many LED luminaires, a cooler color temperature is slightly more efficacious, although this gap has mostly closed over the last several years. Additionally, a static white color temperature is typically more efficacious than dynamic white lighting in a side-to-side comparison.

EL4 Binning

LEDs are subject to variations in manufacturing that requires LED modules going through a “binning” process. Binning sets the limits of acceptable variations within a given chromaticity and power target (See EL1). The amount of variance between two luminaires is illustrated by a mathematical formula known as MacAdam steps. These are also called MacAdam ellipses or standard deviation color matching (SDCM), as shown in Figure 5-27. The greater the number of steps, the greater the variability between luminaires.

When designing lighting systems for schools, consider no greater than four MacAdam steps for individual luminaires. Three or fewer is preferred, particularly for continuous luminaires.

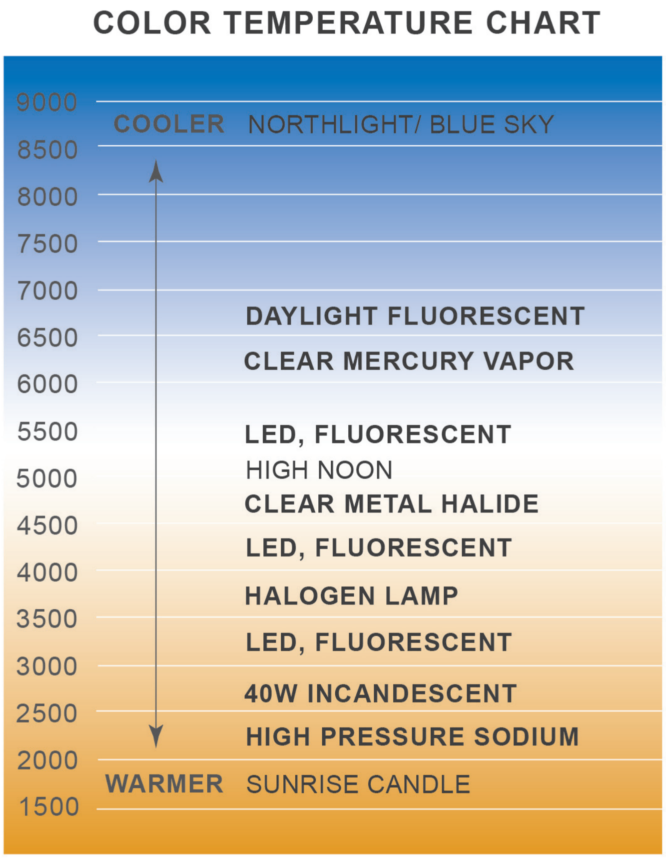

Figure 5-26 (EL3) Color temperature chart.

Evaluating Color Rendition and Quality

Two additional emerging metrics may be useful to note as ways to evaluate color rendition and quality.

Fidelity Index

The fidelity index, denoted as TM-30-15 Rf (IES 2015b), functions in a similar way to the older color rendering index (CRI) scale (CIE 2017). The major difference is that instead of the eight pastel reference colors of CRI, it uses 99 reference colors in 16 bins and containing saturated hues. The goal of the fidelity index is to give a more realistic evaluation of how well a light source will render objects in the real world. For example, many traditional discharge lamp sources have a spiky SPD and may not be able to render all colors equally well. Therefore, they may have a lower fidelity value than they would under CRI. A TM-30-15 85+ Rf lamp source is appropriate for all but a few interior environments.

The fidelity index has not been available long enough to establish baseline recommendations to apply to different space types. However, the recommendations likely will remain similar to CRI. At the time of this publication the majority of manufacturers are not yet consistently publishing fidelity data and are still using the CRI scale.

Gamut Index and Color Vector Graphic

The Gamut Index color metric denoted as TM-30-15 Rg, takes another major step beyond CRI to evaluates the extent to which a test lamp source increases or decreases mean color saturation in comparison to a reference source (reference). It determines if the lamp source creates a visual pop of color or if it desaturates finishes, shading these toward the muddy side. The Gamut Index is also based on a 100-plus-or-minus point scale, where 100 it represents no change in saturation in comparison to the referent source. More than 100 points indicates an average increase in saturation and is not desirable for general use except in certain applications. Fewer than 100 points indicates an average desaturation. A TM-30-15 Rg value of 100 is appropriate for most applications unless a particular light quality is desired. A high TM-30-15 Rf value typically will have a TM-30-15 Rg value of close to 100.

Caution: The Gamut Index offers an average color saturation/desaturation. It does not indicate which hue range may be more or less saturated. Examining the color vector graphic will provide detailed information about the color performance of the specified light source. Neither fidelity nor Gamut indexes indicate or take into account human preference.

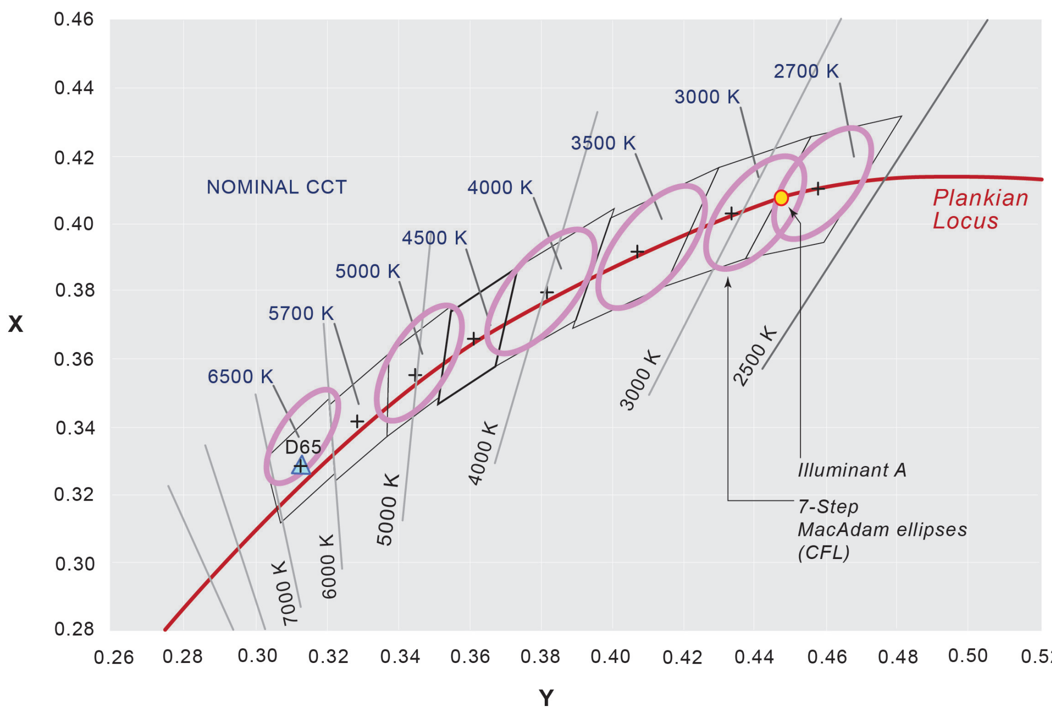

Figure 5-27 (EL4) MacAdam steps—standard deviation color matching.

Chapter 5

EL

DESIGN STRATEGIES

EL5 Visual Comfort

While pursuing the goal of reducing energy for lighting it is important to also focus on several design considerations necessary to creating a visually comfortable lighting scheme. These include providing appropriate horizontal and vertical illumination as well as uniformity ratios, and minimizing excessive luminance, flicker, contrast, and light patterns. Each of these is detailed below. The importance of visual comfort in the school environment is discussed in the visual comfort section of Chapter 2.

The selection of the SSL system should be coordinated to closely correspond with the interior designer's or architect's color palette for interior finishes. Interior finishes are further discussed in DL12.

EL6 Horizontal and Vertical Illuminance Targets

It is important to provide the appropriate illumination levels to both vertical and horizontal surfaces within recommended targets. While horizontal light levels are more commonly used, providing both an illuminated ceiling and walls will create the perception of a more voluminous and well-illuminated space. Vertical illumination is especially critical in learning environments, which rely heavily on vertical teaching surfaces. Specific illuminance targets are discussed in the space-specific strategies section (EL24-EL27)

EL7 Glare

Spaces should be designed to minimize glare. There are several forms of glare and several conditions in which glare may be created including glare from uncontrolled sunlight, unshielded or poorly designed luminaires, or from highly reflective surfaces.

***Caution*:** Additional concerns include the following:

- Avoid LED luminaires where diodes are visible. If luminaires are not properly shielded they will likely create unpleasant or distracting glare.
- There needs to be a balance between efficacy and visual comfort. Avoid luminaires that have a heavily frosted or milk white lensing as these fixtures will have a reduced efficacy. Avoid luminaires that create highly unpleasant visual environments.
- Avoid locating a luminaire adjacent to or aimed at a specular surface.

EL8 Flicker

Flicker can be perceived or imperceptible. Excessive flicker may cause eye strain, headaches, impaired vision, or seizures. It may also cause interference with cameras, which may be problematic in gymnasiums and exterior sports fields. Studies have shown that people are sensitive to both 60 Hz flicker and a certain percentage of the population is sensitive to frequencies of up to 200 Hz or more (ASSIST 2015).

Flicker occurs across all lamps; it had been a significant issue with legacy fluorescent magnetic ballasts and is also an issue with LED SSL sources.

Flicker occurs in luminaires from driver and/or dimming instability as well as voltage changes or external noise. IEEE Standard 1789-2015 provides a method for determining the maximum allowable percentage of flicker (IEEE 2015). While this standard is useful for specifications, a mockup of the luminaire and dimming control system is also valuable in most areas.

EL9 Contrast, Patterns, and Uniformity

Appropriate use of contract provides visual interest and “sparkle” in a space, which can increase visual comfort. However, high contrast may reduce visual comfort and decrease acuity for older adults. Patterns created by the luminaires’ distribution or lensing may become distracting or visually displeasing.

Caution: Additional concerns include the following:

- Avoid indirect luminaires located below fans or architectural elements, as they will create patterns on the ceiling.
- Avoid only using circular downlights in narrow spaces such as corridors. These create scallop patterns and cause dark ceilings with poor uniformity. Figure 5-28 illustrates this issue.

Similar to flicker, poor illuminance uniformity can create eye fatigue, headaches, or reduced visual acuity. The three basic uniformity ratios include maximum to average, average to minimum, and maximum to minimum. In most cases, when reviewing uniformity targets for visual comfort,

Figure 5-28 (EL9) Example of scalloping patterns and dark ceilings.
Photo reproduced with permission by Shanna Olson

average to minimum takes priority. When designing for a fixed, task-specific location, the uniformity is considered across the task plane, such as a vertical teaching surface. If the task is less specific and simplified, such as walking down a corridor, the uniformity is considered to be across the entire corridor. The suggested uniformity targets for visual comfort are 4:1 average to minimum or less (IES 2014c).

Additionally, poor luminance uniformity may decrease visual comfort, visual acuity or adaptation, and may cause headaches. When utilizing a direct/indirect or indirect-only pendent luminaire, look for a wide batwing indirect distribution. This may allow for a wider spacing of luminaires while retaining greater ceiling uniformity. This not only reduces the lighting power used, but also material and labor cost. (IES 2014c, Section 3.0, Luminaire Systems Classifications)

Finally, consider the mounting height of the luminaire. Most suspended luminaires require an 18 in. minimum separation from the ceiling to avoid striping patterns on the ceiling. However, recommendations will vary by luminaire manufacturer, indirect distribution qualities, and by the height of the space.

EL10 Visual Interest and Wayfinding

Lighting can add excitement and interest to any space. It can alter how occupants feel, can provide comfort, or add to a sense of school spirit. Much of this has to do with illuminating sur-

Figure 5-29 (EL10) **Example of asymmetric versus symmetric luminaire layouts.**
Photo courtesy Ballogg Photo.com, Nagle Hartray Architecture, IMEG Corp. Lighting Design & Engineering

faces, adding layers of light (including daylight and views), and incorporating lighting that enhances architectural elements. Lighting can also be used to highlight important elements such as school logos, trophies, or merchandise. While these elements are important to how a school environment feels, decorative or architectural lighting needs to be balanced with a reduction in energy use in other areas.

Through layout and luminaire shape, lighting can create a sense of urgency, movement, or quietness. An asymmetric linear layout in a corridor or lobby will illustrate a sense of movement while a symmetric layout may emphasize a quiet seating group as illustrated in Figure 5-29.

Lighting is also an excellent means of providing wayfinding. By utilizing a variety of luminaire types, mountings or color accents, lighting can indicate a change in level or corridor, important meeting areas, focal points, or key entrances. This can be done with minimal impact to the LPD. Figure 5-30 illustrates how small-in-grade blue-colored luminaires, shown near the corner of the wall, work like bread crumbs to move people through a complicated building.

Wayfinding lighting may also be paired with flooring patterns to further emphasize the change in location or to highlight gather points. Strategies to provide wayfinding are included in EL26.

CONTROL STRATEGIES

EL11 Controls

Technology advancements in control systems provide numerous functions, come in many varieties, and may be combined with other devices. Several simple control systems are widely in use today. Given the wide range of available control systems and the options for functionality, level of complexity, and their associated costs, discussion on controls direction should happen at an early stage of design. In many cases, control systems with higher material costs have lower installation costs because of simplified wiring. It is useful to have a contractor on board early to determine the overall installed controls cost.

Most dimming drivers will dim the luminaire down to 10%, while other drivers are available with 5%, 1%, or even lower. Often, 10% dimming is perfectly appropriate. However, in cases such as auditoria and classrooms with A/V requirements, additional dimming is often desired. (IES 2014c, Section 5).

There is also a difference between actual measurable dimmed light levels and perceived dimmed light levels. The human eye typically perceives very little difference in a luminaire that is changed by 20%. On the low end of dimming (10% or lower), luminaires are often perceived to be of greater output than they are. For example, as shown in Figure 5-31, a luminaire dimmed to 10% light output may be perceived as dimmed to only 30%. (IES 2013a). A simple mockup of the luminaire and controls with facility staff is useful to determine what level of dimming is preferred. This can be the same mockup as the one used to test dimming compatibility and flicker concerns. (See EL8)

Caution: Highly complex control systems require training to properly use and maintain.

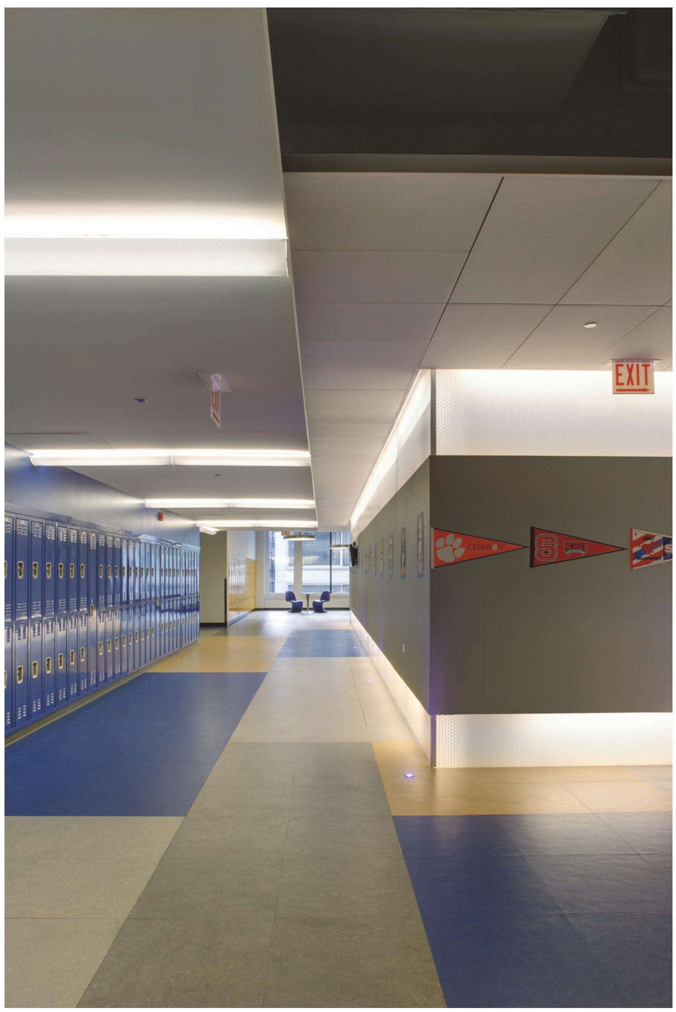

Figure 5-30 (EL10) Lighting as wayfinding.
Photo courtesy Tricia Shay Photography, Wheeler Kearns Architects, IBC Engineering Services Lighting Design and Engineering

EL12 Network versus Stand-Alone Controls

Stand-alone control systems are systems that provide lighting control for individual spaces. This type of system does not communicate with systems in other areas. Often these are analog wired systems that include basic controls such as occupancy sensors, switch stations, and daylight sensors. These may also include distributed wireless stand-alone controls.

Network control systems include controls that communicate with one another and where holistic changes may be pushed out from a central processor. These systems may also provide energy use and notification of maintenance of individual luminaires. Networked control systems may have a higher cost and require greater user training, but can also provide greater long-term energy savings

EL13 Wired versus Wireless Controls

Wireless lighting controls are offered in a wide variety of protocols and styles. In many circumstances these include electronic components that are either added to an individual luminaire or a zone of lighting. If the former is provided this creates an addressable system similar to a digital addressable lighting interface (DALI) based system that can substantially increase the flexibility and control of the system. See EL15 for more information on DALI systems.

If a wireless device is installed in a luminaire there may be an additional luminaire cost. However, the overall installation cost may be lower than a wired system because of reduced quantity of wiring and the associated labor to install it. A variety of user interfaces are avail-

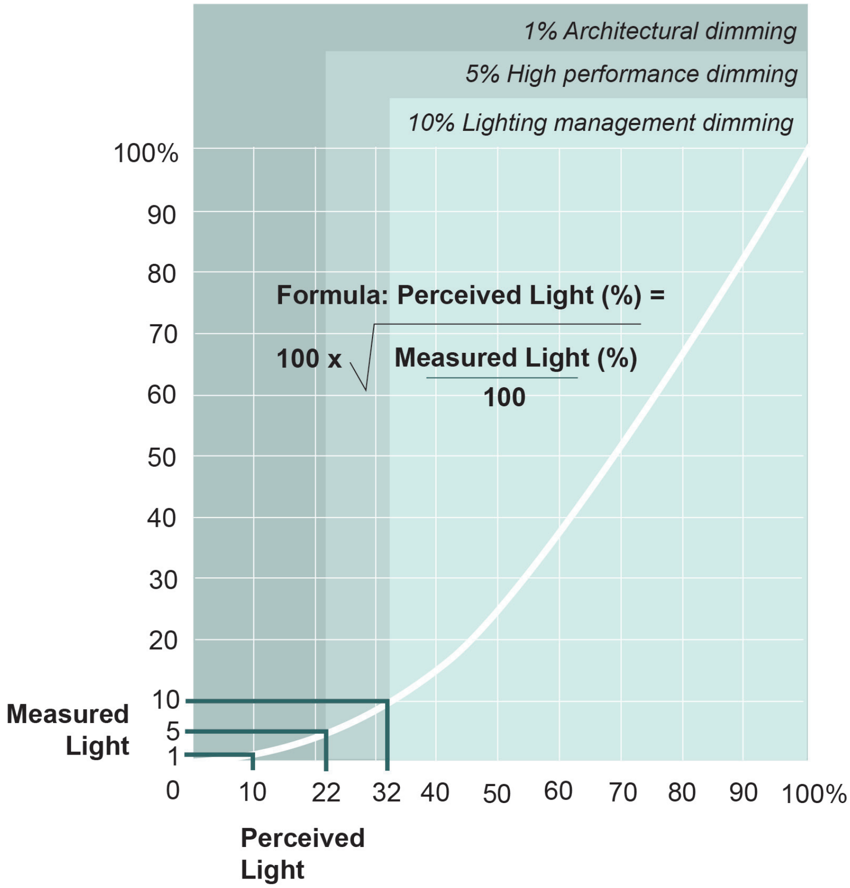

Figure 5-31 (EL11) Measured versus perceived light.
Source: *IES Lighting Handbook*, 9th edition (IES 2000)

able. These include battery-powered switch stations that reduce wiring costs and interfaces that are tablet or smart phone based. See EL16 for more information on occupancy sensors.

EL14 0-10 V Dimming Control Protocol

Numerous dimming protocols are available with 0–10 V dimming being widely used. 0–10 V dimming is a four-wire control protocol. The four wires are a pair of line voltage power wires and a pair of low voltage control wires, that latter of which modulates between 0–10 V dc to vary the light output. This protocol is available as a stand-alone system or can be connected to a distributed or centralized format for networked control. 0–10 V dimming is available to control older fluorescent systems as well as some metal halide products. Additionally, while 0–10 V dimming it is most commonly used to control static white sources it can also be used to control either dynamic white or color-changing LED luminaires.

Although widely available and quite simple, a significant downside to 0–10 V dimming is the high installation cost because of wiring requirements. 0–10 V dimming is a zone-specific control protocol that means a home run is required for each zone. See Figure 5-32 for a wiring scheme example. It also means it cannot be reconfigured without rewiring.

A 0–10 V relay system may also be considered central or distributed. In a central system, all the home runs are running back to a single point. In a distributed system, the home runs are running back to a smaller processor or hub located close to the area being controlled, and these are then linked back to the main processor. The distributed hubs are typically capable of handling one to eight zones. The determination to use one type or another typically is predicated on the building layout and location of electrical room(s) (IES 2011c).

EL15 Digital Addressable Lighting Interface (DALI) Control Protocol

DALI is an open standard; however, there are proprietary versions currently on the market. DALI provides two-way digital communication and scene-based control by giving each luminaire its own IP address. It may be a whole-building solution or used only in more complex spaces where multiple scenes are required and are then tied into a whole building control system that is capable of handling several protocols. For example, it may be used in multipurpose or conference room spaces with electronic partitions. It also allows for luminaires to be rezoned and reconfigured as needed in the future without rewiring. This is especially useful in spaces that are reconfigured, such as open labs, and administrative offices where workstations may be reconfigured. The format of the system also allows for status feedback to be monitored to alert facility staff when drivers have failed and inform the public on current energy use. (IES 2011c)

While DALI systems typically handle static white lighting only, multi-channel DALI drivers are available to control either dynamic white or color-changing luminaires. This digital system allows the control wiring to be configured in a variety of ways so that it is essentially topology free. While material cost of DALI-based systems is often higher than other systems, the labor/installation cost may be lower because home runs are not required and the control wiring can be configured in several ways. See Figure 5-32 for a DALI wiring scheme example.

EL16 Occupancy Sensors

Occupancy sensors use motion to determine occupancy in spaces. These sensors can provide significant savings if used properly. They need to be located far enough away from doors and HVAC diffusers to prevent false activations and may also need to be partially masked with field adjustments to properly function.

There are three technology variations: passive infrared (PIR), ultrasonic, or a combination thereof:

- *PIR* detects the difference between the heat from people and the heat of the background. It requires line of sight and is best used in spaces where the occupants perform basic tasks with large hand motions or in high-ceiling applications where ultrasonic does not function.

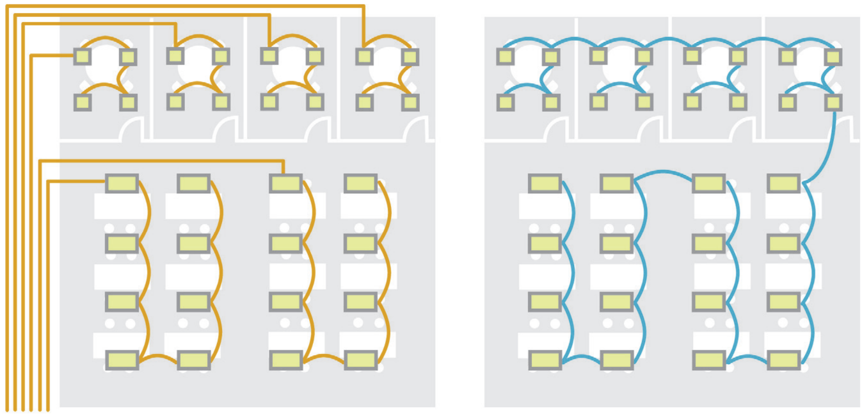

Figure 5-32 (EL15) (Left) 0-10 V and (right) DALI wiring schemes.

- *Ultrasonic* sends out sound waves and reads their bounceback. These do not require line of sight, making them excellent for spaces with partitions and spaces where it is not advised to give manual control to occupants, such as multistall toilet rooms. Ultrasonic also detects fine movement. It does not typically function over 12 to 14 ft high.
- *Dual* technology combines both technologies to reduce failures. This type of sensor works particularly well in classroom or office environments.

Occupancy sensors are also available in three operation options: automatic on (known as *occupancy type*), manual on (known as *vacancy type*), and 50% automatic on:

- *Automatic on (occupancy)* sensors save the least energy of all occupancy sensor types and can be relevant for spaces such as public toilet rooms.
- *Manual on (vacancy)* sensors save considerably more energy than automatic on, as they engage the occupants to manually turn off the lights, encouraging them to turn off the lights. If they forget, the lights will be automatically cycled off. These work well in areas with daylighting, as users can determine if they "need" the lighting.
- *50% automatic on* sensors may be the best of both worlds. A study from the California Lighting Technology Center (Papamichael et al. 2010) shows that these sensors save the most energy of the three, the premise being that if occupants manually turn the lights on, they will more likely turn them on to 100%. However, if the luminaires turn on to a generally acceptable light level the occupants will not feel the need to manually increase the light level. Figure 5-33 is a graphic representation of the results of the Bi-Level Switching in Office Spaces study (Papamichael et al. 2010). It illustrates the energy saving of the three sensor options listed above.
  - Another version of the 50% automatic on is a partial-off occupancy sensor. This is essentially the opposite and works to reduce the light levels to 50% or lower when the space is unoccupied. It is appropriate for spaces such as stairwells or corridors (IES 2013a).

EL17 Daylight Harvesting Sensors

Like occupancy sensors, daylight sensors are required by many energy codes. Dimming daylight sensors save considerably more energy than the switched variety and are also preferred by occupants. Most people notice when a luminaire suddenly shuts off, but don't notice if it dims down gradually. In classrooms for example, ON/OFF daylight sensors are distracting to students. The cost of dimming has dropped significantly with LED luminaires. As LED efficacy continues to increase, resulting in lower LPDs, the energy savings from daylight sensors decreases. For this reason, daylighting design tends to be focused more on effective side day-

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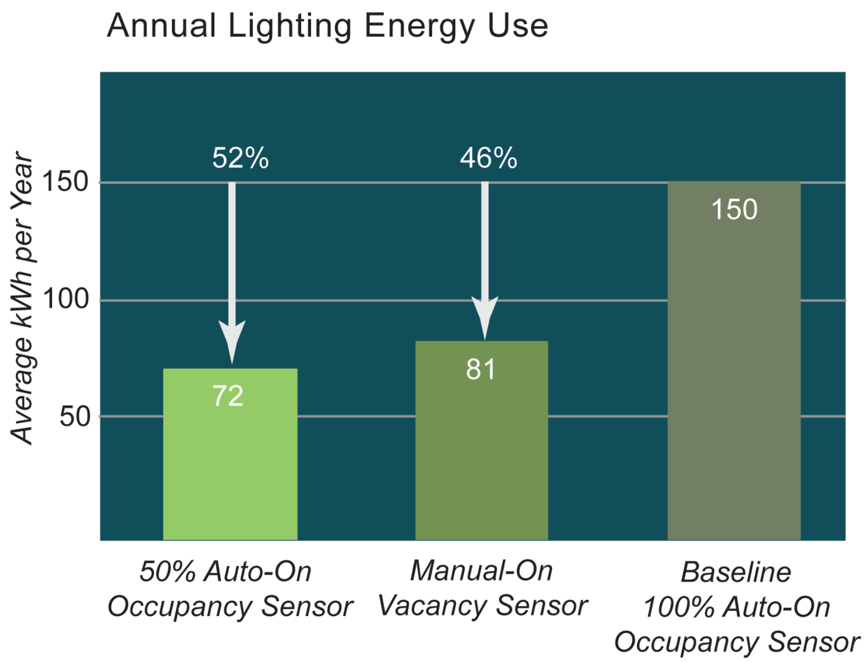

Figure 5-33 (EL16) Sensor study findings.
Figure adapted from LCA (Dilouie 2009)

lighting to daylight a portion of the space and use electric luminaires to balance the lighting in the entire space. (See also DL2 and DL14-DL18). This preserves the daylighting, views, and provides higher user satisfaction from the overall lighting system while meeting the lighting goals (Aumann et al. 2004). For example, lighting and exterior shade systems may be configured to provide both daylight harvesting and visually comfortable interior spaces (IES 2013b). See DL8 and DL9 for information on shading strategies.

EL18 Photosensor Placement and Lighting Circuits

When designing, consider how a lighting layout and control wiring plan will complement the daylighting strategy. It is essential to design the photosensor location considering its characteristics. For example, in sidelighted classrooms, locate luminaires in rows parallel to the window wall, allowing the row nearer to the window to be a zone controlled by the daylight sensor. In a space that has a roof monitor or skylight, install one photosensor that controls all the perimeter lights and a second that controls all the lights around the top lighting (IES 2013b).

EL19 Switches, Scene Control Stations, and Touch Screens

Control switch options range from a simple toggle switch to a personal tablet; however, for most spaces in a K–12 school the control interfaces somewhere in the middle. The key is to ensure the control station is user-friendly, meets the staff expectations, and is appropriate for their level of comfort with technology

Dimming push-button control systems provide most spaces with both flexibility and simplicity. Engraving the push buttons is critical to long-term functionality. The engraving can be as simple as “ON” or “AV” (for audio-visual). Most button stations can be used to control either zones or scenes. Zoning would include a group of luminaires. For example, in a classroom, a button or control station may control only the vertical teaching surface luminaires. The switched controls must be easily understood by anyone using the space for success. A mockup of the controls is critical to gaining user acceptance.

Scene-based control systems may include multiple zones of luminaires or, if protocol allows, groups of individual luminaires to create a predetermined scene. A classroom AV scene may include substantial dimming or turning off the luminaires closer to the screen while the balance of the luminaires are dimmed to a lesser extent. Again, proper and easy to use labeling is critical.

LCD touch screens are another control station that has grown in popularity. Typically these are employed as a central user interface in spaces with more complex scenes such as an auditorium, or where color-changing luminaires are controlled. These tend to be more expensive, but are typically self-explanatory with easy-to-understand graphics. This concept is being carried over to tablets and smart phones, which allows for both mobile and individual control points. It allows teachers to modify light level settings from anywhere in the classroom. It is also highly useful when tuning light levels or controlling color-changing luminaires. It allows the user to make broad-stroke changes while in view of the luminaires.

EL20 *Emergency Lighting and Controls*

LED is instant on and low wattage and is therefore an excellent source for emergency illumination. There are several means for LED luminaires to be powered and used as emergency sources.

Some jurisdictions require two or more lamps, ballasts, or drivers to limit the loss of emergency illumination caused by the failure of a single component. Backup power sources for emergency LED luminaires include integrated battery packs, microinverters, larger inverters, and generators. Integrated battery packs work well in circumstances where a generator is not an available. Microinverters also work well for LED luminaires.

Some codes may require the emergency luminaires to remain continuously illuminated, while others either allow or require that they be controlled.

Intelligent control systems allow emergency luminaires to be controlled with the normal luminaires and return to 100% when loss of normal power is sensed. Some control systems can also provide more sophisticated security settings allowing for what's known as a “follow me” setting. This setting allows the lighting to turn on as staff moves through the school. It also allows security to see where people are located while still reducing everyday energy use. One of the best ways to reduce lighting energy is to reduce to near zero the energy required to operate the building when the building is unoccupied.

EL21 *Convergence and IoT (the Internet of Things)*

Convergence is the concept of bridging a building's lighting, shade, AV, and mechanical systems together into one cohesive control system. This currently is completed through various connections such as an RS232 control point or via BACnet®. Once configured, it allows the end user to control all subsystems through a single point or perhaps a single scene. For example, in classrooms, the AV scene may lower the shades, dim the lights, and turn on AV equipment.

The concept of convergence is evolving with the move to the Internet of Things (IoT). Generically, IoT is associated with lighting and lighting controls that are connected via the Internet, such as wireless lighting controls. However, it is also used when describing visible lighting communication (VLC), Beacon technology, and Li-Fi (Light Fidelity), which transmit binary data through light.

> ***Caution:*** The use of Internet-enabled control systems does open up the potential for hackers to disrupt school operations by seizing control of lighting or HVAC controls and turning off these systems. Work with the IT team to ensure security of systems.

EL22 *Calibration and Commissioning*

When working with an intelligent, complex control system the key is to ensure that the end user interface is both simple and meets needs and expectations. To meet this ambitious goal, communication needs be prioritized from the start of the project with a discussion between

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design team and end users. The sequence of operations in the contract documents should detail how the system functions, providing valuable information to the contractor and programmer. Before installation, details such as engraving for user interfaces should be reviewed with the end user.

All lighting controls must be calibrated and commissioned after the finishes are completed and the furnishings are in place. Most daylight sensors require daytime and nighttime calibration sessions. The daylight sensor manufacturer and commissioning authority (CxA) should be involved in the calibration. The design team should work with staff and facilities personnel to tune their lighting systems dialing down controls to meet the illuminance needs of the space using the least amount of energy. Even a few days of occupancy with poorly calibrated controls can lead to the staff permanently overriding the system and a loss of savings.

Document the calibration and operating settings of each room's lighting control system and work with the school's teachers and staff individually to train and help them understand how to operate their controls. Consider videotaping the training for a later refresher or in case of staff turnover. Schedule periodic recalibrations as part of the annual school maintenance program (IES 2011d).

SPACE SPECIFIC STRATEGIES

Table 5-11 shows recommended lighting power densities as determined by the energy simulation model to achieve zero energy. The information that follows provides sample layouts for reaching these lighting levels.

EL23 Classrooms

Minimum illuminance targets in classrooms with hard copying and writing are 300 lux horizontal at 2 ft 6 in. AFF and 100 lux vertical at 4 ft AFF (IES 2014c). However, many

Table 5-11 Lighting Power Densities

Space Type	LPD (W/ft^2)
Whole building—primary school	0.40
Whole building—secondary school	0.45
Gymnasium/multipurpose room—primary school	0.50
Gymnasium/multipurpose room—secondary school	0.80
Cafeteria	0.40
Classroom	0.40
Mechanical	0.40
Restroom	0.40
Auditorium	0.50
Office	0.50
Art room	0.60
Kitchen	0.60
Corridor	0.25
Library/media center—primary school	0.40
Library/media center—secondary school	0.50
Lobby	0.70

schools have mainstreamed special needs children into general classrooms and also provide space for adult education community activities in the evenings. To accommodate these changes, consider adjusting illuminance targets to 400 lux horizontal and 150 lux vertical. Moving to a higher illuminance target may impact the lighting power densities.

In classrooms with ceilings above 9 ft 6in. and/or daylighting, consider designing a series of pendants parallel to the window wall, preferably with semi-indirect or direct/indirect distributions. Specifying a wide batwing distribution and laying out the luminaires appropriately will mitigate hot spots on the ceiling and provide greater uniformity. In classrooms with ceilings below 9 ft 6 in., 2 × 4 volumetric luminaires may be appropriate.

Vertical teaching surfaces need sufficient vertical illumination (up to 150 lux) with an average to minimum (Avg:Min) ratio of not more than 3:1. Depending upon classroom configuration, a reaching surface luminaire may be necessary. A linear asymmetric pendant or recessed mounted luminaire above and in front of the teaching surface may provide the additional vertical illuminance required. Be cautious in the placement of the luminaire to minimize reflected glare. See the selected luminaire manufacturer's recommendations for appropriate placement.

Dual technology 50% automatic on occupancy sensors and dimming daylight harvesting are recommended for classrooms. Depending on the configuration more than one daylight zone and sensor may be required to function appropriately. Typical control scenes in classrooms include a general lighting scene as well as an AV mode. If stand-alone teaching surface lighting is used, this will typically be separately controlled. Zoning is required for many control systems; up to three to four zones may be needed to provide both daylight harvesting and the appropriate control scenes depending on the room and luminaire layout.

Straightforward and easily identifiable push button controls are preferred by most instructional staff and school maintenance personnel over complicated lighting control schemes.

For classrooms, provide a minimum of two control stations with at least two scenes. Consider providing a control station at the door as well as one immediately adjacent to the AV position in the classrooms. Each station should allow for control of the teaching surface lighting (if provided) as well as either simple dimming of the general lighting or a general lighting and AV scene, each with dimming. Additionally, integration with AV controls as well as motorized shade control, if they have been included in the design, may provide more seamless control. However, this will require additional user training and may require more costly upkeep.

An example of a common ceiling classroom layout is shown in Figure 5-34. In this example:

- LED direct/indirect luminaires are parallel to the window and are suspended approximately 8 ft AFF with a daylight harvesting sensor for each row.
- A single, dual tech 50%-on open protocol occupancy sensor is incorporated into the daylighting and classroom control system.
- Daylight programming should include energized light fixtures at minimum power when daylighting meets the room's lighting needs, and scale up in proportion to the daylighting component.
- Luminaires are static, white, semi-indirect linear luminaires with a wide batwing indirect distribution providing approximately 880 lumens at 6.8 W/ft with an efficacy of 129 lumens per watt.
- Average illumination at the work plane is approximately 320 lux with an Avg:Min ratio of 2.46:1
- Vertical illumination on the teaching surface is approximately 200 lux.
- LPD is 0.40 W/ft^2.

EL24 Gymnasiums/Multipurpose Rooms

Minimum illuminance targets of 250 lux horizontal at 2 ft 6 in. AFF and 100 lux vertical at 5 ft AFF are recommended in gymnasiums for the purpose of physical education (IES 2014c). K–12 gymnasiums may be used for a variety of different events, such as school assemblies,

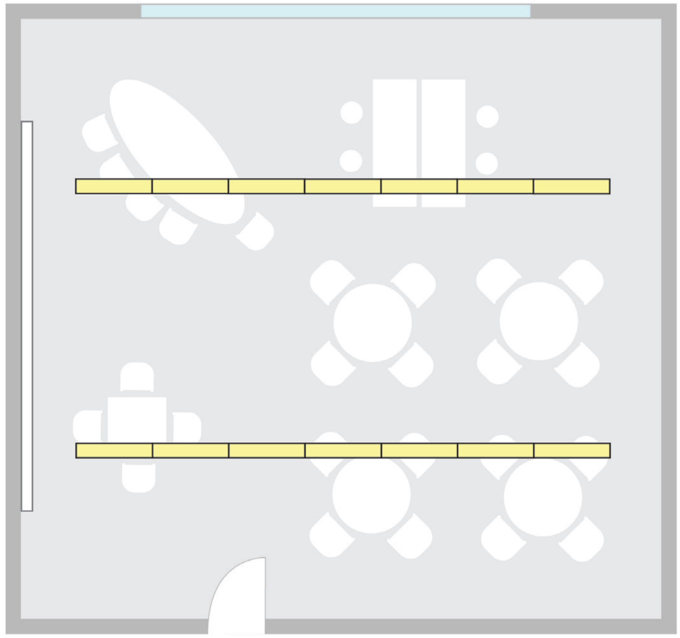


Figure 5-34 (EL23) Typical classroom ceiling layout.

dances, plays, community events, and competitive sports. Illuminance targets should be adjusted to reflect the many planned and potential uses of the space and ensure flexibility.

General recommendations for gymnasiums with areas of competitive sports may include a minimum 300 lux horizontal at 3 ft AFF and 100 lux vertical with a 4:1 maximum to minimum (Max:Min) for elementary schools, and 500 lux horizontal and 100 lux vertical with a 3:1 Max:Min for high schools (IES 2015c).

Gyms are primarily illuminated with LED low-bay or high-bay industrials. Many industrials are available with lenses that cut down on glare and/or protect the luminaire from sporting equipment.

PIR 50% automatic-on occupancy sensors and dimming daylight harvesting are recommended. In many cases, the occupancy sensor may be embedded into the luminaire. LED dimming capabilities in the specified luminaire will provide flexibility of use and variable lighting levels for the various activities in the gymnasium. Theatrical lighting may be desirable depending on the functions intended for the space. Control stations should be accessible to staff only. Zoning and scene control will depend on the court layout and potential spectator seating. Provide a partition sensor if there is a partition splitting the gymnasium. The lighting controls should allow the spaces to function independently when the partition is closed and together when it is open.

An example of a potential elementary school gymnasium layout is shown in Figure 5-35. In this example:

- Ceiling is canted between 24 and 28 ft AFF with glazing on two ends
- Luminaires are mounted at 22 ft AFF
- Selected luminaires are static direct high-bay luminaires that provide 28,000 lumens at 245 watts
- Luminaire spacing is 25 ft × 25 ft
- The space has an average of 300 lux at 3 ft AFF, with a Max:Min of 2.3:1 and LPD of 0.42 W/ft^2, which is slightly under the recommended level of 0.50 W/ft^2
- PIR 50% occupancy sensors and dimming daylight sensors are incorporated into the lighting control systems

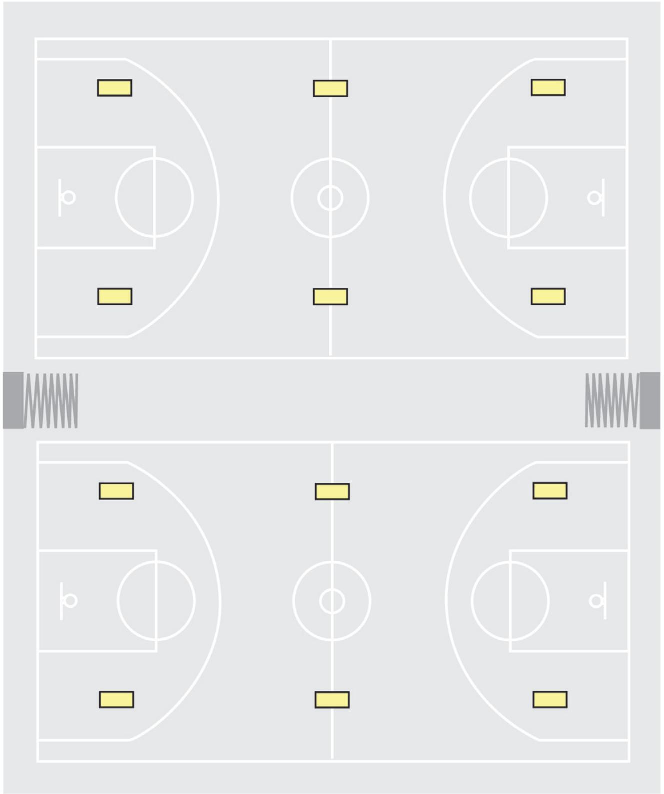


Figure 5-35 (EL24) Typical elementary school gymnasium/multipurpose room layout.

The same luminaire could be applied to both elementary and high schools by providing different lumen packages. For a high school, this may be increased to approximately 45,000 lumens at 394 watts. Using the same layout as the elementary school provides an average of 485 Lux with a Max:Min of 2.4:1 and a LPD of 0.67 W/ft^2.

EL25 Library

Illuminance targets for a library are between 50 and 250 lux horizontal AFF at 2 ft 6 in. depending on the area within the library and the task being performed (IES 2011b). Minimum illuminance targets for book and magazine stacks, which may be of low heights in elementary schools (around 42 in. AFF), are 150 lux horizontal and 100 lux vertical at 2 ft 6 in. AFF. Areas with computers should be provided with 150 lux horizontal and reading carrels with 250 lux horizontal. If the computer stations or reading carrels are made available for the community target illuminances should reflect this (IES 2013c).

Depending on the layout and stack heights, the lighting may be provided in several different ways:

- For low-height stacks and above computer workstations use semi-indirect pendants, direct indirect linear pendants, continuous row luminaires, or recessed volumetric lighting.
- In study carrel areas, a lower level of general lighting may be used if LED task lighting is provided at the carrel. Consider mounting the task lighting at the side instead of the front of the carrel to mitigate potential shadowing or reflections.
- The lending library desk is an appropriate location to add decorative lighting in addition to general lighting. Architectural features of the library may be highlighted with accent lighting. This is also a subtle way to add wayfinding to the space (see also Figure 5-30).

- Task lighting may be required to provide the recommended light levels for staff. Ensure that occupancy sensor controls are incorporated into all task lighting.

Dimming daylight harvesting should be provided where appropriate. Automatic control via time clock or occupancy sensors is required. Control stations should be accessible to staff only. Consider zoning such that each basic task can be tuned appropriately and independently.

An example of a potential elementary school library layout is shown in Figure 5-36. In this example:

- Above the stacks and slants, the ceiling height ranges from 8 ft AFF to 14.5 ft AFF.
- Above the low stacks a recessed volumetric 2 × 2 provides approximately 2100 lumens at 18 watts per 4 ft luminaire with an efficacy of 115 lumens/W.
- Above the reading areas the higher ceiling calls for a direct indirect linear pendent, which provides approximately 2100 lumens at 15 W per 4 ft luminaire with an efficacy of 141 lumens/W.
- Over the lending desk, decorative lighting provides visual cues and adds a bit of fun.
- The low vertical stacks provide 120 vertical lux average
- The space has an average of 250 lux with an Avg:Min of 2.25:1 and an LPD of 0.33 W/ft^2.
- Dual tech 50% occupancy sensors and dimming daylight sensors are incorporated into the lighting control system.

EL26 Corridors

Recommendations for light levels in corridors vary depending on location and usage (IES 2011b):

- Corridors adjacent to building entries should be provided with a slightly higher light level to allow the eye to transition to interior light levels.
- Corridors that have lockers or are used for study groups will also require higher light levels than a simple passageway.
- Where lockers are present, vertical illumination is the priority.

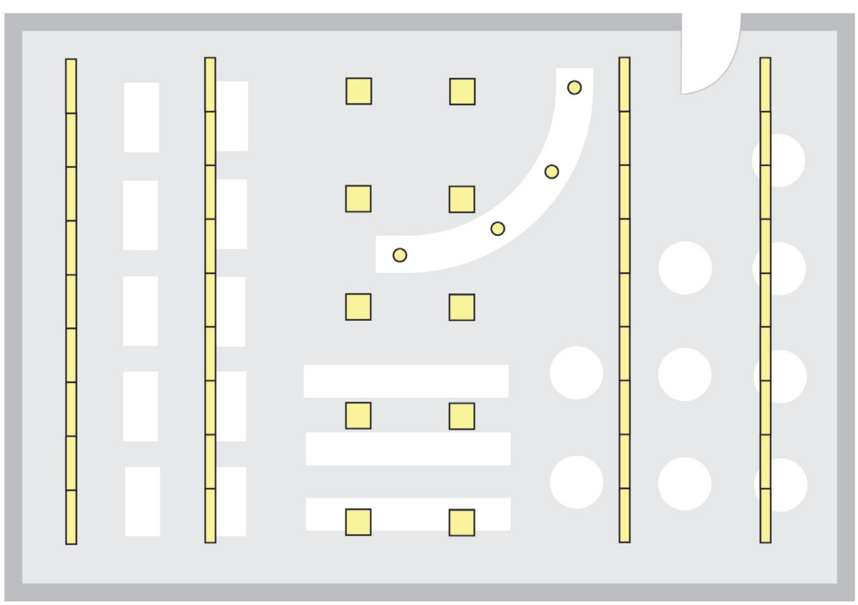


Figure 5-36 (EL25) Typical elementary school library layout.

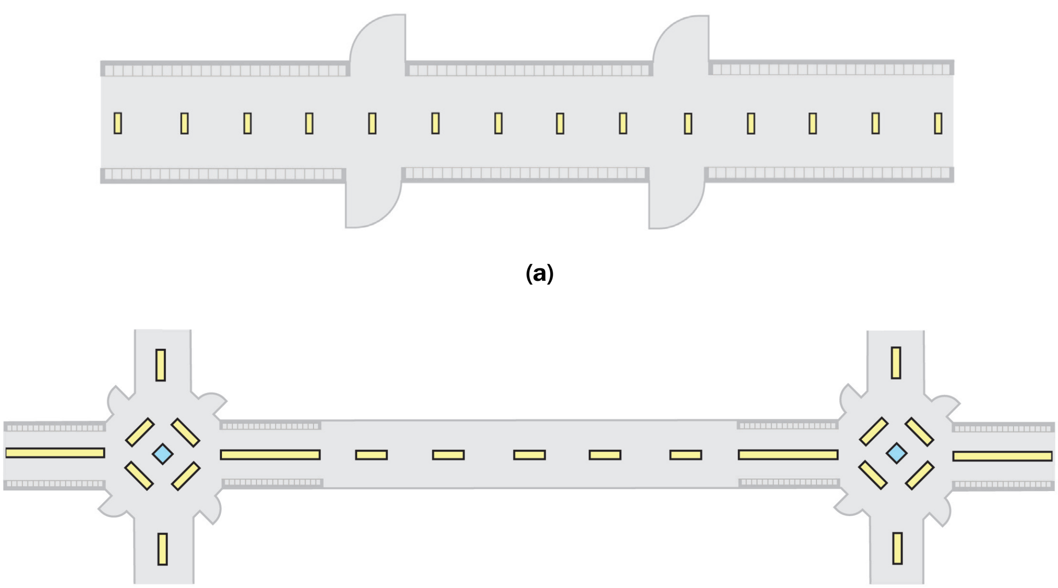
In corridors, especially in larger schools, lighting for wayfinding is not only practical but can be used to create visual interest, show school spirit, and create a visual rhythm throughout the school. This can be accomplished by using different luminaire types, mounting installations, or splashes of color. Decorative lighting, including color-changing lighting, may be used at critical gathering points or main entrances such as gyms and auditoriums. Note that the additional energy used for wayfinding or visual interest must be balanced by reducing energy elsewhere.

There are two basic methodologies for controlling lighting in corridors. A time clock and bell system may be tied together such that the lighting lowers during classes and raises in between, or occupancy sensors may be employed to lower the light levels from 50% to 90% when the corridor is unoccupied. While the former provides a visual indication of time, the latter will likely save more energy. Occupancy sensors may also be used after hours for security patrol or to alert security if anyone is in the building. If daylight is available, dimming daylight harvesting should be incorporated. All controls need to be accessible to staff only.

Two examples of potential layouts are shown in Figure 5-37. In the first example (Figure 5-37a), a straightforward run length of corridor with lockers on each side. In this example:

- Ceiling height is 8.5 ft AFF and the luminaires are recessed into the ceiling
- 1 × 4 recessed volumetric provides approximately 2300 lumens at 32 watts with an efficacy of 126 lumens per watt
- An approximately 14 ft on center spacing provides an average of 90 lux at the floor and a Avg:Min of 1.44:1
- Vertical illumination along the locker at 4 ft AFF is approximately 50lux
- This layout provides LPD of 0.138 W/ft^2
- Partial-off occupancy sensors are incorporated into the lighting controls system.

The second example (Figure 5-37b) illustrates a breakout study corridor, breaking up a long corridor and adding a bit of wayfinding to an otherwise pedestrian space. A small amount of additional power is spent, but task lighting as well as interest and wayfinding are achieved.



(a)

(b)

Figure 5-37 (EL26) (a) Corridor layout 1 and (b) corridor layout 2.

The uniformity differs to provide higher illumination at the lockers and potential huddle areas and lower illumination at the pure egress paths. In this example:

- Vertical illumination along the locker at 4 ft AFF is approximately 120 lux
- Low output continuous recessed slot luminaires are configured to illustrate points of travel, highlight lockers, and show where gathering areas are intended
- Architectural or color 2 × 2 tiles in the intersections illustrate wayfinding
- The layout provides an average of 130 lux at the floor, a Avg:Min of 2:1, and a LPD of 0.2 W/ft^2
- Partial-off occupancy sensors are incorporated into the lighting controls system

EL27 Administrative Offices

Illuminance targets for office workstations are a minimum 300 lux horizontal AFF at 2 ft 6 in. and 75 lux vertical at 4 ft AFF for schools (IES 2012). Depending on ceiling height and workstation configuration, several different design strategies may be used. In offices with lower ceilings, a recessed 2 × 4 volumetric is the most cost effective and efficient means of providing lighting. For ceilings above 9 ft 6 in., parallel pendants with semi-indirect or direct indirect distributions are preferred. A wider batwing distribution and appropriate luminaire layout will mitigate hot spots on the ceiling, allowing for greater uniformity. This will also mitigate glare off the ceiling. Additionally, a general lower ambient light level may be provided if it is coupled with sufficient task lighting provided at the workstation(s).

Dimming daylight harvesting and dual tech 50% automatic-on occupancy sensors are recommended in enclosed offices. In a large open office, giving individuals control of the luminaire above their work station may be favored. Depending on the control protocol this may be achieved with a remote or via their computer, tablet, or phone. In both enclosed and open offices controlling plug loads is typically tied into the lighting control system. Details are provided in PL3.

Two examples of offices lighting layouts are shown in Figure 5-38. In the first example (Figure 5-38a):

- Recessed volumetric 2 × 4 provides approximately 4000 lumens at 32 watts with an efficacy of 123 lumens per watt.
- An average of 300 lux at the 2.5 ft AFF, an Avg:Min of 1.8, and a LPD of 0.43 W/ft^2
- Dual tech 50% occupancy sensors and dimming daylight sensors are incorporated into the lighting control system

The LPD and light level could be further reduced by going to 3000 lumen package. This would result in an approximately 230 lux average, with an LPD of 0.33 W/ft^2. However, a LED task light would be required at the workstation. These types of energy reducing strategies should be discussed with the facilities to confirm their comfort with general reduced light levels.

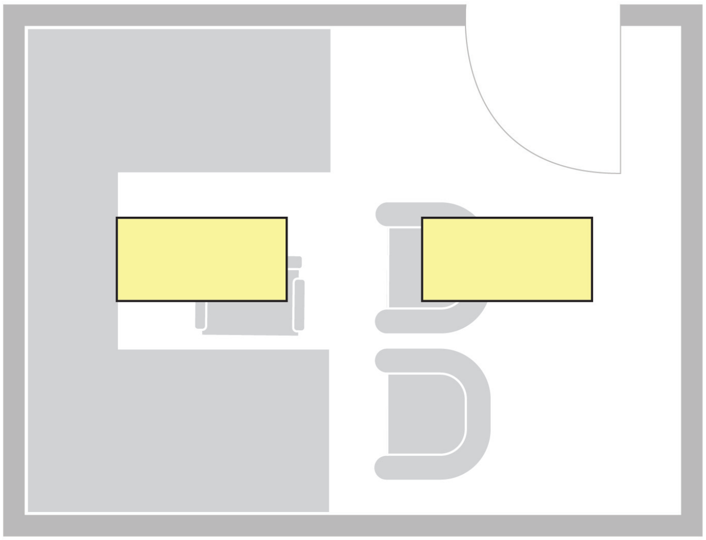
In the second example (Figure 5-38b):

- Ceiling height is slanted from 9ft to 11.5 ft AFF
- Selected luminaire is a static white direct indirect linear pendent luminaire providing approximately 775 lumens at under 6 watts per foot with an efficacy of 136 lumens per watt.
- There is an average of 260 lux at the 2.5 ft AFF, an Avg:Min of 1.6:1, and a LPD of 0.45 W/ft^2
- LED task lighting would need to be provided to meet appropriate lighting levels at the task plane
- Dual tech 50% occupancy sensors and dimming daylight sensors are incorporated into the lighting control system

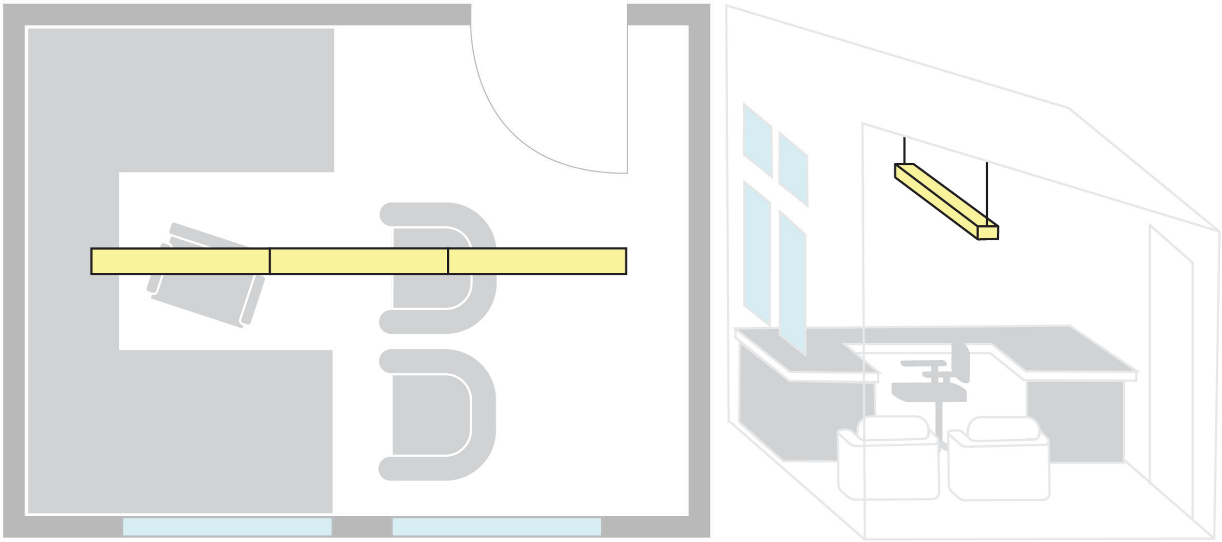
EXTERIOR LIGHTING

EL28 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. Figure 5-39 shows an example of a luminaire's BUG rating. 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. These zones are determined by density and type of the surrounding areas. They are typically based on a 0–4 or 1–4 basis. A rating of 1 is for rural areas and a rating of 4 is for densely populated areas such as New York City's Times Square.



(a)



(b)

Figure 5-38 (EL27) (a) Administrative offices layout 1 and (b) administrative offices layout 2.

BUG ratings can also be used by designers with or without an ordinance to provide an appropriate exterior lighting solution. 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.

Where reasonable, move exterior pole mounts away from perimeter. This will reduce spill light and provide greater flexibility in luminaire choice and spacing.

EL29 *Exterior Lighting Controls*

Like interior lighting controls, exterior lighting control systems include both wired and wireless options, dimming, and the potential for integrated or stand-alone occupancy sensors. These can dramatically reduce energy use as well as mitigate security concerns. See EL11–EL19.

EL30 *Building Facade*

Building facade lighting may be designed with several different functions in mind, such as providing general security, illuminating pathways around the building, identifying the building, and providing aesthetic accents. Depending on the programmatic goals of the facade lighting the selections will differ significantly. Begin by determining these goals as well as what lighting zone the project falls in. This will help determine the appropriate BUG ratings for the luminaire types. Consider providing facade lighting for building identification and wayfinding. This can be done with minimal impact to LPD by using low-watt luminaires to highlight specific architectural elements. Be cognizant of sky glow and limit uplighting as much as possible. Also consider providing a slightly higher light level at heavily used entrances. This will provide a focal point and will improve the transition into the interior higher light levels.

Many energy codes require building facade and landscape lighting to be turned off at building close or in late evening and turned on again between when the building opens and dawn. This can be handled by an astronomic time clock with photocell. However, luminaires designated for safety or security may remain on. In these instances, a partial-off occupancy sensor may be used to provide both energy reduction and improved security. From a security standpoint, the luminaire should be on at 100% if activity is detected adjacent to it (IES 2014d).

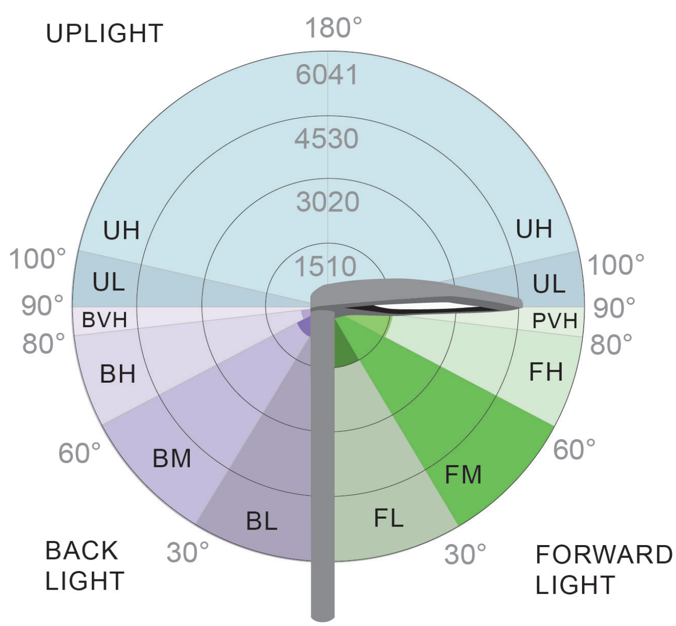


Figure 5-39 (EL28) BUG rating chart example.

Exterior Sports Field Lighting

High school and community use sports fields are commonly used up to 600 hours per year. While metal halide light sources have been used for many years for illuminating sports fields, the advantages and reduced costs of LED lighting fixtures are transforming the industry as older, hazardous and inefficient sources become legislated out of usage or as the marketplace self-selects more efficient, less costly sources. The projected savings for LED lighting over a ten year period are $133,000 for a typical sports complex of two softball fields and four soccer fields (depending on the area of the country and the utility rates). Over a 25 year expected life period of sports field lighting, the projected savings can reach $288,000 when using a total cost (peak demand charges and time of use charges for a typical municipality) of $0.20 per kWh.

Example of sports field lighting.
Photo reprinted with permission of Musco Sports Lighting, LLC

Competitive, public, and professional sports facilities are embracing LED lighting for a variety of reasons, including:

- *Reduced glare.* Up to 75% reduction, depending on the photometric design of the fixture's optic and the surrounding terrain. Photometric control with LED is flexible and individually configurable. Reducing glare on roadways is important where fields are adjacent to roadways and highway access ramps.
- *Better control of vertical illuminances.* High vertical illuminances result in high glare, which can contribute to fielding errors. At 18° above maximum candela, an LED lighting system with advanced optics and glare control provides zero candelas versus a metal halide luminaire that produces more than 133,000 candelas at the same beam angle, resulting in glare and poor playability.
- *Higher spill and light trespass control.* Adjacent property owners may require no light trespass onto their property. LED fixtures allow for precise beam angle control, limiting light trespass to zero lux at the property line.
- *Higher maintained illuminance levels and precise lighting level controls.* Light depreciation is much lower with LED than with metal halide. This allows the field to maintain good reliable lighting over time.

- *Reduced maintenance costs.* Metal halide fixtures burn out frequently, whereas LED sports fixtures are available with up to a 25 year life at 600 hours per year.
- *Instant-on lighting.* This results in no warm-up time. Metal halide typically requires 15 to 20 minutes to come to full brightness as opposed to LED sources, which are instantly lighted. Safety lighting is often incorporated into the sports field poles, with no time delay in restart after a power loss as with metal halide fixtures.
- *Remote monitoring.* These monitor outages, maintenance, and operation, which allows for turning on and off by remote link.
- *Higher lumens per watt.* This provides significant energy savings over time.
- *Increased sustainability.* Metal halide requires hazardous waste disposal because of the toxic metals contained in the arc tube.

LED lighting systems also provide for greater flexibility in the configuration and use of sports fields. With easy and inexpensive dimming, different events can use different lighting levels. These systems also allow for the use of lower mounted LED fixtures to provide “walk around” lighting after an event has ended or before the field lights need to be energized, such as during setup times. These lower mounted lights may also be used for safety and security lighting.

Caution: Be cognizant of potential flicker that can occur between incompatible luminaire and control systems.

EL31 Parking Lot

Illuminance targets for parking lots are between 5–10 lux horizontal at grade depending on surface material and time and 1–5 lux vertical at 5 ft above finished grade (AFG). When designing for parking lots, start by considering the luminaires’ location and how they relate to the property line. Look at the luminaires’ BUG ratings to ensure they are appropriate for the location and zone. The Max:Min ratio should be no greater than 4:1. This is important, as a high Avg:Min ratio will make it more difficult to see (IES 2016).

Many energy codes require that parking lot luminaires be either dimmed later in the evening or be controlled by occupancy sensors. Several manufacturers provide control systems that accommodate both. For example, the luminaires may be at 100% when the parking lot is occupied and drop to 70% when unoccupied during earlier evening hours when the school is still open. During later evening hours, the luminaires may be set to 70% when occupied and 50% when unoccupied. Although this type of combined control scenario has a higher first cost, the payback may be relatively short and will save significant energy over the long term.

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PLUG LOADS AND POWER DISTRIBUTION SYSTEMS

OVERVIEW

In the commercial sector and schools in particular, plug loads consume ever increasing power even when the school is unoccupied. Plug loads may consume up to one third of a building's energy consumption and are a significant contributor to a building's energy consumption (EIA 2012).

Plug loads consist of the many and varied devices that are plugged into receptacle outlets in buildings. A typical school may include computers, servers, laptops, copiers, vending machines, space heaters, small computer monitors, coffee makers, microwaves, toaster ovens, portable sound systems, smart boards or other large monitors, cooking equipment in student demonstration kitchens, refrigerators in break rooms or resource rooms, and hot plates. Aquariums and heated animal cages for turtles, guinea pigs, hamsters, and other small animals are also found in many classrooms.

Kitchen equipment used in school kitchens and cafeterias is covered in a separate section in this document (see the next section, Kitchen and Equipment).

Plug loads can be controlled either with a management plan requiring human actions or with a passive system where plug load devices are controlled by an automation system that removes human action from the equation. The management plan can be as simple as banning all extraneous devices from classrooms and offices and achieving buy-in through an education process explaining the "why" of plug load management.

PLUG LOAD MANAGEMENT

PL1 Building Systems Considerations

Energy use in the school should be managed and monitored over time to ensure that energy goals are met. It also interacts with other systems such as sizing for the cooling system and the size of the renewable energy system. Most schools cannot achieve the zero energy goal without effective plug load management. (See PL2 and PL3.)

Plug load management also presents a challenge on designing for thermal comfort. Building occupants often address thermal comfort issues with space heaters and fans. The HVAC systems should be designed to ensure appropriate thermal comfort with adjustability, and then thoroughly commissioned to ensure proper installation. Excessive plug loads can be a result of poor HVAC systems. (See also Chapter 2, HV16, HV18.)

PL2 Establish a Plug Load Management Policy

Establish a plug load management policy that allows only approved equipment and applications for educational purposes. This may mean the elimination of coffee hot plates, small refrigerators, toaster ovens, microwaves and refrigerators located in individual classrooms, teacher workrooms and resource rooms. Items that are part of the educational curriculum such as personal electronic devices, as well as aquariums and small animal cages, may be allowed, although many schools adopt a policy of no equipment in the classrooms and administrative offices other than a school furnished computer and smart board or monitor. The image in Figure 5-40 illustrates the energy impact of personal plug load devices on a teacher's desk.

Conduct staff training and encourage student/teacher engagement through contests by classroom or grade levels or by challenging the entire school to reduce overall plug load energy.

When designing the power distribution systems, keep in mind the options and desires of the school educators and maintenance staff for monitoring and measuring electricity use by group and type in the building. Seeing the power consumed in a building and being able to translate it into trees, energy cost dollars, or another meaningful metric, helps illustrate energy use and opportunities for savings.

PL3 Install Plug Load Controls

Plug load controls minimize waste energy from devices being left on even when the user is not present, but provide power availability when needed. Automated controls are explicitly required by ANSI/ASHRAE/IES Standard 90.1-2010 and later versions, and by CEC Title 24 (CEC 2016). Specifically, Standard 90.1 requires plug load control of 15 amp and 20 amp, 120 volt receptacles.

Generally, the requirement for plug load control is that 50% of the receptacles be controlled by an automatic shutoff device. Receptacles typically have a port that is uncontrolled and a port that is controlled. Monitors, task lighting, portable appliances, personal fans and even teacher workstations should be plugged into the controlled section of the receptacle. Computers with automatic sleep mode may be connected to the non-controlled circuit if necessary to maintain operations. Devices requiring continuous power such as servers or security equipment are not required to be part of the plug load control system and may be plugged into the uncontrolled section of the receptacle. For most applications, IT equipment should only be powered when it is needed and turned off when the building is not occupied. ENERGY STAR® settings can help deploy this option turning down power when equipment is not being used.

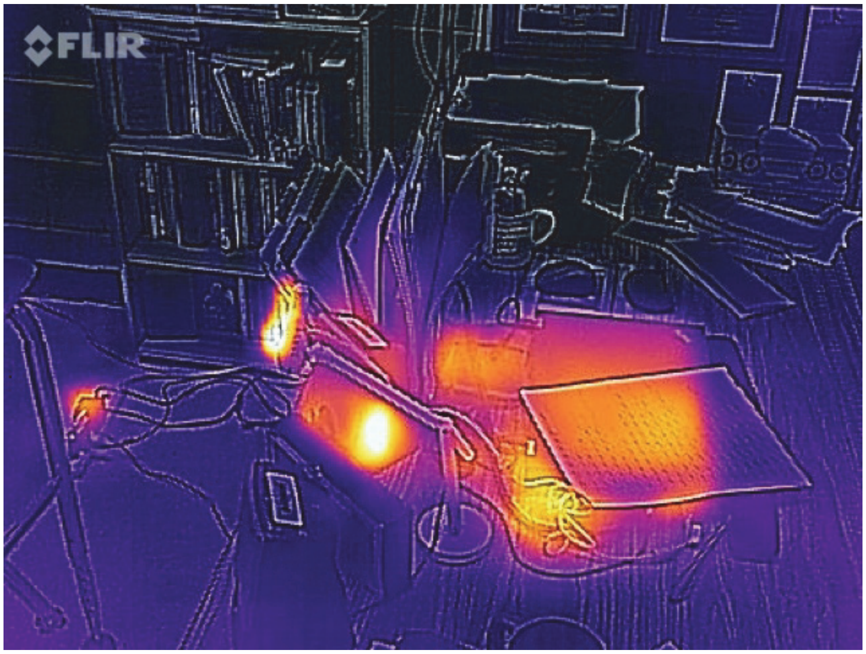

Figure 5-40 (PL2) Thermographic image of teacher's desk.
Image courtesy of Thrive Architecture, PC

Plug load control devices may consist of time of day control, where receptacle circuits are controlled via a contactor, relay, or other power management device that is in turn controlled through a time of day schedule via the building automation system or a time clock. Controlled receptacles are required to be identified with a permanent, distinct marking to prevent a 24-hour load from being plugged into an interruptible outlet. An options is to use color coded outlets to represent switched outlets. A popular option is to integrate the plug load controls with the lighting control systems as many lighting control manufacturers incorporate an option to control local receptacle outlets in a classroom or office. Lighting control systems also incorporate occupancy sensors that may be used as a further measure of plug load controls in individual spaces. While these solutions can control plug loads, occupant behavior must still be engaged to plug items into the correct type of outlet.

> ***Caution:*** The use of smart plug strips, even with occupancy sensors built in, does not meet the intent of ANSI/ASHRAE/IES 90.1 and should not be considered as the primary source of plug load control. These devices can be used successfully as a secondary means of plug load control.

Plug load controllers should turn off devices at specific, programmed times, primarily when the building is unoccupied. The program should:

- Incorporate areas of 5000 ft^2 or less.
- Provide manual override for weekends, holidays, and summers with the provision that the programmed state resumes after a set time of two hours.
- Program occupant sensors to turn off power within 20 minutes of students, teachers or staff leaving the room.
- Turn off the devices 20 minutes after an occupant has left the room as sensed by the lighting control system, when the devices are controlled via the lighting control system,.

In spaces with local lighting controls and no need for 24 hour power, the lighting controls can be used to provide on-off control of all the receptacles in a room, such as classrooms and offices. In other spaces, the need for 24 hour power may require lighting controls for the controlled ports of the receptacles and uncontrolled wiring for the 24 hour loads. Each classroom should have at least one uncontrolled receptacle to allow for flexibility of use. Another wiring option is to use centrally controlled receptacle circuits from the circuit breaker panels, for example when time switch controls are used. Uncontrolled receptacle circuits are then run from the panel directly, bypassing the central control system. Dual wiring scenarios are more popular due to the flexibility they offer.

> ***Caution:*** If end use metering is desired for measuring plug loads and lighting loads separately, care must be taken to not mix lighting and plug load circuits, especially if a lighting controller is used for plug load management.

Plug load control options include the following:

- Smart power strips sensing occupant with radio frequency or other BAS/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 switched outlets controlled via an automatic system
- Radio Frequency receptacle controls via occupancy sensor or power pack
- Contactor control through Building Automation System
- Compatibility with stand-alone or networked control systems in the building
- Written policies distributed to staff
- Enforcement of plug load management policy
- Signage reminding the importance of plug load management
- Competitions among schools or classes
- Awareness of staff and building occupants
- Education of users to ensure 24 hour operations continued power
- Removal of equipment not approved for use in the school

PL4 *Choose Energy-Efficient Equipment*

When possible, purchase plug load devices with a sleep mode option. In school offices, monitors may account for up to 50% of the plug load so it is especially important to have plugged into the controlled receptacle port and to have a sleep mode.

IT servers for a school should be chosen to be scalable to minimize wasted or unused power capacity. DC powered servers are commercially available and may be complimentary with a PV power system that also contains battery storage.

Another means to reduce plug loads is to require ENERGY STAR appliances be used throughout, including copy equipment, cooking equipment, servers, all non-cafeteria refrigerators, vending machines, and all computers and monitors. Many zero energy schools adopt a policy of no vending machines. It is important that the ENERGY STAR settings enabled on this equipment. In addition, some equipment can also be scheduled through internal software. Server hard drives and printers are examples.

PL5 *Specify Low-Energy Elevators*

While not plugged in, any load that is not HVAC or lighting should be documented and efforts made to reduce its energy consumption. An example of such a load are elevators. Elevators in schools should be the low energy, “machine-room-less” type in order to reduce energy demand. Hydraulic elevators typically have larger motors than the electric traction type that has the motor mounted to the elevator rails. Heaters for the hydraulic oil also consume power even if the unit it not in use. As the elevator knows the weight of the cab including the occupants, most elevator software can be controlled to turn off the cab lights and fan when the elevator is not occupied. This is easy to accomplish with specifications at time of construction.

PL6 *Monitor Plug Load Usage*

All low voltage (120/208 V) power should be separately metered to display power consumed by each electrical panel. Totals on a daily and monthly basis to ensure that no “power creep” is occurring. Power creep occurs when staff adds equipment into the building or classroom (See PL2). As time goes on, additional equipment may be added, but old equipment must also be retired to keep the plug load within the energy budget.

Plug load consumption monitoring (controlled and non-controlled) should be part of the energy dashboard monitoring system for the school along with the other major power systems (lighting, HVAC, service hot water, and kitchen equipment. The monitoring system should display the actual energy consumed, which can be compared with the predicted energy use for each of these systems. Corrective actions are necessary if the variance between predicted and actual cannot be reconciled by occupancy, hours of use, or other factors affecting energy consumption.

POWER DISTRIBUTION SYSTEMS

PL7 *Rightsizing Power Distribution Systems*

The 2014 National Electrical Code (NEC 2014) inserted a new provision that allows the design engineer to design to a lower general lighting load volt-ampere per area number when the facility is designed to comply with an energy code adopted by the local authority having jurisdiction. A power monitoring system is required when using this option 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 exception is used, the designer may not apply any further demand factors in sizing the lighting infrastructure. This exception 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 one volt-amperes per square foot under certain conditions. (NFPA 2017)

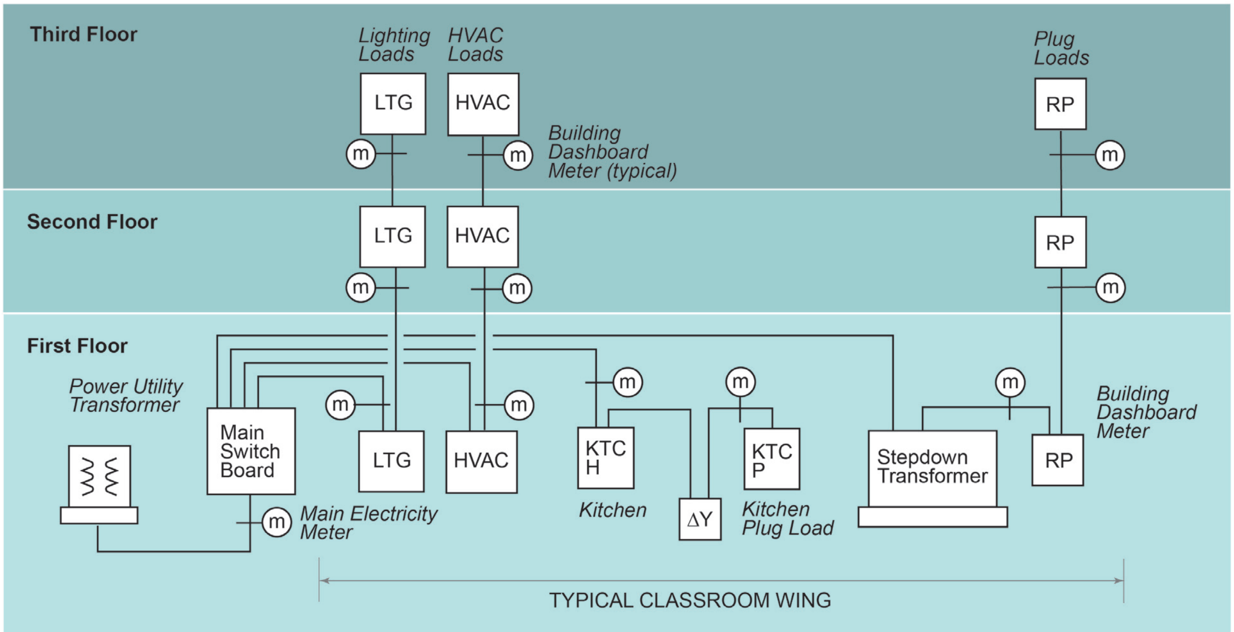

Figure 5-41 (PL7) Typical classroom wing power distribution.

In schools with 480/277 V power distribution systems, 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 to 208 V. Transformers fall under DOE minimum efficiency rules. The DOE efficiency standards apply at a single 35% load point, a common demand load point for transformers (DOE n.d.). However, this may result still in oversized transformers and higher than desirable losses due to lower efficiencies at light loads. When designing power distribution systems for schools, the step down transformers for plug loads should be sized as closely as possible within the National Electrical Code (NFPA 2017) requirements. When 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 2016 transformer efficiencies will result in most schools having transformers with losses of only 1.6% to 1.26% (45 kVA 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 school. 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. A typical classroom wing power distribution design is shown in Figure 5-41. 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. The engineer should study the usage patterns proposed for the school and design accordingly. The transformer losses are an important part of the energy modeling and are considered in the overall energy target of the building.

PL8 Reducing Line Losses

Other options for reducing power distribution line losses is to properly size (rightsize) feeders to minimize voltage drop, and to locate power distribution centers close to the load.

Each classroom wing should have its own power center with associated step down transformer and lighting panels. Each power panelboard and transformer should have its own power monitoring meter, connected to the schools building dashboard as illustrated in Figure 5-39.

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KITCHEN EQUIPMENT

OVERVIEW

Food service operations within K–12 schools usually includes a full service kitchen serving one or two meals per day. According to the EPA Target Finder, kitchen and cafeteria operations could account for up to 20% of school site energy consumption. Despite the wide range of appliances within a food service operation and the resulting variation in energy intensity of a particular building, the appliance selection process and best-practices design strategies apply to all food service facilities. To impact the energy consumption of the kitchen, it is best to include the administrator in charge of food services and operations in the design process. Strategies for conserving energy are detailed in following sections.

KE1 General Guidance

Select ENERGY STAR equipment as a minimum standard for designs that include any of the eight appliance categories currently available, including reach-in refrigerators and freezers, as suggested in KE2. For other categories, refer to the commercial publications from Consortium for Energy Efficiency (CEE 2015a) and Appliance Performance Reports from Food Service Technology Center (FSTC 2015a).

Select exhaust hood styles and designs that allow a reduction in the exhaust and makeup airflow rates, as described in KE4. Where feasible, incorporate separate exhaust fans for hoods that operate over appliances that will be used during different times of the day. Doing this improves the return on investment (ROI) of variable-speed or demand-controlled kitchen ventilation (DCKV) systems.

Consider transferring available “outdoor” air from the dining and circulation area to the kitchen area as a contribution to the makeup (replacement) air requirement of the exhaust hoods, also described in KE4. Select walk-in freezers and coolers with high-performance thermal envelopes and refrigeration systems. The refrigeration system should comply with Section 312 of the Energy Independence and Security Act of 2007 (EERE 2015).

The application of LED lighting in both exhaust hoods and walk-in refrigeration units is recommended. (See also EL12 and KE10.)

KE2 Energy Efficiency in Menu Design

The essential role of K–12 school food service is to provide healthy, nutritious, and appealing food to students. That goal cannot be compromised, but consideration of energy efficiency can guide menu designers to select certain foods over others. Certain types of cooking are more effective at conveying heat to the food to be cooked, resulting in less heat input to the system, less heat transferred to the kitchen, and/or a shorter cooking time. Less heat for a shorter time not only reduces the amount of fuel or electricity required for cooking, but it may also reduce the amount of exhaust air that must be removed from the kitchen, either through reduced exhaust flow rate or reduced hood operating time.

Menus in schools must conform to the National School Lunch Program for the school to retain federal meal program assistance. This program stipulates that the school meals program must meet meal pattern and nutrition standard based on the latest Dietary Guidelines for Americans. The meal pattern in the 2015 version of this document increases the availability of fruits, vegetables and whole grains in the school menu and sets specific calorie limits to ensure age-appropriate meals for grades K–5, 6–8 and 9–12 (FNS 2017, USDA 2015). Some of the modifications to this document are consistent with reduced cooking requirements. While the school menu must meet these guidelines, the specific contents of the menu and preparation methods are left to the discretion of the local school food authorities.

Certain menu items simply require less cooking than others. Fruits and vegetables may even be served uncooked. Foods prepared in small batches may be more efficiently cooked on an electric induction cooktop rather than a gas cooktop. Some foods may be warmed using microwave ovens using a fraction of the energy of a standard oven or cooktop. While cooking is necessary for many dishes, nutrient content of the food is often negatively impacted by both higher cooking temperatures and longer cooking periods, so that less cooking may serve both the nutritional and energy-efficiency goals of the menu design.

A part of the planning of the kitchen should include the engagement of the school nutritionist to design a menu that meets the requirements for variety, nutrition and appeal while reducing the overall energy consumption for preparation and cooking. Cooking requirements for the menu selections can be reviewed and an energy analysis, incorporating both cooking and kitchen ventilation implications of the menu items can be performed to optimize the menu for both benefit to the consumer and energy conservation. The resulting menu may enable the kitchen equipment designer to avoid appliances that are relatively inefficient in transferring heat to the food, such as open griddles, deep fat fryers, and various types of broilers, while maximizing use of energy-efficient cooking devices, such as combi-ovens.

EQUIPMENT AND DESIGN STRATEGIES

KE3 Use Energy-Efficient Kitchen Equipment

Specify energy-efficient appliances, including dishwashers, solid-door freezers, fryers, hot-food holding cabinets, ice machines, refrigerators (walk-in and reach-in), and steamers. In addition, select low-flow hot-water fixtures to minimize both water and energy use. ENERGY STAR-qualified commercial food service equipment has been tested in accordance with appropriate ASTM Standard Test Methods, and the specifications for ENERGY STAR certification ensure that the “cooking” performance (from a food safety perspective) is equal to or better than non-ENERGY STAR appliances.

Both fuel selection and method of delivery of heat determine the source energy efficiency of cooking methods. Convection ovens can significantly reduce cooking time compared with conventional ovens. Closed loop steamers typically use only 40% of the energy consumed by conventional steamers over the course of a school year. Each appliance, including variations between electric and gas appliances, interacts with the ventilation system. As a result, an energy analysis is required to determine whether a change in cooking equipment and energy source results in a reduction in source energy. The designer should consider the source energy impact of all of these components of the cooking activity when selecting fuel source and types of components for food preparation and cooking.

The Commercial Kitchens Initiative (CKI) and ENERGY STAR websites provide efficiency strategies including ENERGY STAR rated commercial kitchen equipment (CEE 2014a; EPA 2015). The goal is to provide clear and credible definitions in the marketplace as to what constitutes highly efficient energy and water performance in cooking, refrigeration, and sanitation equipment and to help streamline the selection of products. There are also resources from FSTC (2015a), including links and guidance on efficient design for commercial kitchens. FSTC, supported by California public goods energy-efficiency funding, is the industry leader in commercial kitchen energy efficiency and appliance performance testing. The Center has developed more than 35 standard test methods for evaluating commercial kitchen appliance performance.

While there are only eight categories of commercial kitchen equipment in the ENERGY STAR program, there are more than 35 ASTM International standard performance test methods that provide a recognized method to test the capacity, cooking performance, and energy use and efficiency of appliances. Using a specification that requires the manufacturer to provide test results from an ASTM Standard Test Method ensures that appliances submitted for approval during construction meet the project's design energy goals. Many of these appliances are specialized and are not relevant for K–12 School food service facilities. Table 5-12 lists ASTM International performance test method standards for those appliances that are often seen in food applications. (FSTC 2015b). Performance specifications based on these Standard Test Methods are a recommended design strategy.

KE4 Performance Specifications for Food Service Appliances

The Consortium for Energy Efficiency (CEE), through their Commercial Kitchen Initiative has published a number of performance specifications for food service appliances. Some of the performance standards conveyed in these specifications are related to ENERGY STAR performance specifications, while others incorporate a higher level of performance referred to as "Tier 2." Kitchen designers for schools should seek to surpass the minimum ENERGY STAR requirements for appliances and should comply with CEE Tier 2 standards. Some of the performance standards developed for the CEE Commercial Kitchen Initiative are shown in Tables 5-13 through 5-17. Additional information is available in the performance specification sheets available on the commercial CEE program resources on the CEE website (CEE 2015a).

KE5 Design Exhaust and Ventilation Energy Use

Emphasis should be on designing exhaust ventilation systems with proper layout of cooking equipment and proper hood design to minimize total airflow while still providing adequate exhaust flow for complete capture and containment of the cooking effluent. After minimizing ventilation needs, consider variable-speed exhaust hood flow systems, otherwise known as DCKV systems. The design and specifications of a kitchen hood system, including the exhaust hood, ductwork, exhaust fan, and makeup air, need to be addressed by the food service consultant and the mechanical engineer, which requires collaboration and communication between these two disciplines. Additional opportunities include exhaust air energy recovery using dedicated exhaust heat recovery ventilation (HRV) units. However, energy recovery from grease-laden exhaust air may be considered too expensive when wash-down and fire protection systems are included. There are also limitations within the International Mechanical Code (IMC) with respect to the installation of an HRV in kitchen exhaust systems (ICC 2015).

Table 5-12 (KE3) Commercial Food Service Appliance ASTM Standard Test Methods

ASTM #	Appliance Type
F1275-03	Griddles
F1361-05	Open deep fat fryers
F1484-05	Steam cookers
F1496-99(2005)	Convection ovens
F1521-03	Standard test methods for performance of range tops
F1639-05	Combination ovens
F1696-96(2003)	Standard test method for energy performance of single rack hot-water Sanitizing, door-type commercial dishwashing machines
F1704-05	Standard test method for capture and containment performance of commercial kitchen exhaust ventilation systems
F1785-97(2003)	Steam kettles
F1786-97(2004)	Braising pans
F1920-98(2003)	Rack conveyor, hot-water sanitizing, commercial dishwashing machines
F1964-99(2005)	Pressure and kettle fryers
F2022-00	Booster heaters
F2140-01	Hot food holding cabinets
F2142-01	Drawer warmers
F2324-03	Pre-rinse spray valves
F2473-05	Water bath rethermalizers
F2474-05	Standard test method for heat gain to space performance of commercial kitchen ventilation/appliance systems
F2519-05	Standard test method for grease particle capture efficiency of commercial kitchen filters and extractors

Table 5-13 (KE4) Convection Ovens[1]

Performance Tier	Tier 1	Tier 2
Electric, Half Size		
Cooking energy efficiency[2]	≥71%	≥75%
Idle energy rate	≤1.0 kW	≤1.0 kW
Electric, Full Size		
Cooking energy efficiency	≥71%	≥76%
Idle energy rate	≤1.60 kW	≤1.0 kW
Gas, Full Size		
Cooking energy efficiency	≥46%	≥52%
Idle energy rate	≤12,000 Btu/h	≤10,000 Btu/h

1. CEE 2015b
2. Based on heavy load (potato) cooking test

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Table 5-14 (KE4) Gas-Fired Steamers[1]

	No. of Pans	Tier 1A[2]	Tier 1B**
Cooking Energy Efficiency[3]	All sizes	38%	38%
Idle Energy Rate (Btu/h)	3	6250	6250
	4	8350	8350
	5	10400	10400
	6	12500	12500
	>6	2083 per pan[4]	2083 per pan[4]
Water Consumption (gal/h)	All sizes	≤15 per compartment	≤4 per compartment

1. CEE 2009. Source: https://library.cee1.org/content/cee-high-efficiency-specifications-commercial-steamers
2. Tiers 1A and 1B energy performance levels are equivalent to ENERGY STAR performance levels. ENERGY STAR does not have a water consumption performance requirement.
3. Based on heavy load (potato) cooking test
4. The maximum idle rate for ENERGY STAR qualified steamers with more than six pans is 12,500 Btu/h.

Table 5-15 (KE4) Electric Steamers[1]

	No. of Pans	Tier 1A[2]	Tier 1B[2]
Cooking Energy Efficiency[3]	All sizes	50%	50%
Idle Energy Rate (watts)	3	400	400
	4	530	530
	5	670	670
	6	800	800
	>6	133 W/pan[4]	133 W/pan[4]
Water Consumption (gal/h)	All Sizes	≤15 per compartment	≤4 per compartment

1. CEE 2009.
2. Tiers 1A and 1B energy performance levels are equivalent to ENERGY STAR performance levels. ENERGY STAR does not have a water consumption performance requirement.
3. Based on heavy load (potato) cooking test
4. The maximum idle rate for ENERGY STAR qualified steamers with more than six pans is 800 Btu/hour.

Table 5-16 (KE4) Commercial Fryers[1]

Equipment	Corresponding Base Specification	Heavy Load (French Fry) Cooking Energy Efficiency	Idle Energy Rate
Natural gas standard open deep-fat fryers	ENERGY STAR	≥50%	≤9,000 Btu/h
Electric standard open deep-fat fryers	ENERGY STAR	≥80%	≤1,000 W
Natural gas large vat open deep-fat fryers	ENERGY STAR	≥50%	≤12,000 Btu/h
Electric large vat open deep-fat fryers	ENERGY STAR	≥80%	≤1,100 W

1. CEE 2012

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Table 5-17 (KE4) Hot Food Holding Cabinets[1]

Specification	Corresponding Base Specification	Maximum Idle Energy Use, W/ft^3
CEE Tier 1	ENERGY STAR	40
CEE Tier 2	ENERGY STAR + 50%	20

1. CEE 2007

Augmenting relevant design information provided by the *ASHRAE Handbook—HVAC Applications* chapter on kitchen ventilation (ASHRAE 2015), commercial kitchen ventilation design guides developed by the FSTC provide additional guidance for energy efficiency:

- *Design Guide 1: Improving Commercial Kitchen Ventilation System Performance-Selecting and Sizing Exhaust Hoods* (SCE 2004) covers the fundamentals of kitchen exhaust and provides design guidance and examples.
- *Design Guide 2: Improving Commercial Kitchen Ventilation System Performance-Optimizing Makeup Air* (CEC 2004) augments Design Guide 1, with an emphasis on the makeup-air side of the equation.
- *Design Guide 3: Improving Commercial Kitchen Ventilation System Performance-Integrating Kitchen Exhaust Systems with Building HVAC* (SCE 2009) provides information that may help achieve optimum performance and energy efficiency in commercial kitchen ventilation systems by integrating kitchen exhaust with building HVAC.
- *Design Guide 4: Improving Commercial Kitchen Ventilation System Performance-Optimizing Appliance Positioning and Hood Configuration* (PG&E 2011) discusses the influence of appliance positions under a hood on the exhaust requirements.

KE6 Minimize Exhaust Rates for Hooded Appliances

Selection of cooking appliances can impact the code-mandated exhaust rate for the kitchen. In general, kitchen exhaust fans can drive the energy consumption of a school. Minimizing and rightsizing the appliances and related fans is critical to reach energy targets. Appliances that produce heat, steam or products of combustion and do not produce grease or smoke, such as steamers, kettles, pasta cookers and other light duty commercial cooking appliances may use a Type 2 hood. The type of hood required for an assembly of cooking appliances is dependent upon the appliance in the group having the most stringent requirements. If a kitchen has only one appliance requiring a Type 1 hood, then that appliance may be located and exhausted separately using a Type 1 hood, while the other appliances use a Type 2 hood. In addition to reduced exhaust rate requirements and resulting reduced energy costs, Type 2 hoods have lower installation costs than Type 1 hoods

Research sponsored in part by ASHRAE shows that the position of appliances under a hood can make a significant difference in the required exhaust rate-up to 30% (ASHRAE 2005). Some key recommendations are as follows:

- Position heavy-duty equipment (such as underfired broilers or wok ranges) in the middle of the cook line.
- If a heavy-duty appliance is on the end, incorporating a side panel or end wall is imperative.
- Fryers and broilers should not be placed at the end of a cook line. Ranges can be located at the end of a cook line because under typical operating conditions the plume strength is not as high as that of broilers.

Table 5-18 (KE8) Pre-Rinse Spray Valve Specification[1]

	Tier 1	Tier 2
Flow Rate, gal/min	<1.28	<0.75
Spray Force, Ounces-Force	≥4	≥4
Life Cycle, No. of Cycles	≥250,000	≥250,000
Performance Criteria Equivalency (For Reference Purposes Only)	WaterSense™ Version 1.0	Subset of units meeting WaterSense Version 1.0

1. CEE 2014b
Note: Testing bodies test PRSV performance with water pressure at 60 psi. Significantly higher or lower water pressure will impact PRSV performance.

- Locate double-stacked ovens or steamers at the end of the hood. This has a plume control effect that tends to assist in capture and containment. However, this does not replicate the value of adding a partial side panel or end wall. Both strategies should be considered.

Repositioning of appliances requires approval of the kitchen manager and kitchen consultant. If these recommendations are followed, let the kitchen hood manufacturer and design mechanical engineer know why these decisions were made, and reference the ASHRAE research (ASHRAE 2005) or FSTC Design Guide 4 (PG&E 2011). The resulting design exhaust and makeup air rates should be less than those of a conventional design.

KE7 Minimize Hot-Water Use

The FSTC publishes a hot-water system design guide for commercial kitchens that provides key information to restaurant designers and engineers on how to achieve superior performance and energy efficiency with their systems. The information is relevant to the design of hot-water systems in K–12 schools with lengthy distribution piping. This design guide, Improving Commercial Kitchen Hot Water System Performance-Energy Efficient Heating, Delivery and Use (Fisher-Nickel 2010), describes the design process and reviews the fundamentals of commercial water heating, including the following topics:

- Reducing hot-water use of equipment while maintaining performance
- Increasing the efficiency of water heaters and distribution systems
- Improving hot-water delivery performance
- Incorporating "free heating" technologies, such as waste heat recovery and solar preheating

KE8 Performance Specifications for Appliances Using Hot Water

The CEE has published performance specifications for several kitchen appliances that use hot water. Appliances meeting these energy and water consumption metrics is highly recommended for zero energy K–12 schools.

The first of these specifications is for pre-rinse spray valves that offers both Tier 1 and Tier 2 levels of performance is shown in Table 5-18.

The commercial dishwasher also uses significant energy and hot water. The specification for multiple types of dishwashers is shown in Table 5-19.

KE9 Commercial Freezers and Refrigerators

Many school cafeterias will use single package reach-in refrigerators or freezers (upright and chest-type) for quick access in the food preparation area. These units typically reject heat directly into the kitchen space. ENERGY STAR versions of these appliances are available and performance of units used in a zero energy school should be equal or better than the ENERGY STAR performance specifications. Table 5-20 shows the maximum daily energy consumption metric, commonly used to rate refrigerators, allowed for CEE Qualified Commercial Food-grade Refrigerators and Freezers (CEE 2010).

Table 5-19 (KE8) Dishwasher Specification[1]

Equipment	Corresponding Base Specification	High Temperature Efficiency Requirements[2]		High Temperature Efficiency Requirements[2]	
		Idle Energy Rate[3]	Water Consumption	Idle Energy Rate[3]	Water Consumption
Under counter	ENERGY STAR	≤0.9 kW	≤1.00 gal/rack	≤0.5 kW	≤1.70 gal/rack
Stationary single tank door[4]	ENERGY STAR	≤1.0 kW	≤0.950 gal/rack	≤0.6 kW	≤1.18 gal/rack
Single tank conveyor	ENERGY STAR	≤2.0 kW	≤0.700 gal/rack	≤1.6 kW	≤0.790 gal/rack
Multiple tank conveyor	ENERGY STAR	≤2.6 kW	≤0.540 gal/rack	≤2.0 kW	≤0.540 gal/rack

1. CEE 2008
2. Machines designed to be interchangeable in the field from high temperature to low temperature and vice versa, must meet both the high temperature and low temperature requirements to qualify
3. Idle energy rate as measured with door closed and rounded to two significant digits
4. Includes pot, pan, and utensil machines

Table 5-20 (KE9) Maximum Daily Energy Consumption Requirements (kWh/day)[1]

Product Volume, ft^3	Corresponding Base Specification	Refrigerator	Freezer
Vertical Configuration—Solid Door Cabinets			
0 < V < 15	ENERGY STAR Version 2.0	≤0.089V + 1.411	≤0.250V + 1.250
15 ≤ V < 30		≤0.037V + 2.200	≤0.400V + 1.000
30 ≤ V < 50		≤0.056V + 1.635	≤0.163V + 6.125
50 ≤ V		≤0.060V + 1.416	≤0.158V + 6.33
Vertical Configuration – Glass Door Cabinets			
0 < V < 15	ENERGY STAR Version 2.0	≤0.118V + 1.382	≤0.607V + 0.893
15 ≤ V < 30		≤0.140V + 1.050	≤0.733V + 1.000
30 ≤ V < 50		≤0.088V + 2.625	≤0.250V + 13.500
50 ≤ V		≤0.110V + 1.500	≤0.450V + 3.500
Chest Configuration			
Solid or Glass Door Cabinets	ENERGY STAR Version 2.0	≤0.125V + 0.475	≤0.270V + 0.130

1. CEE 2010/
Note: V = Association of Home Appliance Manufacturers volume in ft3

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While ENERGY STAR ratings are provided for different configurations, the objective is to have the smallest energy use per year. As a result, it is better to have a solid door cabinet over a glass door cabinet. The less overall energy, the easier it will be to hit the overall building energy goal.

WALK-IN COOLERS AND FREEZERS

KE10 High Efficiency Construction and Controls

Rigorous specifications for walk-in coolers and freezers are important because walk-ins are normally custom built on-site, whereas reach-in refrigerators are completely constructed in a factory. There are, however, factory-manufactured components to walk-in boxes, and there is an ability to specify how those components are built and how they are put together. Reducing system load is probably the simplest and sometimes easiest way to save energy. Increasing insulation on walk-in cases is a prime example of reducing system load.

Walk-in boxes fall into two categories that are applicable to schools:

- Small walk-in coolers/freezers with typical ceiling heights of 7 to 8 ft.
- Medium walk-in coolers/freezers with typical ceiling heights of 9 to 10 ft.

New amendments to the Energy Policy and Conservation Act, scheduled to become active in 2020, established a performance standard for “walk-in coolers” and “walk-in freezers” defined as enclosed storage spaces refrigerated to temperatures, respectively, above, and at or below 32°F that can be walked into, and have a total chilled storage area of less than 3000 ft^2.

The rule includes a number of prescriptive standards that apply to the refrigerated enclosure. These include the following:

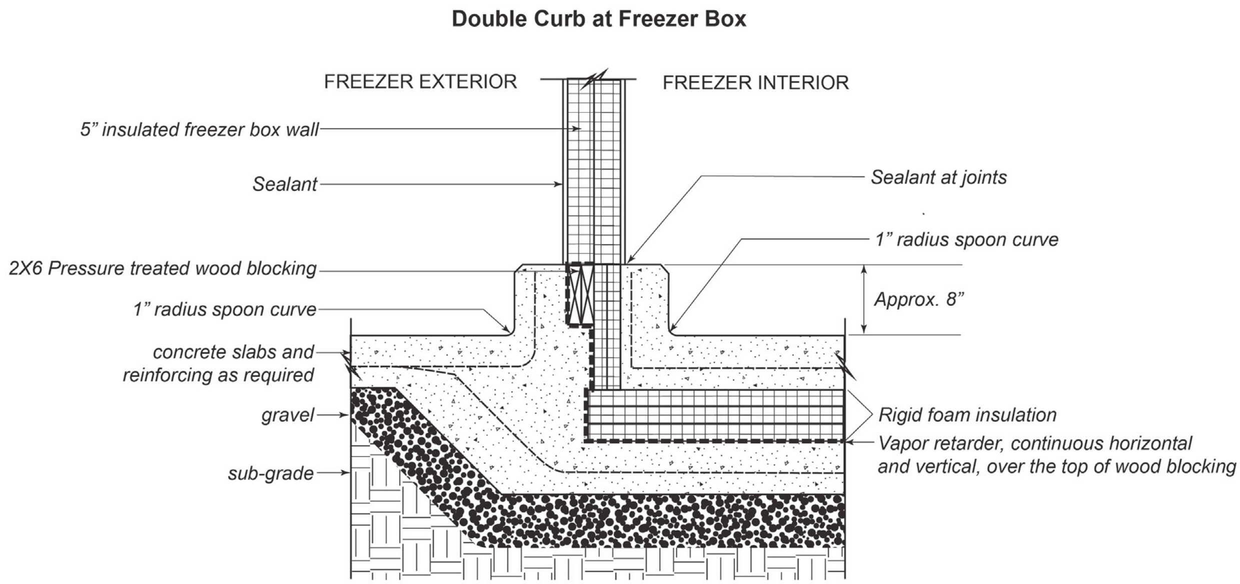
- Automatic door closers that firmly close all walk-in doors that have been closed to within 1 in. of full closure, for all doors narrower than 3 ft 9 in. and shorter than 7 ft
- Strip doors, spring hinged doors, or other methods of minimizing infiltration when doors are open
- Wall, ceiling, and door insulation of at least R-25 for coolers
- Wall, ceiling, and door insulation of at least R-32 for freezers
- Floor insulation of at least R-28 for freezers
- Evaporator fan motors of under 1 hp and less than 460 V must be electronically commutated motors (brushless direct current motors) or three-phase motors
- Interior light source efficacy greater than 40 lumens per watt

The new rule establishes the annual walk-in energy factor (AWEF) as the governing metric for performance of refrigeration components of these systems. This metric is defined as the ratio of heat removed from the envelope to the total energy input of the refrigeration system. A calculator is available to determine whether the performance of a proposed system.

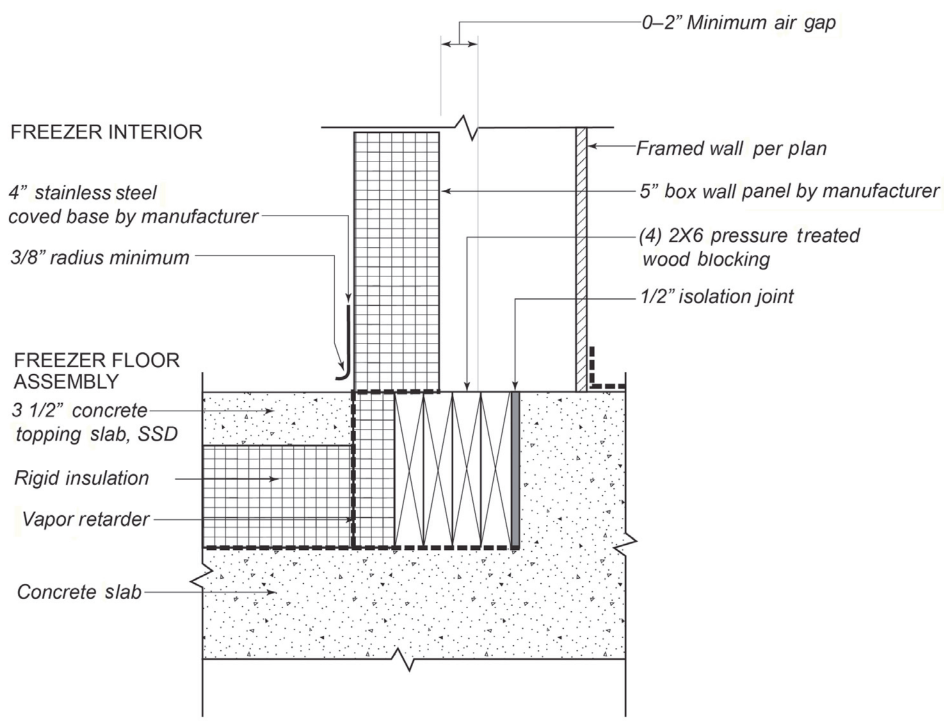
KE11 Insulation and Infiltration

The insulation thickness below the slab of the freezer box is determined by the temperature within the freezer box. These values are shown in Table 5-21. *ASHRAE Handbook—Refrigeration* (ASHRAE 2014) further recommends that the floor insulation have a heating system installed to avoid underfloor ice formation, which can lead to heaving of the floor.

Site-built freezer boxes need to be constructed so as to prevent moisture problems due to thermal bridging at the intersection of the slab and wall. Figure 5-42 presents construction details to avoid the moisture problem: Figure 5-42a illustrates how to avoid moisture problems with a double curb at the freezer box while Figure 5-42b provides a comparable solution without the curb.



(a)



(b)

Figure 5-42 (KE11) Freezer slab edge details (a) with double curb at freezer box and (b) without curb.

While the new standard recommends wall, ceiling, and door insulation of at least R-25 for coolers and freezer wall ceiling and door insulation of at least R-32, best practice increases the insulation value for these assemblies in freezers to R-40.

Overlapping strip curtains or vinyl swinging doors are recommended for all walk-in doors to prevent air and moisture infiltration while the main door is open. Installations should cover the entire opening to within 1/4 to 1/2 in. of the floor threshold.

Walk-in box doors are generally constructed of the same material used in walk-in box insulated wall panels. A magnetic compression gasket is recommended for the two sides and top edge of the door seal with a wiper-style gasket to seal between the door bottom and the threshold.

KE12 *Hinges, Closers, and Alarms*

Automatic door closers should be used for all doors. Swinging doors that latch upon closure are recommended for all applications to facilitate automated closing devices.

For all doors less than 48 in. wide, use cam-lift self-closing gravity hinges or a hinge set with spring-assisted operation. For all doors greater than 48 in. wide, a spring-action door closer is recommended. All doors should use a hydraulic door closer for securing the door against the gasket. This provides a “snap” closure when the door is open less than 1 in.

For produce prep areas and other high-temperature walk-ins, a double-action swinging door may be specified to facilitate higher traffic volume. In these cases, gravity hinges are recommended along with flexible wiper seals on all four sides.

Walk-in box freezer and cooler doors are opened more frequently and are left open for longer periods of time than necessary. Over time, self-closing doors may fail to fully latch on their own, allowing them to be left slightly open for extensive periods of time. Door alarms remind employees to keep doors shut and notify them when a door has not been completely shut or latched. This helps decrease the amount of time doors are left open, which in turn reduces energy use due to reduced box loads. (These door alarms should not be confused or combined with the very important leak detection alarms required for safety reasons.)

Each latching walk-in box door should be installed with a door switch to sense when the door is open. The recommendation is that whenever a door is opened, the refrigerant flow to the coil should be stopped (typically with a liquid-line solenoid) and the evaporator fans should be turned off to minimize air circulation-and therefore infiltration. Safeties should be in place to turn the refrigerant flow and evaporator fans back on in the event that the door is left open for too long in order to prevent product loss.

The most effective alarms have both visual (e.g., strobe light) and audible (e.g., horn) alarming functions. When a door first opens, the visual alarm should activate. After a predetermined time limit, the audible alarm should be activated. Once the door is closed, the alarms should turn off and reset. More or less aggressive alarming sequences can be applied to maximize effectiveness with respect to different owners' operations.

All walk-in cooler and freezers should be equipped with vaportight LED lighting fixtures with motion/vacancy sensors and door trigger controls.

KE13 *Fan Control*

Dual-speed evaporator fan motors are recommended with two-speed electronically commutated (EC) motors set for 100% and 80% speed. Speed control should be based on the position of the evaporator's electronic expansion valve (EEV). When the valve is in a greater than 50% open position, the fan motors run at 100%, and when the EEV is operating at 50% or less, the fan motor ratchets back to the 80% speed mode.

KE14 *Cooler or Freezer Defrost*

While electric and hot-gas defrost are both used frequently for many different reasons, electric defrost is recommend where time-off air-defrost is not sufficient. However, if implemented poorly, electric defrost can perform worse than hot-gas defrost from an energy perspective. It is important to always apply electric defrost with a temperature termination. This can be

Table 5-21 (KE11) Freezer Box Floor Insulation Levels

Temperature, °F	R-Value
35°	23
25°	25
10°	29
0°	31
–10°	33
–20°	36
–30°	38
–40°	40
–50°	43

accomplished either by adding a separate defrost termination temperature sensor or by adding small defrost termination thermostats to the coils. The temperature rise of the coil while in defrost can be sensed after all the ice is cleared from the coil, at which point the defrost cycle can be terminated.

Electric defrost should also have a timed termination programmed into the controller in the event that the system fails to terminate by temperature. More aggressive approaches to initiate defrost are possible, but due to the critical need to always have an efficiently operating coil that is free of ice and due to the lack of a mainstream, accepted method for a demand defrost technology, defrost should be initiated based on time and defrost cycles should be allowed to be shorter when possible.

KE15 High Efficiency Refrigeration Systems

The refrigeration systems for a walk-in cooler or freezer is typically a split system with an indoor refrigerated case, cabinet or walk-in compartment and an outdoor unit to reject refrigeration heat to the exterior environment.

Refrigeration systems consume a significant fraction of the energy consumed by a cafeteria, because these systems operate continuously. Many recommendations are targeted at reducing compressor energy by reducing compressor lift.

Reducing compressor lift means reducing head pressure and/or increasing suction pressure. By bringing these two pressures closer together, compressors don't need to work as hard to "lift" the refrigerant gas from low pressure to high pressure. There are several design techniques and recommendations presented in this guide that help to increase suction pressure, reduce head pressure, decrease load, or provide a blended benefit between all three. The goal of all of these energy conservation measures is to meet requirements of the amendments to the Energy Policy and Conservation Act of 1975 (EPCA) that are scheduled to go into effect in 2020. These metrics are in the form of the annual walk-in energy factor (AWEF), which is the ratio of the heat removed from the envelope of the refrigerated container to the total energy input to the refrigeration over a year, measured in Btu/W·h. See Table 5-22.

Multiple strategies are suggested for meeting these performance requirements depending upon whether the system has a dedicated condensing unit for one or more evaporators located in a single refrigerated enclosure and whether the condensing unit is located indoors or outdoors. Table 5-23 provides suggested strategies for meeting the requirements in Table 5-20.

KE16 Floating Head Pressure

Floating head pressure often provides more refrigeration system energy savings than other energy-saving measures. As a rule of thumb, one degree of reduction (°F) in condensing temperature saves 2% compressor energy. While systems must be designed to operate properly and maintain temperatures at the highest ambient conditions that may occur, maximum energy savings is achieved when the head pressure is controlled to take advantage of the lower hourly

Table 5-22 (KE15) Minimum AWEF EPCA 2020 Amendments[1]

Equipment Class	Net Capacity, q_{net}	Minimum AWEF, Btu/W·h*
Dedicated condensing system—low, indoor	<6500 Btu/h	$9.091 \times 10^{-5} \times q_{net} + 1.81$
	≥6500 Btu/h	2.40
Dedicated condensing system—low, outdoor	<6500 Btu/h	$6.522 \times 10^{-5} \times q_{net} + 2.73$
	≥6500 Btu/h	3.15
Unit cooler—medium		9.00
Unit cooler—low	<15,500 Btu/h	$1.575 \times 10^{-5} \times q_{net} + 3.91$
	≥15,500 Btu/h	4.15

1. U.S. Government 2016, Table IV-4
Where q_{net} is net capacity as determined in accordance with 10CFR 431.304 and certified in accordance with 10 CFR part 429

Table 5-23 (KE15) Strategies for Energy Reduction of Walk-Ins

Dedicated Condensing Unit, Outdoor (L Temp/ M Temp)	Dedicated Condensing Unit, Indoor (L Temp/ M Temp)	Multiplexed Condensing Unit, Outdoor (L Temp/ M Temp)
Floating head pressure Floating head pressure with electronic expansion valve Modulating evaporator fan motors Electronically commutated motors Improved evaporator fans Improved condenser fans Improved coil Hot gas defrost Temperature initiated, temperature terminated defrost control Variable speed compressor Continuously variable speed condenser fan motors Continuously variable evaporator fan motors Ambient subcooling	Modulating evaporator fan motors Continuously variable speed evaporator fan motors Improved coil Improved condenser fans Electronically commutated motors Improved evaporator fans Temperature initiated, temperature terminated defrost control Hot gas defrost	Modulating evaporator fan motors Continuously variable speed evaporator fan motors Improved evaporator fans Temperature initiated, temperature terminated defrost control Hot gas defrost

temperatures throughout the year. In practice, there are numerous factors to consider to operate reliably with the lowest energy usage, including both compressor and condenser energy.

Aside from the very few hours that compressors and condensers run near their maximum capacities, there is a constant opportunity to employ controls to optimize the total power used by the compressors and condenser fans. Floating head pressure is the overall effort to control to the lowest total energy use of compressors and condensers throughout the year. There are three elements to floating head pressure that are discussed in the how-to tips that follow:\

- Minimum condensing temperature—how low can the condensing temperature (discharge pressure) go at minimum weather conditions?
- Condenser fan control—How are the condenser fans themselves controlled?
- Set point optimization—How is the control set point determined?

KE17 Minimum Condensing Temperature

The refrigeration system should be designed to operate down to 60°F saturated condensing temperature (SCT) or lower where weather permits. School cafeteria store refrigeration systems routinely operate down to 70°F SCT, and there is experience operating at lower than 60°F SCT in colder locales. System design considerations include compressor operating envelopes, oil separator sizing, defrost design, and, most importantly, the ability of the control system to provide stable condenser pressure at the lowest pressure conditions.

KE18 Condenser Fan Control

For both evaporative and air cooled condensers, fans should be controlled in unison with variable speed, rather than fan cycling. The use of all condensing surface, all of the time, is the most efficient means of condenser capacity utilization. Condenser heat rejection capacity (at given entering air and condensing temperature conditions) is nominally directly proportional to fan speed and airflow whereas power varies with the cube of fan speed. Selected packaged refrigeration systems should have the following characteristics to insure both energy efficiency and stability of the refrigeration system:

- Control fan operation to a minimum speed (e.g., 10% to 15%) followed by fan cycling after reaching minimum speed with a single variable-speed drive (VSD) for all fans designed to allow fans to cycle
- If fans are cycled off, cycle the fans back on as soon as they can be employed (at reduced speed) and match required speed to avoid pressure discontinuities and hunting.
- Operate all fans at minimum speed and “ride” on the condenser holdback valve setting.

KE19 Set Point Determination

The essential objective is balancing the compressor and condenser power to obtain the lowest total power. Increasing condenser fan speed and energy consumption for its motor will reduce the head pressure and energy consumption of the compressor. Packaged refrigeration systems should be equipped with a smart controller that identifies the correct condensing control set point that achieves the lowest combined energy consumption for the condenser fans and the compressor.

KE20 Refrigerant Piping Insulation

Refrigeration piping for site-built walk-in coolers and freezers will be field installed and should be installed with the correct insulation to minimize energy consumption of the system. Refrigeration piping insulation has typically used flexible closed-cell rubber or closed-cell plastic insulation material. Suction-line insulation has typically been based on the insulation required to prevent condensation and external frost build-up rather than being based on an economic thickness calculation, with a common wall thickness of 1/2 in. and sometimes 3/4 in. on low-temperature suction lines. Also, as a practical matter, with individual circuit piping to central compressor racks, the wall thickness affects the area taken up by piping.

While no specific insulation thicknesses are recommended, a greater insulation thickness should be considered with trunk piping. With far fewer and larger pipes, it is possible to consider insulation sizing based on economic thickness for energy savings, increasing thickness to 2 in. on low-temperature suction lines and 1 in. or greater on medium-temperature and subcooled liquid lines. Indirect CO_2 and glycol piping should have similar insulation levels.

Heat gain in direct-expansion (DX) system refrigerant lines and indirect system fluid lines can have significant disadvantages in both systems. While heat gain on a DX suction line is not a direct load; the heat gain does not increase mass flow but only decreases density, it causes compressors to run more to maintain mass flow. Heat gain has on an indirect cooling pipe results in a direct addition of refrigeration cooling load, requiring more work for the refrigeration system.

Vapor retarders should also be considered in areas most susceptible to insulation failure due to harsh conditions such as ultraviolet (UV) exposure or extreme humidity and heat. With many users installing refrigeration systems on roofs, cold suction piping and are exposed to warm, humid outdoor air, which can adversely affect system efficiencies in the event of insulation failure. Vapor retarders can protect insulation from UV damage as well as keep moisture and ice from destroying the efficacy of the insulation. There are several options for vapor retarders, such as polyester and aluminum films, rubberized membranes, mastics, and others.

HEAT RECOVERY

KE21 Refrigerant Heat Recovery—Service Water Heating

Refrigerant heat recovery for domestic hot-water heating is covered in WH6. Because water heating requires temperatures well above the refrigeration system condensing temperature, the heat is only recovered from the superheat portion of the refrigeration heat of rejection. Superheat is a small fraction of the available heat. In addition, the actual discharge temperature of a system varies with the type of refrigerant and the system application. A medium-temperature system using R-507, at average head pressure, may have an actual (superheated) discharge temperature of 115°F or lower. A low-temperature system would have a significantly higher actual discharge temperature and would be more suitable for water heat recovery.

The heat removed through desuperheating to preheat domestic hot water is a small fraction of the total heat of rejection, and the remaining available heat obtained through condensing is still available for space heating. Care must be taken to minimize discharge pressure drop, but it is possible to use a system for both service water heating (SWH) and space heating.

KE22 Operating Considerations

While not directly part of the design process, providing staff training to encourage best practices within the food service operation is critical to sustaining an energy-efficiency operation through measures including but not limited to the following:

- Institute a start-up and shutdown schedule for all cooking and holding equipment, including the exhaust hood.
- Properly adjust air shutters on gas appliances. Flames should be hard and blue, not soft and yellow.
- Repair or replace damaged door gaskets on cooking and holding appliances and replace missing control knobs.
- Install occupancy sensors or timers on lights in areas of infrequent use, for example, closets, storage rooms, break rooms, and restrooms.
- Maintain refrigerator doors by replacing worn gaskets, aligning doors, enabling automatic door closers, and replacing worn or damaged strip curtains.
- Clean evaporator and condenser coils and ensure proper airflow. Straighten damaged fins and remove objects that block air to the coils.
- Check and properly set thermostats on all refrigeration equipment.
- Install strip curtains or plastic doors on walk-in cooler and walk-in freezer exterior doors.
- Set the thermostat of storage water heaters at the minimum temperature consistent with avoiding microbiological growth in the tank (typically 135°F) or the minimum required to supply temperature for the end use (e.g., 140°F for dishwashing machines).
- Control the hot-water recirculation pump with a time clock so that the pump is turned off when the facility is closed.
- Improve capture and containment performance of exhaust hoods so that exhaust airflow rates may be reduced, saving fan energy and makeup air conditioning loads. Ensure cooking appliances are pushed as close as possible to the back wall, maximizing hood overhang. Use end panels where practical (most cases).
- Install a low-flow prerinse spray valve at the dishwashing machine, to meet or exceed federal standards to go into effect in 2019.
- Have a professional check and maintain the dishwashing machine. Properly set rinse temperature and pressure and overflow-bypass and replace worn rinse-arm nozzles.
- Consider installing a time clock to control the ice machine and restrict operation to off-peak utility hours. Peak hours are typically noon to 6:00 p.m. Many ice machines are designed to melt ice to keep it "fresh." Turn on ice machine in the morning at an appropriate time to make the correct amount of ice and turn off just before the last service time. This can also be done with the plug load controller.

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SERVICE WATER HEATING

OVERVIEW

The first step to reducing the energy consumption of the service water heating system in a school is to reduce the demand for hot water. The simplest step to achieving this end is to specify low flow handwash sinks and showerheads. These fixtures should comply with the criteria in the EPA WaterSense program. Kitchen fixtures, specifically prerinse spray valves and dishwashers should meet the criteria in sections KE7 and KE8. When hot water usage has been minimized the efficiency of the systems and equipment that provide the hot water can be addressed.

Water heating requirements for K–12 schools fall into two general categories: distributed hand wash sinks and centralized food service applications. While showers in gyms and sports team locker rooms were previously a major user of hot water, many schools are designed without large showering facilities.

WH1 General Guidance

The first step for determining service water heating strategies is to develop an inventory of service water end-use applications. The second step is to establish the frequency of use and flow requirements for these end-uses. With that programmatic information the appropriate strategy for each end-use can be identified. energy-efficiency strategies for these applications should emphasize both the efficiency of generation of the hot water, and minimization of energy losses in delivering the hot water to its end use. In general, the distributed end uses should be served by simple local hot water generators to avoid the need for pumped loops to insure quick availability, while the larger food service requirements can be met by more sophisticated strategies that might use heat recovery or solar thermal strategies.

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SYSTEM TYPES

WH2 System Descriptions (Climate Zones: As Indicated Below)

Several different types of water heating systems are used in K–12 schools. System selection depends upon fuel availability, fuel cost differentials in the location, and the magnitude of the loads to be served. The ENERGY STAR system designates water heaters as either residential or commercial depending upon nominal energy input and water storage capacity. Depending upon end use and size, the water heaters in this guide may fall into either of these two categories. Systems considered in this guide are as follows:

Gas-fired storage water heater. This system consists of a water heater with a vertical or horizontal water storage tank. A thermostat controls the delivery of gas to the heater's burner. The heater requires a vent to exhaust the combustion products as well as outside combustion air. An electronic ignition is recommended to avoid the energy losses from a standing pilot. Sealed combustion systems can better control combustion air yielding additional savings.

Gas-fired instantaneous water heater. This system consists of a water heater with minimal water storage capacity. Such heaters require vents to exhaust the combustion products. An electronic ignition is recommended to avoid the energy losses from a standing pilot. Instantaneous, point-of-use water heaters should provide water at a constant temperature regardless of input water temperature or flow rate. Sealed combustion systems can better control combustion air yielding additional savings.

Electric resistance storage water heater. This system consists of a water heater consisting of a vertical or horizontal storage tank with one or more immersion heating elements. Thermostats controlling heating elements may be of the immersion or surface-mounted type. Electric resistance water heaters are not included in the ENERGY STAR rating system.

Electric resistance instantaneous water heater. This system consists of a compact under-cabinet or wall-mounted water heater with an insulated enclosure and minimal water storage capacity. A thermostat controls the heating element, which may be of the immersion or surface-mounted type. Instantaneous, point-of-use water heaters should provide water at a constant temperature regardless of input water temperature or flow rate.

> ***Caution:*** These electric resistance instantaneous water heaters can save energy for small loads, such as restroom sinks, but larger systems should be avoided, as they may add to electrical demand charges if they operate coincidently with the peak load of the rest of the building.

Heat pump electric water heater (climate zones: 1, 2, 3, 4, 5, 6). This system is a storage-type water heater using rejected heat from a heat pump as the heat source. Water storage is required because the heat pump is typically not sized for the instantaneous peak demand for service hot water. The heat source for the heat pump may be the interior air (within the kitchen is ideal because of the internal heat gain from cooking or a server room that needs spot cooling), which is beneficial in cooling-predominant climates; the circulating loop for a water-source heat pump (WSHP) system, also beneficial in cooling-dominated climates; or a ground-coupled hydronic loop. These types of water heaters should be considered for projects as alternatives to an electric resistance tank type water heater. Heat pump water heaters should have an energy factor of at least 2.2. Currently commercial (large heating capacity and/or storage capacity) heat pump water heaters are not included in the ENERGY STAR program.

Where electricity is the preferred energy source for SWH, consider specifying a heat pump water heater, meeting the ENERGY STAR criteria for residential heat pump water heaters, for additional energy savings. Products, now available using CO_2 as a refrigerant have demonstrated much higher COPs than systems using more common refrigerants, but even residential size versions of these products do not yet have an ENERGY STAR rating as the official test procedures for the products have not yet been finalized.

DESIGN STRATEGIES

WH3 *Properly Size Equipment*

The water heating system should be sized to meet the anticipated peak hot-water load. In a K–12 school, the hot water loads include, sinks and dishwashers in food service areas, and handwash sinks in bathrooms and special use areas, such as laboratories, workshops, or art studios. Calculate the demand for each water heater based on the fixture units served by the heater according to local code.

Hot-water temperature requirements for restrooms and academic areas of a school 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 provided at 100°F–110°F. Hot water is also a requirement in the school kitchen with a delivered temperature of 120°F–140°F. Use booster heaters on dishwashers to bring the temperature to the 180°F–190°F required for sanitation. Some facilities use chemical sanitizers, such as chlorine, in the final dishwasher rinse, allowing them to achieve proper sanitation with a water temperature of only 140°F. Note that production of service hot water at temperatures below approximately 135°F may result in bacterial growth in storage-type water heaters, so that 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 school and the associated life-cycle costs, consider installing instantaneous water heaters in most locations. Only in areas where large volumes of hot water are required (such as the cafeteria, and culinary vocational classrooms) should large water heaters or smaller circulating hot-water systems be installed.

WH4 *Equipment Efficiency*

Efficiency levels are provided in this guide for gas-fired instantaneous, gas-fired storage, electric resistance instantaneous, and electric resistance storage water heaters and electric heat pump water heaters. ENERGY STAR divides water heaters into residential and commercial classifications, and provides specifications for gas heaters and electric heat pump heaters. It no longer lists electric resistance heaters. Unfortunately, heat pump type water heaters are available only in larger tank sizes, and may not be appropriate for the small distributed end-uses.

The small tank-type water heaters recommended for small distributed end-uses, in WH4, are classified as residential water heaters, under previous the ENERGY STAR rating system, and are typically rated for the uniform energy factor (EF) that reflects the ratio of the heat added to the delivered hot water to the total thermal input to the heater over a prescribed schedule of hot-water delivery.

Commercial tank-type water heaters, suggested for central larger end-uses, and which will likely have a far different schedule of hot-water delivery, are currently rated by thermal efficiency Et and standby heat loss. Standby heat losses are dependent upon tank volume and configuration in addition to jacket insulation value and are typically established by a standardized testing procedure.

For commercial gas-fired storage water heaters, the standby loss criteria is given by the following equation:

$$\text{Standby loss (Btu/h)} \le 0.84 \cdot (\text{input rate [Btu/h]} / 800) + 110 \cdot \sqrt{\text{volume (gal)}}$$

For gas-fired instantaneous water heaters, the EF and Et levels are nearly the same because there are no standby losses. The incorporation of condensing technology is recommended for all gas-fired water heaters to achieve a minimum Et of 94%.

Table 5-24 gives performance requirements for residential and commercial gas-fired water heaters of various capacities and sizes.

The levels of performance specified in this guide for gas water heaters require that the units be of the condensing type, not only recovering more sensible heat from the products of combustion but also recovering heat by condensing moisture from these gases. The construction of a condensing water heater as well as the water heater venting must be compatible with the acidic nature of the condensate for safety reasons. Disposal of the condensate should be done in a manner compatible with local building codes.

Efficiency metrics for residential and commercial high-efficiency electric storage water heaters are also provided in this guide. These efficiency metrics represent premium products that have reduced standby losses, but that are no longer rated by ENERGY STAR. Table 5-25 summarizes required EFs for electric resistance water heaters and thermal efficiency and standby loss limits for commercial electric resistance water heaters, according to a previous version of the ENERGY STAR rating. Because these heaters are recommended only for distributed, small loads, performance ratings are given only for smaller size units. Standby losses for electric storage water heaters are calculated in the same way as for gas storage-type water heaters.

Electric instantaneous water heaters are a more efficient alternative to high-efficiency storage water heaters for very-low-volume distributed end uses because they have no tank losses. In addition, they can be located near the end use, minimizing pipe losses. However, their impact on building peak electric demand may be significant and should be taken into account during design. For some distributed end-uses, such as a bank of handwash sinks in a large restroom, an electric resistance heater with a small tank, (20 gal), would require a much smaller electrical service and would have a much lower potential peak electric demand than would providing an instantaneous electric resistance heater for each sink. In this case, an electric resistance heater with a small tank may be the most effective selection to minimize jacket losses and to avoid peak electric demand issues. Where unusually high hot-water loads (e.g., dishwashers) are present during periods of peak electrical use, electric heat-pump storage water heaters are recommended over electric instantaneous water heaters. Current ENERGY STAR standards require heat pumps for all electric water heaters. Table 5-26 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. For electric water heaters serving substantial water heating loads, this guide recommends using a product with the highest EF available for a competitive price.

Table 5-24 (WH4) Gas Water Heater Performance

Storage Volume, gal	Capacity, kBtu/h	UEF (Residential)	TE % (Commercial)	Standby Loss, Btu/h (Commercial)
0	Varies	0.87	0.94	N/A
55.0	70	0.68	N/A	N/A
55.1	75	0.80	N/A	N/A
140	75	N/A	0.94	1380

Table 5-25 (WH4) Electric Resistance Water Heater Performance

Storage Volume (gal)	EF (Residential)	Et, % (Commercial)	Standby Loss, %/h (Commercial)
0.0	.98	0.98	NA
30	.96	0.98	1.2
40	.96	0.98	0.98

Table 5-26 (WH4) Heat Pump Performance Requirements

Storage Volume, gal	UEF (Residential)
≤55	2.0
>55	2.16

WH5 Minimizing System Losses

School SWH requirements consist of low-volume distributed end uses, such as handwash sinks, and high-volume end uses such as food service areas. To achieve quick hot-water response, many SWH systems use a pumped return (recirculation) to ensure immediate hot-water delivery. For low- and moderate-volume end uses, the circulation heat loss through the piping may outweigh the actual energy consumption for producing the required hot water. The problem worsens as the distance increases between the hot-water generator and the loads. In addition, energy from the instantaneous system may be less than the circulation pump energy. Low flow sinks help justify the instantaneous system as well as the ability to use a one-pipe system rather than a three-pipe system for a circulation based water system and minimize system losses.

The primary water heater should be located close to the hot-water fixtures and hot-water-using equipment (e.g., dish machines or showers) to avoid the use of a hot-water return loop or of heat tracing on the hot-water supply piping. Potential locations for gas-fired water heaters may be limited by flue and combustion air and local code requirements.

Accommodation of renewable or free heat sources necessitate a centralized SWH system, typically with a tank to accommodate the asynchronicity of heat sources with hot-water demand. These systems should be located immediately adjacent to the end use to avoid recirculation and its attendant losses. If the provision of a centralized service water heater requires the use of a recirculation pump and hot-water return pipe to ensure prompt delivery of hot water at the end use, the supply and return pipes should be insulated as discussed in WH6. In most school applications, the recirculation pump should be controlled by a time clock to disable it when hot-water end use is not active. In addition, further pumping reductions can be achieved with a temperature sensor on the return loop.

An alternative is to incorporate a control strategy that operates the recirculation pump only when there is a need for hot water, otherwise known as demand circulation.

Low-volume end uses, including handwashing sinks, and implement-washing sinks in the food preparation areas likely do not justify service from a central source with required recirculation and should be served with point-of-use water heaters, either instantaneous, for single fixtures, or small tank-type heaters for groupings of fixtures. Note that even though janitorial closets are low-volume, the volume is large for a very short period of time to fill mop buckets. A small tank-type heater is effective in this application and often can be placed on a time-clock corresponding to the building cleaning schedule.

WH6 Pipe Insulation

All SWH piping should be installed in accordance with accepted industry standards. Required pipe insulation thickness varies with the temperature of the water, the size of the pipe, and the thermal resistance of the insulation material per Table 5-27

WH7 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 cafeterias, solar hot-water systems are often viewed as important strategies in meeting energy targets.

Table 5-27 (WH6) Minimum Piping Insulation Thicknesses for SWH Systems[1]

Fluid Operating Temperature Range, °F	Insulation Conductivity		Nominal Pipe Size		
	Conductivity, Btu·in./h·ft²·°F	Mean Rating Temperature, °F	< 1 in.	1 to < 1 1/2 in.	> 1 1/2 in.
141°F to 185°F	0.25 to 0.29	125	1.5	1.5	2.0
105°F to 140°F	0.22 to 0.28	100	1.0	1.0	1.5

1. Source: ANSI/ASHRAE/IES Standard 90.1-2016, Table 6.8.3-1
For insulation outside the stated conductivity range, the minimum thickness (T) shall be determined as follows: $T = r\{(1 + t/r)^{K/k} - 1\}$, where T = minimum insulation thickness (in.), r = actual outside radius of pipe (in.), t = insulation thickness listed in this table for applicable fluid temperature and pipe size, K = conductivity of alternate material at mean rating temperature indicated for the applicable fluid temperature (Btu·in./h·ft^2·°F), and k = the upper value of the conductivity range listed in this table for the applicable fluid temperature.

General suggestions for solar SWH systems include the following:

- It is typically not economical to design solar systems to satisfy the full annual service 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 ft^2 of collector heats about 1 gal per day of service 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 service water 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 service 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 service water heat.

Solar collectors for service 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.

WH8 Refrigerant Heat Recovery

A refrigerant-to-water tank-type heat exchanger can be installed between the host refrigeration system's compressor and condenser to recover heat for use in preheating service hot water. Incoming cold makeup water from the city supply is routed through the heat exchanger on its way to the primary service water heater. While in the heat exchanger tank, the hot compressed gas from the refrigeration condenser is cooled almost to its condensation temperature, transferring this heat to the water, hence the name desuperheater. The refrigeration condenser unit completes the process of condensing the hot gas and rejects this heat to the outdoor environment. Under typical conditions a desuperheater can remove 10% to 30% of the total heat that would have been rejected by the condenser.

As shown in Figure 5-43, the water path through the desuperheater is once through; there is no recirculation of water from the water heater back into the desuperheater tank.

A desuperheater reclaim system can be used with distributed point-of-use water heaters if a separate line for tempered water is run from the central desuperheater tank to each of the

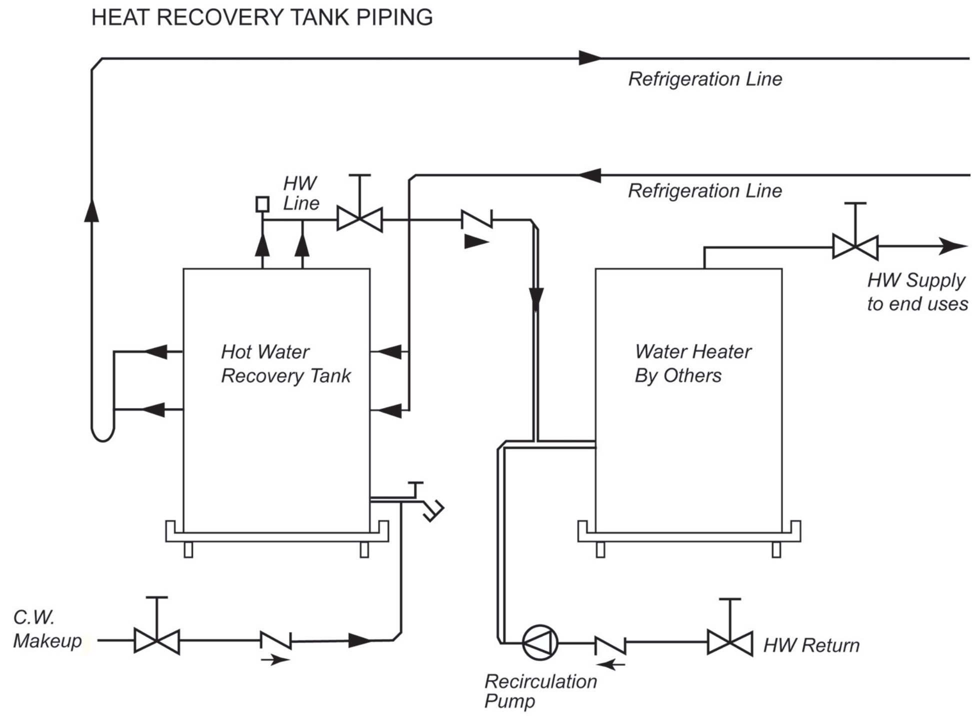

Figure 5-43 (WH8) Refrigerant superheat recovery tank piping for service hot-water preheat.

point-of-use water heaters. A recirculation line connected upstream of the point-of-use water heater could keep water temperature in the line close to the discharge temperature of the desuperheater tank. Heat losses from the tempered water line to the space would be substantially less than losses from a hot-water line from a central water heater to the remote end use.

REFERENCES AND RESOURCES

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HVAC SYSTEMS AND EQUIPMENT

OVERVIEW

The design challenge of a zero energy HVAC system is to maximize energy efficiency while providing indoor environmental quality. Reducing the energy requirements of the building minimizes the renewable energy required to achieve zero energy. Therefore strategies are needed to address energy consumption with respect to cooling generation, heating generation, air distribution fan energy, water recirculation pump energy and outdoor air ventilation energy.

Design strategies that optimize the energy performance will lead to reduced peak cooling and heating demands and downsized HVAC equipment. Benchmarks such as those EUIs provided in this guide should reflect the optimized design and include reduced cooling capacity, often measured in tons/ft^2, to cool the building, reduced heating capacity, often measured in Btu/h·ft^2 to heat the building and lower fan and pump, measured in W/ft^2, to distribute energy.

Sizing the HVAC system for the building load requirements will reduce the cost of the HVAC system. See HV21 for more information on rightsizing of HVAC equipment.

K–12 projects do not have an obvious occupancy schedule. While most school year calendars are approximately 180 days per year, school buildings are often used for more than class instruction. The scheduled occupancy for the remaining 185 days of the year are weekends, summer or other seasonal breaks, transition days between breaks, and holidays. Understanding the day/night occupancy patterns for each of these periods leads to a better modeled HVAC system, especially evening and nighttime needs. Building usage and occupancy patterns are discussed more in the setting project goals section of Chapter 3 and in BP8 in the building planning section of Chapter 5.

GENERAL STRATEGIES

HV1 Climate Zone Considerations

The climate zone will impact the energy reduction strategies that the design team pursues. Normally, design strategies will vary based on whether the climate zone is a heating- or cooling-dominated.

- For cooling climate zones, prioritize strategies that
  - reduce solar heat gain (BP10, EN46, EN48, DL5, DL8)
  - reduce plug load use (PL1-PL6)
  - reduce lighting loads (EL23-EL28), and
  - improve the cooling equipment efficiency.
- For heating climate zones, use strategies that generally favor more efficient thermal envelopes and heating systems (EN7, EN18–EN41) and the integration of solar thermal and thermal mass systems to improve performance (EN3 HV22, HV34).
- For dry climate zones, one option is to use alternative cooling systems to eliminate refrigerant and compressors and to include natural ventilation to reduce cooling energy (BP7, EN57, HV35).

Additional climate dependent strategies are discussed later in the chapter.

HV2 Other Considerations

Decentralized systems are a common theme in this chapter to reduce fan and pump energy; water or refrigerant is used to transport energy through the school in lieu of air. The specific heat for water or refrigerant is much higher than air allowing it to be distributed with less transport energy than can be accomplished with ducted air systems. All HVAC systems modeled use terminal HVAC units immediately adjacent to the thermal zones to provide the heating or cooling required to maintain room air temperature set point to minimize the amount and distance that air must travel.

A zero energy building uses energy recovery. There are many energy recovery strategies available. Many energy recovery strategies are climate-zone-dependent, dry-climate-dependent or dependent upon the diurnal swings of the local climate. Some energy recovery strategies are expensive, so ultimately a comparison must be made regarding the cost of saving energy through or generating more renewable energy to achieve the zero energy balance. Using an energy recovery wheel as part of a dedicated outdoor air system (DOAS) is one common example of energy recovery (see HV15–HV21).

Most zero energy buildings include roof-mounted solar panels because these have the cheapest installation first cost. Location of the mechanical equipment is important as the physical footprint of the mechanical equipment, along with required service clearances and shading, impact the design of a rooftop solar PV system As much mechanical equipment as possible should be located inside the building envelope to give preference to solar panels. This is important to identify at the beginning of the project design so adequate space can be planned during the schematic phases. See also BP17–BP23 and RE2–RE3.

Commissioning the HVAC system and thermal envelopes are critical as systems must operate as designed to achieve energy targets. With respect to the HVAC design engineer, commissioning these systems should give the design engineer the confidence that the HVAC system will operate and the thermal envelope will perform as intended. Commissioning the building envelope should involve a building pressure test to ensure air infiltration is minimized. Refer back to the quality assurance and commissioning section of Chapter 3 that covers commissioning during and post construction.

Measurement and verification (M&V) is another important phase to optimizing the HVAC system performance and should include submetering of the energy-consuming systems. No matter how well the building is commissioned and how well the occupancy schedules were coordinated, rarely will the building initially meet its energy performance goals. A M&V consultant is needed for zero energy projects and can be an architectural/engineering (A/E) team member or the commissioning agent. Trending the monthly actual energy consumption and comparing it to the modeled design energy will highlight the systems that require further commissioning or tweaking of the operation.

HV3 Systems Overview and Design Metrics

The guide includes three HVAC systems to show that the EUI targets can be achieved for a successful zero energy design:

- Chilled-/hot-water system with single-zone air-handling units (AHUs)
- Air-source variable-refrigerant-flow (VRF) multisplit heat pump system.
- Ground-source heat pump (GSHP) system.

All three systems are applicable to a wide range of climate zones.

These systems were modeled with a DOAS to provide a well-ventilated building while minimizing the amount of air that is moved. The metrics used in the modeling are shown in Table 5-28. These values may be used by designers and modelers as a starting point for zero energy projects.

Additionally all three of the selected systems can be designed to keep the air handling equipment and terminal units within the thermal envelope, an attribute to successful zero energy projects that reduces energy usage and helps maintain long-term performance.

CHILLED-/HOT-WATER SYSTEM WITH SINGLE-ZONE AIR-HANDLING UNITS

HV4 System Description

In this system, a separate air handling unit is used for each thermal zone. This could be a small AHU or fan-coil unit as long as there is one thermostat for each fan or fan array. The components are factory assembled and include filters, a fan, heating and cooling coils, controls, and possibly outdoor air (OA) and return air dampers.

AHUs are typically installed in each conditioned space, in the ceiling plenum above the corridor (or some other noncritical space), 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 AHUs are connected to a common water distribution system. Cooling is provided by a centralized water chiller. Heating is provided by a centralized boiler, heat recovery chiller or electric resistance heat (in warmer climates). In Climate Zones 1 and 2, where heating loads are low, the cost-effectiveness of a boiler heating system should be examined. It may be more cost effective to use heat recovery chillers or solar hot-water heating in lieu of a hot-water heating system because of the minimal heating requirements.

OA for ventilation is conditioned and delivered by a separate DOAS. This may involve ducting the OA directly to each fan-coil, delivering it in close proximity to the fan-coil intakes, or ducting it directly to the occupied spaces. Depending on the climate, the dedicated OA unit may include components to filter, cool, heat, dehumidify, and humidify the outdoor air.

Table 5-28 (HV3, HV5, HV13) HVAC System Recommendations

Water- and Ground-Source Heat Pumps with DOAS	
GSHP cooling efficiency[1]	18.0 EER at 59°F entering water
GSHP heating efficiency[1]	3.7 COP at 50°F entering water
WSHP cooling efficiency[1]	14.0 EER at 86°F entering water
WSHP heating efficiency[1]	4.6 COP at 68°F at entering water
Compressor capacity control	Multistage or VSD compressor
Water circulation pumps	VSD and National Electrical Manufacturers Association premium efficiency
Cooling tower/fluid cooler[2]	VSD on fans
Boiler efficiency[2]	Condensing boiler, 92% efficiency
VRF Heat Pump with DOAS	
Air-cooled VRF multisplit with heat recovery (cooling mode)[3]	Comply or exceed ASHRAE 189.1-2017 <65,000 Btu/h; 15.0 SEER; 12.5 EER ≥65,000 Btu/h and <135,000 Btu/h; 11.1 EER; 14.4 IEER ≥135,000 Btu/h and <240,000 Btu/h; 10.7 EER; 13.7 IEER <240,000 Btu/h; 10.1 EER; 12.5 IEER
Air-cooled VRF multisplit with heat recovery (heating mode)[3]	Comply or exceed ASHRAE 189.1-2017 <65,000 Btu/h; 8.5 HSPF ≥65,000 Btu/h and <135,000 Btu/h; 3.4 COP ≥135,000 Btu/h; 3.2 COP
Water-cooled VRF multisplit with heat recovery (cooling mode)[2]	Comply or exceed ASHRAE 189.1-2017 <65,000 Btu/h; 13.8 EER; 15.8 IEER ≥65,000 Btu/h and <135,000 Btu/h; 14.0 EER; 16.0 IEER ≥135,000 Btu/h and <240,000 Btu/h; 13.8 EER; 15.8 IEER <240,000 Btu/h; 11.2 EER; 13.8 IEER
Water-cooled VRF multisplit with heat recovery (heating mode)[2]	Comply or exceed ASHRAE 189.1-2017 <135,000 Btu/h; 4.6 COP ≥135,000 Btu/h 4.2 COP
Compressor capacity control	Multistage or VSD compressor
Chillers with Air Handlers and DOAS	
Air-cooled chiller efficiency[2]	Comply or exceed ASHRAE 189.1-2017 Path B ≥9.78 EER, and ≥ 15.8 IPLV
Water-cooled chiller efficiency[2]	Comply or exceed ASHRAE 189.1-2017 Path B
Compressor capacity control	Multistage or VSD compressor
Boiler efficiency	Condensing boiler, 92% efficiency
DOAS for all systems	
Exhaust air energy recovery in DOAS[2]	A (humid) and C (marine) zones: 72% enthalpy reduction B (dry) zone: 72% dry-bulb reduction
DOAS ventilation control	DCV with VSD

1. Certification in accordance with ISO Standards
2. For water-source heat pump and hybrid systems only
3. Certification in accordance with AHRI Standards

HV5 Chilled-Water Equipment

The cooling equipment, heating equipment, and fans should meet or exceed the efficiency levels in Table 5-28.

Chillers should include variable frequency 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.

Manvel Junior High School

School systems are encouraged to select the most appropriate HVAC system that meets their energy goals, is responsive to the regional climate, aligns with the owner's operational capabilities, and takes advantage of the various renewable energy opportunities. Manvel Junior High School is one example of a chilled/hot water system used to meet a school system's energy goals (See HV4 through HV6).

Manvel Junior High School, Manvel, TX
Photo reproduced with permission of Stantec Architecture

Manvel Junior High School is a located in the Alvin Independent School District south of Houston, Texas. It is a 168,000-ft^2, two story school. The HVAC system is VAV air handling units with a four pipe chilled water and hot water system. Room temperature is controlled via series fan powered terminal boxes. Outdoor air is ducted directly to each space from a variable flow DOAS system. The school is operating at 22.2 kBtu/ft^2·yr.

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 with sufficient efficiency and integrated controls may give the same or better energy performance as an air-cooled chiller. Schools considering water-cooled chillers should follow the ASHRAE GreenGuide (2018)

HV6 Variable Primary Flow

Variable-speed pumps in a chiller system offer significant operating costs savings as the pumps will be optimized to respond to the changing in load conditions. Chillers will need to be selected for the minimal flow requirement of the system plus large turn down on the water side to ensure continued performance at lower flow rates. To optimize pump energy savings, reset the differential pressure to maintain discharge air temperature at the terminal units or air handlers with at least one control value in a fully open condition. The will achieve flow to every unit while achieving pump savings at low load conditions (ASHRAE 2015a)

AIR-SOURCE VARIABLE-REFRIGERANT-FLOW MULTISPLIT HEAT PUMP

HV7 System Description

This system is composed of a fan-coil in each thermal zone with air-source heat pump and heat recovery units located outside the occupied space. It is also called a *variable-refrigerant flow* (VRF) system. This type of equipment is available in preestablished increments of capacity. The components are factory assembled and include a filter, fan, refrigerant to air heat exchanger, compressor, and controls. A system example is shown in Figure 5-44.

Attributes that distinguish VRF from other DX system types are multiple indoor units connected to a common outdoor unit to achieve scalability, variable capacity, distributed control and recovered heat simultaneous heating and cooling (ASHRAE 2016a, Chapter 18). The advantage is the ability to have individual zone control while also able to transfer energy from one indoor space to another using one energy source. For example, this would allow a school with one set of classrooms on the east side of the building with a morning cooling load caused by solar heat gain to provide cooling, while the west side of the building could be in heating. Using the heat recovery cycle, the air-source condenser may only need to run at a very low capacity to make up the difference in the balance or may not need to run at all.

Terminal units are typically installed in each conditioned space, in the ceiling plenum within the space. However, the equipment should be located to meet the acoustical goals of the space, permit access for maintenance, and minimize fan power, ducting, and wiring. Consideration should also be given to any future modifications to the space. Refrigerant piping supplying the terminal unit will need trained technicians to reroute should any space reconfigurations require HVAC changes.

OA for ventilation is conditioned and delivered by a separate DOAS. This may involve ducting the OA directly to each fan-coil, delivering it in close proximity to the fan-coil intakes, or ducting it directly to the occupied spaces. Depending on the climate, the dedicated OA unit may include components to filter, cool, heat, dehumidify, and/or humidify the outdoor air

HV8 Sizing Indoor with Outdoor Units

Outdoor units are sized based on the higher of the peak cooling or heating load. The consideration for supplemental heating will be needed in climate zones where the outdoor ambient heating design temperature is below –4°F and needs to be included in the sizing of the outdoor

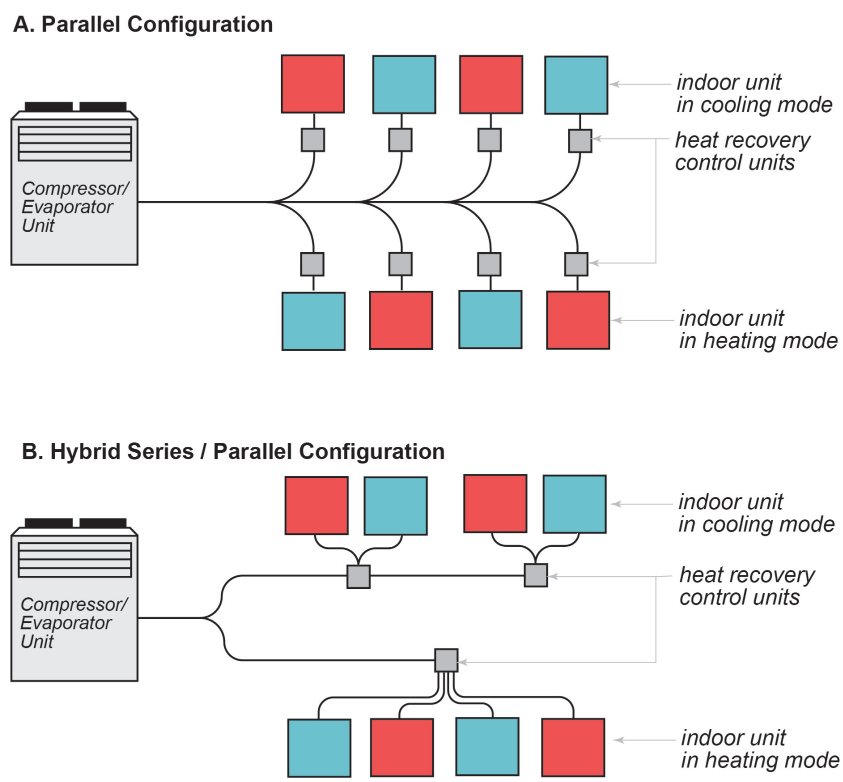

Figure 5-44 (HV7) Three-pipe heat recovery VRF system examples.
Figure 4 from Chapter 18.2 of *ASHRAE Handbook—HVAC Systems and Equipment* (2016a)

condenser systems. Derating of the outdoor systems also needs to be taken into account on both heating and cooling sizes (ASHRAE 2016a, Chapter 18). VSDs are highly recommended for at least one compressor on the outdoor unit. This will help with capacity control throughout the range of the equipment.

Select indoor units based on the design considerations for the space including sound considerations. Sizing for the indoor units takes into account the peak heating and cooling load in the space as well as the sensible to latent ratio. See HV15–HV21 for more information on DOAS systems. (ASHRAE 2016a, Chapter 18)

HV9 Refrigerant Safety

All systems need to comply with ANSI/ASHRAE Standard 15 to provide safeguards to protect occupants (ASHRAE 2016b). It will require 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 VRF system in the event of leak or failure. Typical small spaces that should be examined include bathrooms, electrical rooms, closets, small offices, and egress spaces. As the engineer of record reviews the refrigerant safety applications for the equipment, they may make considerations of layout, condenser type and efficiency to minimize the amount of refrigerant required for the space. If envelope loads (including solar gain) can be further reduced, this will reduce the refrigerant charge in these spaces, making them more attractive.

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. A permanent opening can be added from the smaller occupied space to an adjacent space that has a larger volume. See references for more information (Duda 2012).

HV10 Ambient Condition Considerations

In heating-dominated climate zones, it is important to note that the capacity of the outdoor air-source condensers is decreased in cooler temperatures. Condensers are rated at about 60% capacity at –4°F (ASHRAE 2016a). Thus, systems requiring heat below 40°F design ambient conditions may need to include design considerations for the low ambient conditions. This could include low ambient kits, 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 the low ambient conditions. Furthermore, climates with operating temperatures below 0°F need low ambient design considerations or a backup heating system. This would likely be electric resistance heating for simplicity of cost and controls. Low ambient design considerations should be implemented so as to not impact the cooling design conditions of the air source condenser. That is, the air-source condenser will need unrestricted airflow in cooling mode. All these considerations should be modeled to show the building meets the EUI targets to achieve a zero energy building.

During some temperature and humidity conditions, outdoor air-source condensers can accumulate frost. Defrost cycles are designed into most equipment and can reduce the hourly heating capacity. Without defrosting, the condenser will not have enough airflow over the condenser coil surface and will not perform as designed. Some systems upon sensing frost will reverse the refrigerant flow to heat the condenser for a period of time. Whether installing the system indoors or using a defrost cycle, considerations for heating during low ambient air conditions need to be a part of the design.

GROUND-SOURCE HEAT PUMP

HV11 System Description

A GSHP system consists of terminal GSHP units, an exterior ground-based heat exchanger with vertical bores or horizontal trenches to exchange energy to the ground and a water piping system connecting the GSHP units to this ground heat exchanger. An example of the construction of horizontal trenches is shown in Figure 5-45. Each thermal zone is provided with a separate GSHP terminal unit to provide zone cooling and heating. GSHP units are available in preestablished increments of capacity. The components are factory assembled and include a filter, variable-speed fan, refrigerant-to-air heat exchanger, variable-speed 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.

This system reduces air distribution fan power because it is distributed generation. Individual GSHPs are typically mounted in a closet next to the thermal zone, above the ceiling of the thermal zone's adjacent corridor or above the ceiling of another nearby noncritical space. (Locating the units in a closet increases first cost because of the added building space, but reduces life-cycle maintenance and replacement cost because the units can be more readily serviced.) The equipment should be located to meet the acoustical goals of the space.

The water piping loop allows energy to be transferred from the heat pump units to the ground. The ground-coupled heat exchanger takes advantage of the earth's relatively constant temperature to maintain the loop water between 40°F and 90°F. During the summer, the heat pumps extract heat from the building and transfer it to the ground. When the building requires heating, heat is transferred from the ground into the building. In a perfectly balanced system, the amount of heat stored over a given period of time would equal the amount of heat retrieved. A typical ground heat exchanger includes many vertical pipe bores, each 200 to 400 ft deep, and sometimes even greater depending on ground conditions and space considerations. Examples are shown in Figure 5-46. Multiple vertical pipe bores are circuited together with horizontal piping and typically ganged together in a piping vault. From the vault, supply and return pipe mains are routed to the building and the heat pumps

A GSHP system works in all climate zones; however, it is typically easier and less costly to install a ground loop in climate zones 2, 3, 4, 5, and 6, where the summer and winter loads are more closely balanced than in the other zones. If the annual heating loads are much larger than cooling loads, a high-performance thermal envelope and the use of energy recovery in the DOAS will reduce the building heating load, making a GSHP feasible. The DOAS system may also be provided with supplemental gas-fired heat to provide final tempering of the outdoor air. A GSHP is very efficient when operating in heating mode. If annual cooling loads dominate, as they would

Figure 5-45 (HV11) Geothermal field horizontal trenches.
Photo reprinted with permission of CMTA

in climate zone 1, and possibly in climate zones 2 or 3, a supplemental cooling tower can be added to balance the annual loads. Sometimes, annual load imbalances can be overcome by increasing the capacity of the ground heat exchangers, but unbalanced systems should be modeling using ground thermal simulation software to identify the potential for long-term thermal drift in the ground mass. Extending usage into climates with more unbalanced loads increases the complexity of the system.

A GSHP system offers several other advantages when compared to a conventional WSHP system. In most climate zones, the GSHP system eliminates the need for boiler/cooling tower installation and maintenance. The central plant is substantially reduced in size, which lowers building square footage and construction costs. (An integrated design team will often trade the central plant area reduction for heat pump closets throughout the school.) 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.

Outdoor air for ventilation is conditioned and delivered by a separate DOAS. See HV15 through HV20 on DOASs for additional information.

HV12 Equipment Efficiency

The heat pump unit efficiencies should meet or exceed the efficiency levels noted in Table 5-28. Efficiency levels listed for GSHPs are based on "ground loop" test conditions according to ASHRAE/ARI/ISO Standard 13256-1:1998 (R2012), Water-Source Heat Pumps—Testing and Rating for Performance (ASHRAE 2012a, 2012b).

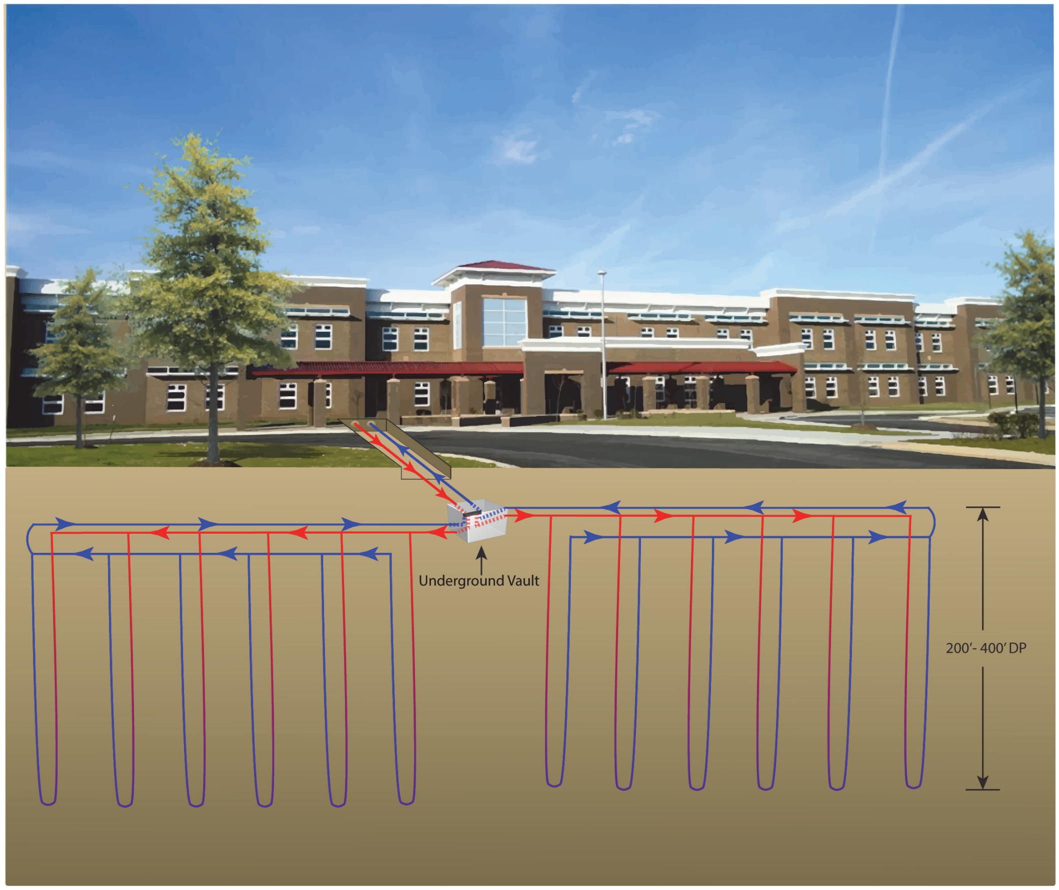

Figure 5-46 (HV11) GSHP vertical water loop illustration.
Photo reprinted with permission of CMTA

The heat pumps should be provided with variable-speed compressors and fans to increase part-load efficiency. During part-load conditions, these units operate at a higher efficiency. A typical school operates a majority of the occupied hours at part-load conditions and this equipment increases the overall system performance.

HV13 Water Piping and Pumping Strategies

Installed pumping power varies from 0.05 to 0.15 hp/ton of heat pump power. (ASHRAE 2015a, Chapter 34) The piping material, pipe sizing, water velocity, and water solution used will all affect the design efficiency. The piping system can be steel or various plastic materials. Maintaining clean water is important to avoid clogging the heat pump unit's refrigerant to water heat exchanger. A steel piping system will require chemical treatment to prohibit rusting. The water solution can be all water or include antifreeze. Many systems have water solutions without antifreeze, because water is more efficient to pump and has reduced life-cycle costs. The obvious drawback to a water only solution is freezing if the water loop temperature is not maintained. Piping designs should reduce the total system pressure drop below 46 ft total dynamic head (TDH) flowing 3 gpm/ton. See ASHRAE Handbook—HVAC Applications Handbook, Chapter 34 (ASHRAE 2015a).

Centrally pumped or distributed pumped are the most common pumping strategies. The centrally pumped system normally includes two variable-speed pumps operating in a lead/lag arrangement. For larger schools, three variable speed pumps, all sized for 50% capacity may be necessary, with two operating as lead pumps to avoid minimum water flow issues. Water flow is varied in response to system differential pressure. The heat pump units should be provided with modulating two-way water control valves that respond to load variations to decrease system water flow and save pumping energy.

A decentralized water pumping system eliminates the central pumps and uses a small inline water pumps 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. It also simplifies the variable-flow controls system.

HV14 Annual System Balance

Very few climate zones strike a perfect balance between heat rejected to the ground heat exchanger and heat absorbed from it. A properly designed ground heat exchanger can accommodate an imbalance between heat rejected and heat absorbed. However, in some climate zones, larger imbalances will exist and a hybrid system should be considered to ensure the ground heat exchanger does not deliver too-hot or too-cold loop water, impacting the operation of the heat pump units, and to minimize the cost of the ground loop system. For example, in a cooling-dominated climate (such as climate zones 1 or 2), a large amount of heat will be rejected to the ground during the cooling season and a smaller amount of heat will be extracted from the ground during the heating season. This imbalance can cause the temperature of the ground surrounding the ground heat exchanger to elevate and become too warm. Ground testing must be performed to ensure that the ground can absorb this amount of heat. For example, ground water flowing through the well field can help dissipate heat rejection.

DEDICATED OUTDOOR AIR SYSTEM (DOAS)

HV15 System Description

A DOAS—also known as *100% outdoor air system*—decouples the OA from the building HVAC systems. A DOAS unit includes supply and exhaust air fans, energy recovery, cooling and heating capabilities, and air filters. The DOAS system should be designed to dehumidify the outdoor air in the cooling months and preheat the OA in the winter months. The terminal HVAC equipment should be sized to meet the rooms sensible and latent cooling or heating

Figure 5-47 (HV15) DOAS unit with water coil.
Photo reprinted with permission of CMTA

requirements, plus any additional preconditioning of the outdoor air. Proper modeling can determine the balance between the load on the DOAS system and the terminal units to maximize energy efficiency.

A DOAS system simplifies the ASHRAE 62.1 calculations and allows for precise outdoor air delivery to each space. In a conventional HVAC system that serve multiple spaces, and outdoor air is introduced directly to the HVAC unit, the outdoor air must be designed to meet ASHRAE 62.1 (ASHRAE 2016c). This approach will often lead to some rooms being overventilated to ensure proper outdoor air is delivered to each space.

The DOAS system includes two ductwork systems, one to supply outdoor air to the thermal zones and the second to exhaust air from the thermal zones. While the air distribution system can be a constant-air volume or a variable-air volume, variable flow helps achieve energy targets. All building exhaust air is normally returned to the DOAS, including restroom exhaust. Special exhaust systems such as range hoods and fume hoods are ducted outdoors independently. The outdoor air should be ducted directly to the thermal zone and not to the terminal unit so that the ASHRAE 62.1 zone air distribution effectiveness is not adversely impacted. K–12 schools that have a second floor can improve the zone air distribution effectiveness by supplying the OA to the second level at the floor and exhausting from the ceiling.

Where possible the DOAS unit should be located within the building thermal envelope to maximize the available roof area for the solar system. Each of the three HVAC systems presented in this chapter leads to various DOAS configurations. For the fan-coil system, usually a 2-pipe or 4-pipe water coil arrangement will be used to match the configuration of the fan-coil units.

Figure 5-47 shows an example of a DOAS unit with a water coil. The VRF system will usually couple the DOAS unit with a refrigerant cooling coil, refrigerant reheat coil, and gas-fired heat exchanger.

HV16 Discharge Air Temperature (DAT) Control

The discharge air temperature supplied from the DOAS unit must always be cooler than room temperature so the zone air distribution effectiveness is not penalized. Several discharge air control strategies are common such as if cooling and dehumidification are controlled via dry-bulb temperature, enthalpy, or dew point. Each strategy will have an economizer mode that stops the energy wheel and any cooling/heating because of mild outdoor air conditions. To minimize fan energy, a bypass can be installed around the energy wheel for these conditions. When OA is below DAT set point, heating will be required. When OA conditions require cooling and dehumidification, DAT will be maintain via the water coil or DX refrigerant coil.

HV17 Avoid Overcooling the DOAS Supply Air Temperature

Zero energy schools require a greater level of energy scrutiny. It is tempting to supply the OA at 55°F so that all necessary moisture is removed at the DOAS unit. This control sequence has the potential to cause air to be reheated or have a resultant building humidity lower than necessary; either will increase energy usage.

A typical classroom will require approximately 400 cfm of OA, which may vary depending on physical size and occupancy. Delivering this quantity of OA at 55°F will overcool the room during many part-load conditions and the terminal equipment will reheat the zone to maintain room temperature.

All terminal units selected in this chapter will provide additional dehumidification. If all require OA moisture is removed at the DOAS, additional moisture will still be removed at the terminal units. The possible exception to this is the fan-coil units if a control strategy is implemented that maintains constant airflow and varies discharge air temperature.

HV18 Demand Control Ventilation

K–12 schools have spaces with varying occupancies throughout the day. While students are mostly in the classroom, they move throughout the day to the cafeteria, gymnasium, science, media center, etc. A variable-flow DOAS system tracks the student movements and delivers proper ventilation to each occupied space.

ASHRAE 62.1, paragraph 6.2.4 addresses DOAS systems and paragraph 6.2.7.1.1 allows dynamic reset for demand control ventilation systems (ASHRAE 2016c). Ventilation reset can be based upon CO_2, population counters, timers, occupancy schedules or occupancy sensors, of which CO_2 is the most common as a predictor of occupancy. Each thermal zone will require a variable-air-volume box that maintains the set point CO_2 ppm differential as compared to outdoor air.

Demand-control ventilation requires the DOAS unit's outdoor air and exhaust air fans to be variable speed. The supply air system maintains a constant static pressure in the outdoor air duct by modulating the fan speed. The OA airflow is approximately 5% higher than the exhaust air (EA) airflow. Any higher and system efficiency is reduced. The EA airflow is tracked to the OA airflow, less the 5%. It is important to maintain some level of exhaust from toilet rooms, pending local code review, if reduction from occupied levels are desired. This can be accomplished with multiple design strategies, but the most common is a separate sub-duct for the toilet rooms and a control damper is placed in the other exhaust duct, which modulates to maintain constant exhaust airflow from the toilet rooms.

To take full advantage of demand control ventilation, a single DOAS unit is preferred as it will serve all rooms with the varying occupant diversities with the ability to direct air to where it is needed. The DOAS unit is sized for the student population, staff and the average number of guest. This will result in a smaller DOAS system, compared with a multiple unit arrangement, saving first cost. On a high school project, a single unit may not be feasible due to building size, but proper selection of spaces served will still decreased the total capacity installed. Gyms may be treated separately as they often have highly variable loads, especially with sporting events where there are large numbers of visitors.

HV19 CO_2 Sensors

Accurate CO_2 sensing is imperative if it is to be used as a predictor of occupancy. Two approaches are often used, distributed sensors or a centralized sensing system. A distributive sensor approach places one CO_2 sensor in each thermal zone along with one outside the school for a baseline measurement. A preset differential between zone and outdoor air CO_2 ppm is established and air delivery to the zone is varied accordingly. All sensors should be wall mounted in the breathing zone. This is the lowest first-cost system, but the drawback to this approach is that there will be many sensors in the schools, all requiring routine recalibration to ensure accuracy. If they are not routinely recalibrated, energy usage may rise or indoor air quality may be reduced. Building sensor accuracy can vary widely (Fisk et al. 2010).

A centralized approach to CO_2 sensing involves a pneumatic air system to return classroom air to a remote panel with a single CO_2 sensor. The system is composed of air inlet stations, 1/4 pneumatic tubing, lab-quality CO_2 sensor, pneumatic actuators, and vacuum pump. Room air is returned to the control panel to be tested and compared to outdoor air parts per million (PPM). Depending on the measurement, the room air damper will open or close accordingly. Prior to sensing the next room, a purge cycle is executed before measuring the next zone's PPM. This system has just one sensor, so if the sensor begins to lose calibration, both indoor and outdoor readings have the same error and the differential is correct. One or multiple control panels may be necessary based on school size. The advantages of this approach is a more reliable system that reduces annual recalibration. The disadvantage is that it is more costly.

HV20 Energy Recovery Options

Because the outdoor air and exhaust air streams flow through the same unit, multiple heat recovery options are available to transfer energy between the two air streams. Energy recovery options available for DOAS systems include total energy wheels, dual-wheel systems, fixed plate heat exchangers, and heat pipes. Each of these energy recovery systems will reduce the energy to precondition the OA but have different first costs, may be more applicable for specific climate zones, and have varying levels of complexity. The most common energy recovery strategy for a DOAS unit is a total energy wheel that can recover approximately 70% of the latent and sensible energy. The wheel rotates and exchanges heat between the two air streams using a desiccant medium. (See Figure 5-48)

STRATEGIES FOR ALL SYSTEM TYPES

HV21 Rightsize Equipment

The key to rightsizing systems and equipment is the application of strategic factors that will impact the load calculation process, rather than the utilization of rule of thumb "safety factors". These strategic factors include the following:

- *Critical service requirement*, which refers to the selection of environmental design criteria that are input to the load calculation. These include both external and internal environmental conditions, ventilation rates and other variables. While normal HVAC sizing criteria use 2% conditions (conditions warmer than all but 2% of hours at the location) and 99% heating conditions (conditions colder than 99% of hours), certain functions may require different strategic factors. Outdoor air systems with energy recovery should be designed to 1% wet-bulb conditions to recognize actual dehumidification requirements.
- *Uncertainty factors* that should be applied to descriptive parameters for which some uncertainty exists. 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 estima-

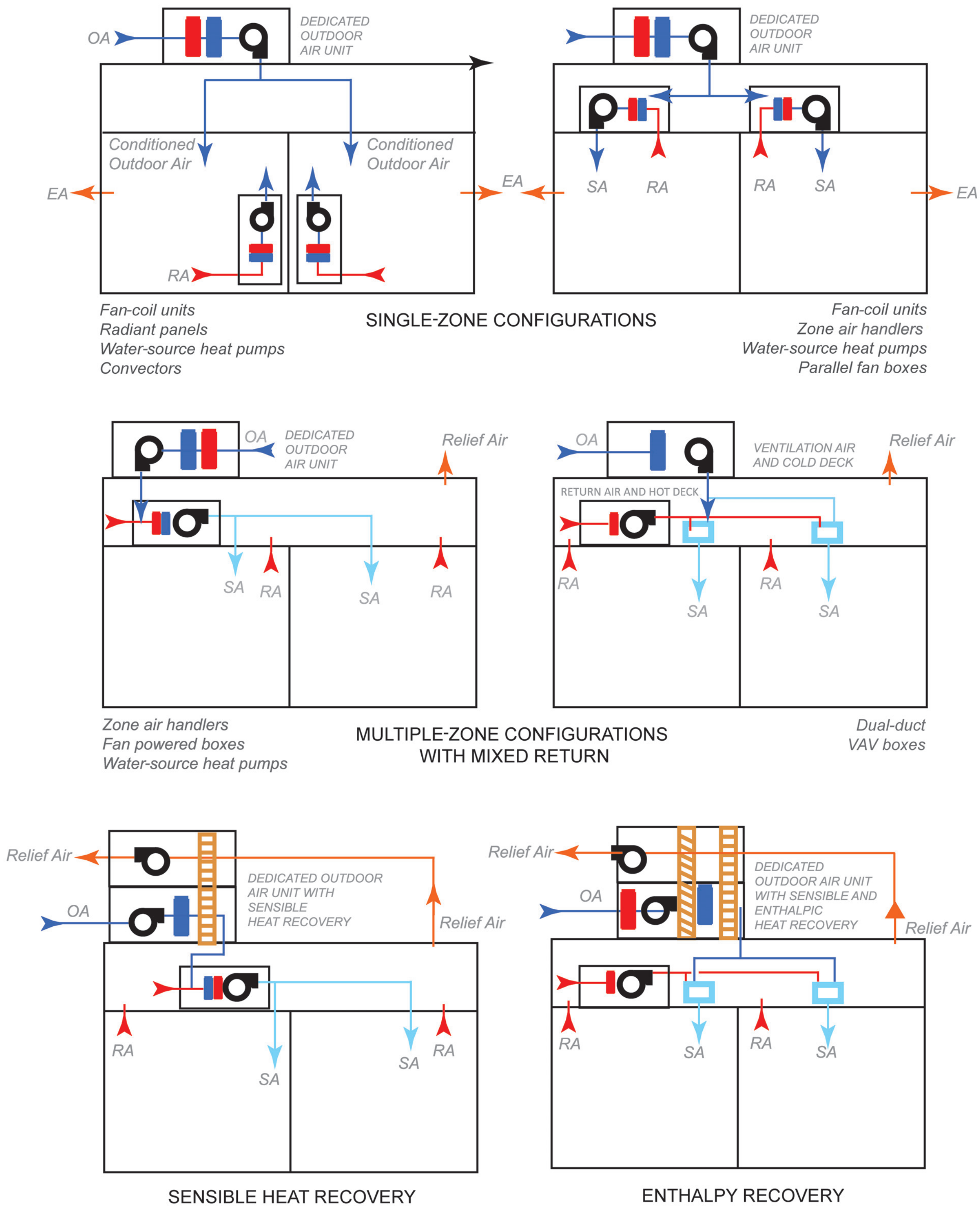

Figure 5-48 (HV20) Conventional series-connected heat recovery.

tions for future use and operation different form the initial program. They may also be applied to diversity assumptions described below. 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. For example envelope testing should minimize the uncertainty of the U-factor.

- *Diversity assumptions* that include both the spatial and temporal aspects of diversity. Diversity factors reduce the magnitude of overall loads because they establish the extent to which peak load component values are not applicable over the entire extent of the building operation. As an example, in an auditorium, either the hall or the lobby can have a certain maximum occupant density but they almost certainly will not have maximum occupancy simultaneously. Similarly, certain areas of a school library may have equipment power densities as high as 3 or 4 W/ft^2 but the entire building will not. Determination of these diversity factors is an exercise that should involve the architect, engineer, and owner. 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 resultant to 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 air handling units, and a 50% factor is used for sizing the chiller plant.
- *Redundancy factor* that 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 more, smaller units may furthermore increase part load operating efficiency. Once again, this factor is determined in concert with the entire project team, including the owner.

Safety factor multipliers should not be applied to calculations that use those parameters, because they then multiplicatively enlarge loads resulting from values for which the engineer has great confidence. Safety factors should also not be applied so that they expand previously applied safety factors. Applying safety factors at the end of calculations can also result in larger central equipment (e.g., chillers, boilers) but with no ability to deliver that capacity to conditioned spaces.

HV22 Thermal Zoning

The three 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.

In the modeled schools developed for this document, most of the thermal zones have exterior exposures and the requirement for zone cooling or heating is generally dictated by the outdoor air temperature and solar exposure. However, in many K–12 projects, large interior-only thermal zones are created that may require cooling when other zones require heating. If the interior zones are large enough, a separate DOAS systems should be considered to maximize energy efficiency.

Thermal zoning should also consider building usage during the unoccupied hours. Summer programs, evening adult education programs, and community events all may occur. It is important to identify the spaces that may typically be used for these events and arrange the building design so that they are isolated in one area. This will minimize the equipment they will have to operate and limit the DOAS unit ventilation air supplied during these periods. The schedules used for modeling the building should account for these uses and sizing of HVAC equipment should ensure that these partially occupied conditions can be efficiently serviced by the HVAC system.

Arranging similar occupancies on the same building exposure provides the design team with the option of using one terminal unit to serve two classrooms. Each classroom can be provided with a temperature sensor and the unit responds to the average condition. This design approach has been used by many school districts to reduce first cost and long term maintenance cost.

HV23 Filters

Another requirement of the HVAC system is to ensure that the air delivered to the conditioned space is relatively clean. This improves system performance (by keeping the coils cleaner, for example) and keeps the air distribution system relatively clean to ensure a healthy learning environment for the students and staff. Some of the contaminants that affect IAQ can be classified as particulates, gases, or biologicals. The methods and technologies for effectively controlling these contaminants differ, so it is important to define the contaminants of concern for a given facility.

Comply with at least the minimum requirements for particulate filtration and air cleaning de-fined by ANSI/ASHRAE Standard 62.1 (ASHRAE 2016c). For more information on using air cleaning to improve the indoor environment beyond minimum requirements, refer to *Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning* (ASHRAE 2009).

Use a filter differential pressure gage to monitor the pressure drop across the DOAS unit filters and send an alarm if the predetermined pressure drop is exceeded. (A pressure gage is not necessary across the filters on the terminals units such as heat pumps, VRF, and fan-coil units because accurate sensing is not possible.) Filters should be replaced when the pressure drop exceeds the filter manufacturer's recommendations for replacement or when visual inspection indicates the need for replacement. The gage should be checked and the filter should be visually inspected at least once every three months.

HV24 Transport Energy—Air

Fan motors should meet at least IE3 efficiency or NEMA Premium efficiency (NEMA 2016). ECMs may be an appropriate choice for many small units to increase efficiency.

Fan systems should meet or exceed the efficiency levels listed in this chapter. Depending on the HVAC system type, the efficiency level is expressed in terms of either a maximum power for supply air (W/cfm) (for systems where fan power is not included in the packaged HVAC unit efficiency calculation) or a maximum ESP loss (for packaged systems where fan power is included in the energy efficiency ratio calculation).

ECMs electronically control the voltage and current. They have a permanent magnet applied to the motor and a stator with electrical windings that generate a rotating magnetic field. As the rotor moves, it commutates the stator windings (i.e., switches phases of the magnetic poles (Roth et al. 2004). ECMs operate without slip-losses, as opposed to AC induction motors, and therefore are inherently more efficient. In addition, the electronic commutation provides a convenient means for speed control. Minimum full-load efficiency requirements for a PSC motor, per ANSI/ASHRAE/IES 90.1-2016 range from 65% to 85% depending upon motor size (ASHRAE 2016d). While the full-load efficiency of an ECM will range from 70%–90%. However, efficiency of a PSC motor drops dramatically in part-load conditions, often falling below 40%, while the efficiency of an ECM remains high. Market factors have driven cost and price down of these motors, and manufacturers now manufacture ECMs up to 15 hp. They are also more reliable, have an inherent soft start, and a longer motor life (Nall 2016).

HV25 Ductwork Design and Construction

Good duct design practices result in lower energy use. Low pressure loss and low air leakage in duct systems are critical to lowering the overall fan energy. Lowering the pressure needed to overcome dynamic pressure and friction losses will decrease the fan motor size and the needed fan energy. Refer to Chapter 21, Duct Design, of the 2017 *ASHRAE Handbook—Fundamentals* (ASHRAE 2017a) for detailed data and practices.

Dynamic losses result from flow disturbances, including changes in direction, duct-mounted equipment, and duct fittings or transitions. Designers should reevaluate fitting selection practices using the ASHRAE Duct Fitting Database (ASHRAE 2017b), a program that contains more than 220 fittings. For example, using a round, smooth radius elbow instead of a mitered elbow with turning vanes can often significantly lower the pressure loss. Elbows should not be placed directly at the outlet of the fan. To achieve low loss coefficients from fittings, the flow needs to be fully developed, which is not the case at the outlet of a fan. To minimize the system effect, straight duct should be placed between the fan outlet and the elbow.

Be sure to specify 45°F entry branch tees for both supply and return/exhaust junctions. The total angle of a reduction transition is recommended to be no more 45°. The total angle of an expansion transition is recommended to be 20° or less.

Poor fan performance is most commonly caused by improper outlet connections, nonuniform inlet flow, and swirl at the fan inlet. Look for ways to minimize the fan and duct system interface losses, referred to as system effect losses. Be sure the fan outlet fittings and transitions follow good duct design and low pressure loss practices. Project teams must address space requirements for good, low-pressure duct design in the early programming and schematic design phases. Allow enough space for low-pressure drop fittings and locate air-handling units that result in short, straight duct layouts. Avoid the use of close-coupled fittings.

The use of flexible duct should be limited because these ducts will use more fan energy than a metal duct system. Recent research has shown that flexible duct must be installed with less than 4% compression to achieve less than two times the pressure loss of equivalent-sized metal ductwork (Abushakra et al. 2004; Culp and Cantrill 2009). If the compression is more than 30%, the pressure loss can exceed nine times the pressure loss of metal ductwork. The loss coefficients for bends in flexible ductwork have a high variability from condition to condition, with no uniform trends (Abushakra et al. 2002). Loss coefficients ranged from a low of 0.87 to a high of 3.3 (for comparison purposes, a die-stamped elbow has a loss coefficient of 0.11). If a project team decides to use flexible duct, the following is advised:

- Limit the use of flexible duct to connections between duct branches and diffusers or VAV terminal units
- Flexible sections should not exceed 5 ft in length (fully stretched)
- Install the flexible duct without any radial compression (kinks)
- Do not use flexible duct in lieu of fittings

Where permissible, consider using plenum return systems with lower pressure loss. When using a plenum return system, design and construct the exterior walls to prevent uncontrolled infiltration of humid air from outdoors (Harriman et al. 2001).

HV26 Duct Insulation

Duct insulation should be installed to ensure conditioned air reaches the space with minimal losses as possible. In addition, all airstream surfaces should be resistant to mold growth and resist erosion, according to the requirements of ASHRAE Standard 62.1 (ASHRAE 2016c).

The following ductwork should be insulated:

- All supply air ductwork
- All outdoor air ductwork
- All exhaust and relief air ductwork between the motor-operated damper and penetration of the building exterior

For zero energy buildings, supply, exhaust and outdoor air ductwork should never be located outside the thermal envelope, in attics, crawl spaces or on the roof.

HV27 Ductwork Design

Low-energy-use ductwork design involves short, direct, and low-pressure-drop runs. The number of fittings should be minimized and should be designed with the least amount of turbulence produced. (In general, the first cost of a duct fitting is approximately the same as 12 ft of straight duct that is the same size as the upstream segment.) Excessive noise from ductwork airflow is a direct result of air turbulence. Round duct is preferred over rectangular duct because of sound considerations. However, space (height) restrictions may require flat oval ductwork to achieve the low-turbulence qualities of round ductwork. Alternately, two parallel round ducts may be used to supply the required airflow.

Air should be ducted through low-pressure ductwork with a system pressure classification of less than 2 in. w.c. Rigid ductwork is necessary to maintain low pressure loss and reduce fan energy. When a unit is serving multiple zones, supply air should be ducted to diffusers in each individual space.

In general, the following sizing criteria should be used for duct system components:

- Diffusers and registers, including balancing dampers, should be sized with a static pressure drop not to exceed 0.08 in. w.c.
- Oversized ductwork increases installed cost but reduces energy use due to lower pressure drop.
- Supply ductwork should be sized with a pressure drop no greater than 0.08 in. w.c. per 100 ft.
- Return ductwork should be sized with a pressure drop no greater than 0.04 in. w.c. per 100 ft.
- Exhaust ductwork should be sized with a pressure drop no greater than 0.05 in. w.c. per 100 ft.
- Flexible ductwork should be of the insulated type and should be
  - limited to connections between duct branches and diffusers or between duct branches,
  - limited to 5 ft (fully stretched length) or less,
  - installed without any kinks,
  - installed with a durable elbow support when used as an elbow, and
  - installed with no more than 15% compression from fully stretched length.
- Hanging straps, if used, need to use a saddle to avoid crimping the inside cross-sectional area. For ducts 12 in. or smaller in diameter, use a 3 in. saddle; those larger than 12 in. should use a 5 in. saddle.
- Long-radius elbows and 45° lateral take-offs should be used wherever possible. The angle of a reduction transition should be no more than 45° (if one side is used) or 22.5° (if two sides are used). The angle of expansion transitions should be no more than 15° (laminar air expands approximately 7°).

HV28 Duct Sealing and Leakage Testing and Balancing

The ductwork should be sealed in accordance with ANSI/ASHRAE/IES Standard 90.1. All duct joints should be inspected to ensure they are properly sealed and insulated, and the ductwork should be leak tested at the rated pressure. The leakage should not exceed the allowable cfm/100 ft^2 of duct area for the seal and leakage class of the system's air quantity apportioned to each section tested.

After the system has been installed, cleaned, and placed in operation, the system should be tested, adjusted, and balanced (TAB) in accordance with ASHRAE Standard 111 (ASHRAE 2017c) or SMACNA's TAB manual (SMACNA 2002).

This will help to ensure that the correctly sized diffusers, registers, and grilles have been installed, that each space receives the required airflow, and that the fans meet the intended performance. The balancing subcontractor should certify that the instruments used in the measurement have been calibrated within 12 months before use. A written report should be submitted for inclusion in the operations and maintenance (O&M) manuals.

HV29 *System Level Control Strategies*

Control strategies can be designed to help reduce energy. Having a setback temperature for unoccupied periods during the heating season or a setup temperature during the cooling season can help save energy by avoiding the need to operate heating, cooling, and ventilation equipment. A good design approach is to equip each zone with a zone temperature sensor and then use a system-level controller that coordinates the operation of all components of the system. This system-level controller contains time-of-day schedules that define when different areas of the building are expected to be unoccupied. During these times, the system is shut off and the temperature is allowed to drift away from the occupied set point.

Optimal start uses a system-level controller to determine the length of time required to bring each zone from the current temperature to the occupied set point temperature. The controller waits as long as possible before starting the system so that the temperature in each zone reaches the occupied set point just in time for occupancy. This strategy reduces the number of hours that the system needs to operate and saves energy by avoiding the need to maintain the indoor temperature at the occupied set point when the building is unoccupied. Controlling energy usage outside of normal operating hours is most successful when the usage culture can be change. Refer to Chapters 2 and 3 for more information on achieving culture change.

Control systems should include the following:

- Control sequences that easily can be understood and commissioned.
- Use of the room motion sensor to setback temperatures during the occupied period when no usage is occurring in the room. Also many times a room may be scheduled ON during the unoccupied period for a function. The room motion sensor will again insure the unit only operates when the room is occupied.
- A user interface that facilitates understanding and editing of building operating parameters and schedules.
- Optimal start systems as a means to limit demand during start-up so the peak demand is not inadvertently set during start-up.
- Sensors that are appropriately selected for range of sensitivity and ease of calibration
- Means to effectively convey the current status of systems operation and of exceptional conditions (faults)
- Means to record and convey history of operations, conditions, and efficiencies
- Means to facilitate diagnosis of equipment and systems failures
- Means to document preventive maintenance

HV30 *Noise Control*

The modeled HVAC systems rely mostly on distributive generation instead of airflow being centrally generated. A distributed generation system normally has fans that operate at low static pressures, and thus noise is not as significant an issue. Some of these systems have integral compressors so acoustical consideration of this noise generated must be considered.

Some areas of the school are larger zones such as the gymnasium, cafeteria, or media center and thus may have larger air-handling equipment. Acoustical requirements may necessitate attenuation of the supply and return air, but the impact on fan energy consumption also should be considered and, if possible, compensated with other duct or fan components. Acoustical

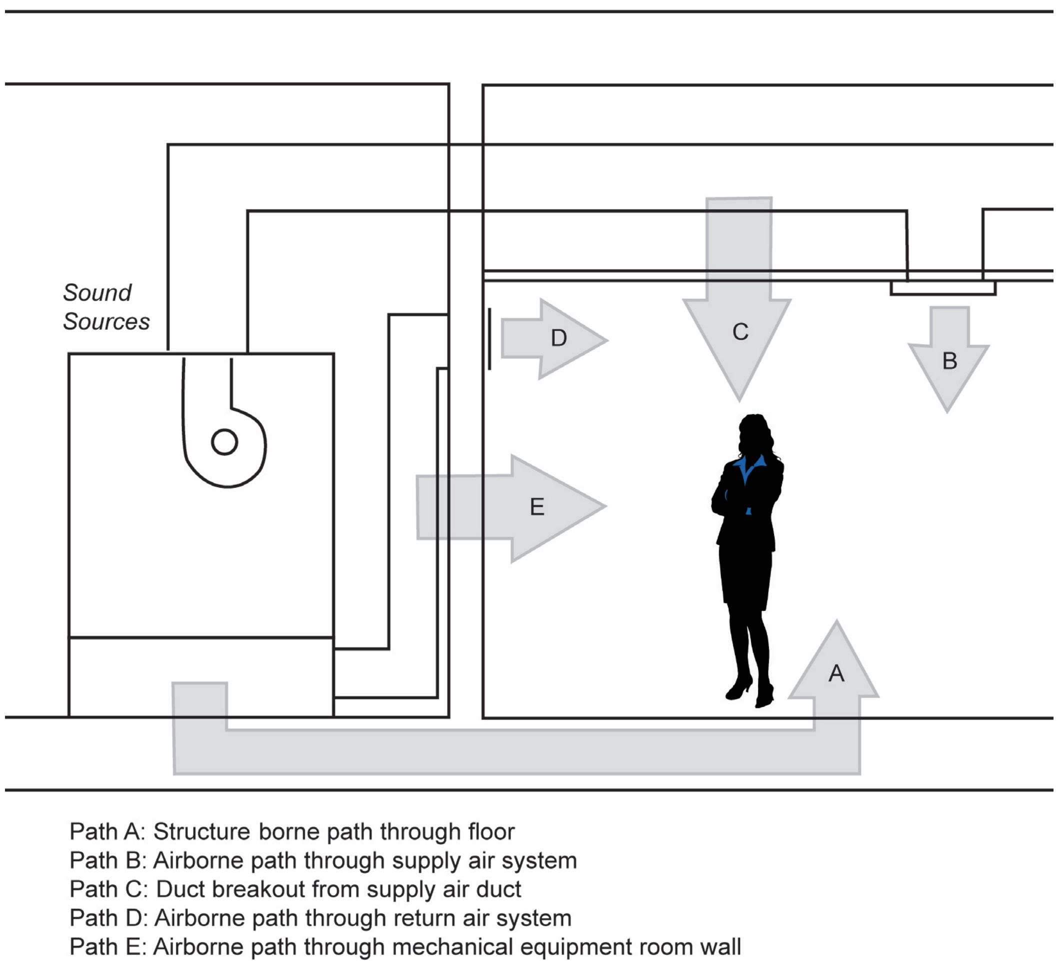

Figure 5-49 (HV30) Typical noise paths for interior-mounted HVAC units.

concerns may be particularly critical in short, direct runs of ductwork between the fan and supply or return outlet.

When equipment is located near spaces with noise level criteria, special care must be taken to address all equipment noise sources and sound paths into the space. The typical path of concern for equipment located nearby or adjacent to a space is shown in Figure 5-49.

HV31 Certification of HVAC Equipment

Rating and certification by industry organizations is available for various types of HVAC equipment. In general, certification is provided by industry-wide bodies that develop specific procedures to test the equipment to verify performance; ANSI/ASHRAE/IES 90.1-2016 (ASHRAE 2016d) has requirements for units for which certification programs exist. Certifications that incorporate published testing procedures and transparency of results are much more reliable for predicting actual performance than are certifications that are less transparent. For types of equipment for which certification is available, preference should be given to certified products. Examples of equipment types that have recognized certifications include packaged heat pumps, chillers, gas furnaces and boilers, and water heaters.

For products for which certification is not available, or those that have not been subjected to certification available for their type of equipment, the products should be rigorously researched for performance claims made by the supplier. The project team should determine the procedure for developing performance data and establish any limitations or differentials between the testing procedure and the actual use.

HV32 Transport Energy—Water

Hydronic systems should be designed for variable flow and be capable of reducing pump flow rates to 30% or less of the design flow rate. Care should be taken to maintain the minimum flow through each chiller, as defined by the chiller manufacturer.

Piping should be sized to comply with the pipe sizing limitations listed in Table 6.5.4.5 of ANSI/ASHRAE/IES 90.1-2016 (ASHRAE 2016d). Using a smaller pipe size increases the pressure drop through the pipe, increases the velocity through the pipe, and may cause erosion if the velocity is too high. A larger pipe size results in additional pump energy savings, but increases the installed cost of the pipe. In systems that operate for long hours, larger pipe sizes are often very economical.

Energy use and installed costs are typically both reduced by selecting chilled water (CHW) ΔT of 12°F to 20°F rather than the traditional 10°F (ASHRAE 2014). This will save pumping energy, permit the reduction of pipe sizes (reducing installation cost), and minimize pump heat added to the water because of the use of reduced pump power, but it will also affect cooling coil performance. This can be overcome by lowering the chilled-water temperature to deliver the same air conditions leaving the coil. Chilled water temperature set points should be selected based on a life-cycle analysis of pump energy, fan energy, and desired air conditions leaving the coil.

HV33 Boilers

Space-heating water boilers. All gas-fired boilers specified for space heating should be condensing with a minimum efficiency of 90% at 125°F return hot-water temperature. Zone heat transfer equipment should be sized based on 140°F entering hot-water temperature and as large a temperature drop through the air heating coil as possible. Boilers should be operated with a maximum leaving hot-water temperature of 140°F and should incorporate a leaving hot-water temperature reset control based on total heating load.

Condensing boilers. This boiler type can operate at up to 90% efficiency and most models operate at higher efficiency at part load. To achieve higher efficiency levels, condensing boilers require that return water temperatures be maintained below 120°F. Designers should compare boiler efficiency curves, as some condensing boilers do not have high efficiencies until the return water temperatures are very low, while others can be above 90% efficient at low fire with 150°F return water.

High-efficiency boilers. These boilers fit well with hydronic systems that are designed with ΔTs greater than 20°F often ranging between 30°F to 40°F. Higher ΔTs also allow smaller piping and smaller pumps, which reduce first costs. It also reduces pumping costs. Because condensing boilers work efficiently at part load, VSDs can be used on the pumps to further reduce energy use.

HV34 Thermal Mass

The thermal mass of the building structure can be incorporated into the building conditioning system in several ways both to improve comfort and to reduce energy consumption. Thermal mass generally tends to mitigate temperature swings that might result from a mismatch between conditioning level and thermal loads at any specific time. 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 set the impact of later conditions that might drive the space temperature in the opposite direction. The perfect example of such storage is the impact of a massive exterior wall on the building internal temperature, when the diurnal exterior temperature oscillates across the comfort band. 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.

Thermal mass as part of the building envelope or internal to the building. The example just given is of thermal mass in the building envelope. The thermal mass is part of the envelope that separates the building interior environment from the ambient external environment. External mass will, in effect, “average” the impact of ambient external conditions on the interior environment. In effect, it will reduce the peak conditioning demand on the space, but may amplify the minimum conditioning demand. This strategy is most effective when the ambient diurnal temperature traverses the comfort zone.

Internal thermal mass is mass that is entirely contained within the building envelope. To “exercise” the thermal mass or 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 air temperature must 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 any event, if the ambient diurnal temperature cycle does not traverse the temperature of the internal cycle, thermal mass will have little effect on the daily heat transfer across the building envelope and little effect on total conditioning required.

Exceptions to this statement are passive solar heating systems in which shortwave 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 will also exchange heat through longwave 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 thermal discomfort that can result from direct solar penetration into the space and visual discomfort that can result from direct solar glare.

Thermal mass can significantly improve thermal comfort, however, in spaces that have significant swings in 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.

Active versus passive thermal mass. Passive thermal mass is thermal mass whose temperature is driven by convective or radiant interaction with the air or the sun. Heat transfer into or out of the mass is not under active control, and is usually driven by variation in air temperature or radiant flux. Exploitation of internal thermal mass, therefore, usually requires a larger variation of internal air temperature than the variation of temperature in the thermal mass.

Active thermal mass on the other hand, can be used to moderate interior air temperature variations. Typically, the active thermal mass is charged or discharged with embedded hydronic tubes or air passages. Conditioning fluid is passed through these conduits to control the temperature of the thermal mass independently of the air temperature. Examples of active thermal mass elements include floor slabs, ceiling slabs, and even the entire internal horizontal structures of buildings. The thermal mass can dampen significant variations in thermal loads, resulting in less variation of comfort conditions. Thermal mass can be precooled before the start of the day to mitigate daytime cooling requirements. Conditioning to the thermal mass can be terminated before the end of the day and thermal mass will maintain space conditions until the end of the operating period. Using natural ventilation at night to precool building spaces for daytime use is discussed in HV18. Active thermal mass can be used as the primary vehicle to maintain the heat balance of a space and constrain internal temperatures within the comfort range. Note that active thermal mass neither ventilates nor, hopefully, dehumidifies, so air systems are required to provide these two functions of the building environmental system. The heating and cooling sources for active thermal mass may require a significantly lower deviation from the average interior temperature because of the extensive surface area available of the massive element. 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, temperatures that can be generated much more efficiently than conventional heating and cooling sources.

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 and solar heat gain.

HV35 Employ Natural Ventilation where Appropriate

Natural ventilation and natural conditioning should be recognized as separate, but related functions. Ventilation is a code regulated function, providing specific rates of outdoor airflow to specific occupancies and specific populations. Conditioning is the maintenance of thermal conditions, but, in most circumstances, is not a regulated activity. While both of these activities usually occur together, it is quite possible, and sometimes desirable, to have natural conditioning in concert with mechanical ventilation, to insure that all space occupants have adequate ventilation.

Natural ventilation through operable windows, skylights, and operable vents in the building envelope can be a very effective energy conservation strategy. Clearly, excess outdoor air inflow to the building, when exterior conditionings are inopportune, increases building energy consumption. On the other hand, deenergizing the building conditioning system when exterior conditions can be used to maintain interior comfort requirements can result in significant energy savings.

The mechanical system can use interlocks on operable fenestration to ensure that the HVAC system responds by shutting down in the affected zone if the window is opened. The fenestration interlock zones need to be designed to correspond as closely as possible to the HVAC zone affected by the opening.

Sensors are often used for security to indicate when windows are open. These same sensors can be linked with the buildings energy management system so that it knows which classrooms or spaces have fenestration open. If the HVAC system has the capability to separately control each classroom, the HVAC system can be disabled when a unit is open. Light signals have also been successfully used to indicate when outdoor conditions are suitable for natural ventilation. A green light comes on when conditions are suitable and fenestration should be opened. When the fenestration units are open, the HVAC system is disabled. A red light comes on to indicate when they should be closed because of high outdoor temperatures or humidity. Opening and closing is the responsibility of the teacher or students, but operation of the HVAC system is constrained by the position of the fenestration openings.

The recognized limitations of ambient conditions to maintain interior comfort requirements, with operable windows, are a upper dry-bulb temperature limit of 68°F, and a lower temperature limit of 48°F, Ambient temperatures higher than this limit cannot provide adequate cooling, especially to spaces significantly inside the building envelope, while temperatures below the limit result in diminished comfort conditions adjacent to the window. Another consideration of natural conditioning is the humidity content of the ambient air. The system should limit natural ventilation to below 62°F dew point to maintain a comfortable interior relative humidity.

If natural ventilation is being considered as a strategy for reducing energy consumption and providing a better learning environment for the student, it is recommended that the school design be modeled using a CFD program. To successfully integrate this strategy, building orientation should align with prevailing wind patterns. (This may conflict with the best daylighting orientation.) Air inlet and outlet openings should be positioned to promote airflow through the rooms. The design team will usually model several architectural design approaches to maximize thermal comfort in the zone. Figure 5-50 is an example of CFD modeling for a classroom environment. See BP7 for additional information on optimizing the building for natural ventilation.

Natural conditioning can be used in schools in concert with interior thermal mass to reduce daytime cooling needs. If the overnight dry-bulb temperature falls below 60°F, the building can be "flushed" overnight to cool the internal thermal mass and the resulting cooling will be "stored" to reduce daytime cooling needs. The designer should recognize, however, that just as there is internal thermal mass, there is also internal moisture mass. The porous materials in the space, including carpets, fabrics, paper, and unsealed wood have the ability to absorb moisture from humid air and slowly release that moisture when exposed to less humid air. In humid climates, overnight low dry-bulb temperatures may be coincident with very high relative humidity, so that overnight flushing may purge the building of sensible heat while charging it with moisture that will later appear as latent load for the air conditioning system. In dry climates, overnight flushing in concert with thermal mass can result in significant energy savings.

Natural ventilation has less cooling capacity than mechanical cooling and it is therefore even more important to design carefully to limit internal and envelope loads. Use of natural conditioning may also be limited by unusually poor outdoor air quality or high degrees of outside noise. Natural ventilation works best when the building owner and occupants are well educated about what to expect about the building performance and are willing to become an active and integral part of the building operation.

HV36 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. The CxA should provide a fresh perspective that allows identification of issues and opportunities to improve the quality of the construction documents and verify the owner's project requirements (OPR) are 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 few of the mechanical and electrical systems in a new facility are "plug and play." Functional test procedures are often written in response to the contractor's

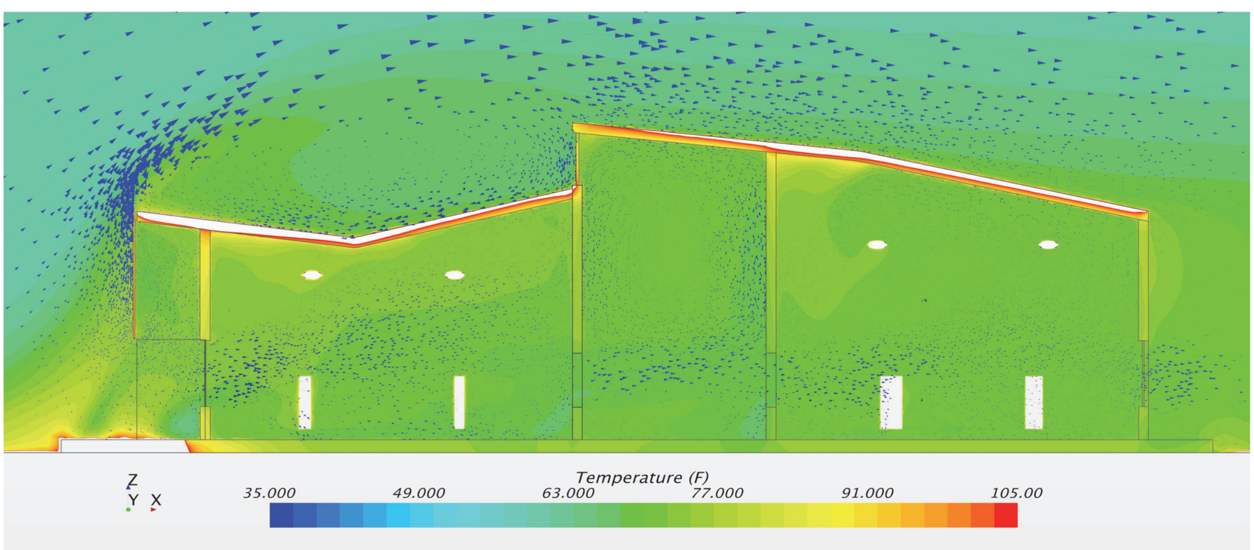

Figure 5-50 (HV35) CFD model for a classroom.
Graphic reprinted with permission of CMTA

detailed sequence of operations. The CxA 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 possible, 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 CxA issues in the issues log have been resolved except for minor issues the owner is comfortable with resolving during the warranty period.

HV37 Employ Proper Maintenance

Continued performance and control of O&M costs require a maintenance program. The O&M manuals provide information that the O&M staff uses to develop this program. Detailed O&M system manual and training requirements are defined in the OPR and executed by the project team to ensure the O&M staff has the tools and skills necessary. The CxA/QA provider 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 zero energy schools are realized when systems perform as intended through proper design, construction, operation, and maintenance.

Extended transition to operations (ETOP) is a management system that automatically produces work orders in accordance with manufacturer recommendations. HVAC equipment that is properly maintained is more likely to continue to perform at the intended energy efficiency. The service requirements for all equipment is entered into a software program that generates the work orders. Additionally all equipment is tagged so that service personnel can electronically access O&M manuals, installation manuals and parts list while performing the maintenance.

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RENEWABLE ENERGY

OVERVIEW

The cost of renewable energy has dropped rapidly in the last decade driven by declining costs of wind and solar. For most building owners, photovoltaic (PV) is a highly versatile renewable energy source and for many has provided the capability for buildings to become zero energy. For purposes of this guide, PV systems will be considered as the primary renewable energy source for getting to a zero energy building. While some small scale wind, micro-hydro, and biomass is available, it is fairly limited. Schools should evaluate whether these sources are economically viable in their area.

Since 2010, the cost of PV power generation has dropped more than half as prices of PV panels and systems equipment have seen prices decrease due to worldwide implementation and manufacturing improvements (Fu et al. 2016). Solar energy is increasing geometrically. In 2016 the installed capacity is in excess of 300 GW having increased 75 GW in the previous year (IEA 2016). The bottom line is that school districts that have not looked at PV in the last year should revisit, as the costs are dropping dramatically.

Other renewable energy systems, such as biomass, 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 design guide.

COMMON TERMINOLOGY

PV systems are made up of an array of PV modules that use sunlight to produce electricity. This electricity is generated as direct current (DC) and must be converted to alternating current (AC) and synchronized with the local utility grid in order to be used in commercial power applications like a school building. PV power generation systems are flexible, and 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, energy storage devices, maximum power point trackers (included in many inverters), disconnecting and combining equipment, mounting hardware, metering, and monitoring. A diagram of a typical PV AC system is shown in Figure 5-51.

RE1 Definitions

Understanding common terms from the renewable energy field is useful when discussing the use of renewable energy for a zero energy school.

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 non-renewable.

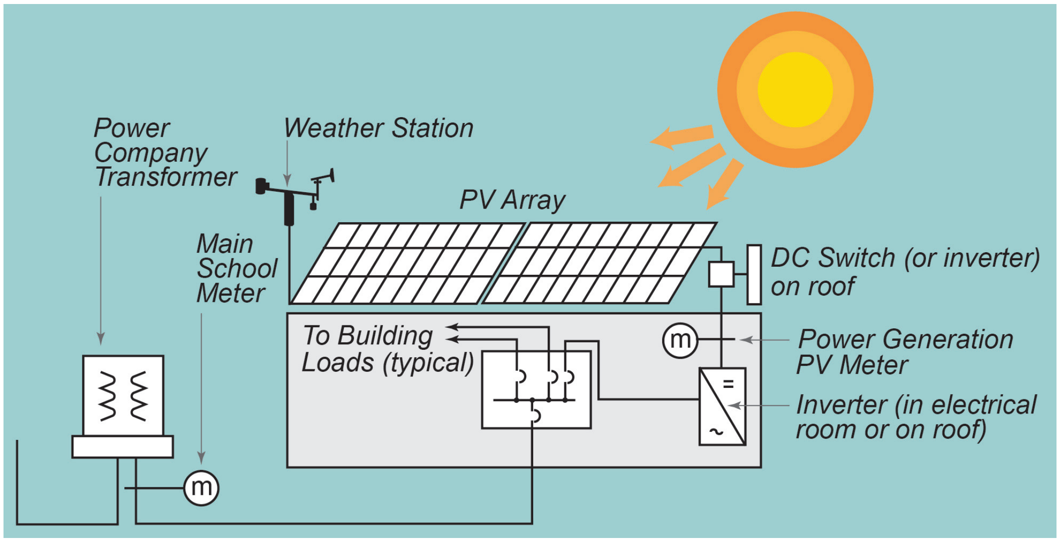

Figure 5-51 Typical PV alternating current system diagram.

Photovoltaic (PV) refers to a type of energy production that uses light to directly generate electricity. PV power is generally produced through the use of sunlight striking a semiconductor material like the chips used in electronics, to produce a direct current across the junction in the semi-conductor. More can be found about PV panels and materials used in creating PV panels at the NASA Science webpage: https://science.nasa.gov/science-news/science-at-nasa/2002/solarcells.

Stand-alone PV systems are those PV systems that are not intended to operate in parallel with a utility grid, and typically are used for small applications in conjunction with battery storage. These are not applicable for school or commercial PV systems.

Interactive or grid-tied PV systems are those that operate in parallel with the alternating current utility grid, whether directly to a utility transformer to back feed directly into the grid, or where interconnected to the facility main switchboard or panelboard in order to offset power consumption in the facility. Interactive PV systems must be synchronized with the grid voltage and phase to ensure that issues of flicker, harmonic distortion, frequency and voltage fluctuations do not occur. The PV system is required to be disconnected from the grid whenever voltage, frequency do not meet utility requirements for stability, or when there are utility power outages and/or grid disturbances.

Wind power is the production of electricity from wind and is considered a renewable source. More information can be found about wind power production at the DOE office of Energy Efficiency and Renewable Energy website under Energy Basics: https://energy.gov/eere/wind/wind-energy-technologies-office.

Energy storage is a device with the capability of storing energy such as batteries.

"Net" metering is where the PV power generated is used to offset power consumption at the facility Net metering allows excess energy to be stored in the form of credits that are then used to balance electricity pulled from the utility grid. For most applications net-metered PV systems are sized to match the consumption of the building (or less) such that excess energy is not produced on an annual basis. For the school to claim the renewable attributes of the PV system, the school must retain the RECs.

"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 electricity certificates*, *green tags*, or *tradable renewable certificates*. These certificates allow a mechanism to purchase renewable energy to and from the electricity grid and documents that 1 MWh of electricity has been generated by a renewable energy source and fed into a shared electric grid that transports electricity to customers. Also known as *SRECs* when solar energy is the source of the renewable energy power generation.

Solar renewable energy certificates are those specifically generated by solar energy.

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 foundations and steel supports that hold the PV panels in place and keep them from wind-driven uplift forces. 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 to install 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. A small, ground-mounted demonstration PV system is useful for educational purposes when the majority of the PV system is on the roof or in a nonvisible location. Note that all electrical components should be enclosed by a grounded, protective fence.

DESIGN STRATEGIES

RE2 System Design Considerations

PV panels are specified with two distinct guarantees: performance and product manufacturing. Performance guarantees are for a power output performance over time. The panel will degrade 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. Manufacturing warranties are usually for a period of one to five years and cover manufacturing defects, not performance. Tier 1 panels should be specified.

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 and height
- Remote shut down from building fire alarm system and by code officials in order to disconnect all power in and on the building.
- Type of roof, flat or standing seam metal roof
- Additional architectural or structural engineering associated with mounting of PV panels on roof
- Location of inverters on roof or in utility yard
- Removal of trees to eliminate shading

Solar-ready design is rooted in determining the optimal placement of potential future solar technology. See BP17–BP23 for additional information regarding how building orientation, roof form, and shading considerations affect system design.

RE3 System Sizing

Determine the size of the PV system needed to achieve zero energy use status. Sizing should be based on the projected energy consumption of the building. An additional allowance should be made if batteries are included to account for their inefficiencies. Size PV systems based on the orientation, solar irradiance and shading studies of the site.

Consider the use of metering separate from the inverter meter. Separate utility grade electricity meters are generally more accurate and easier to calibrate than internal inverter meters. An external metering system is an important part of the overall monitoring and measurement and verification system for the school.

Ideally, a PV system should be sized slightly larger than the predicted loads. In many cases, shadows are not fully accounted for and buildings use more energy than estimates.

RE4 Energy Storage (Batteries)

Battery storage can be an effective means to reduce peak demand charges. However, the use of battery storage is not an effective renewable energy generation source as batteries require energy to recharge daily and after every discharge. Life expectancy of current technologies (lithium ion) is about 10 years or less, depending on number of discharges. Flow batteries will soon be commercially available with an even longer life of more than 1000 discharges.

The use of energy storage is currently at a 20-year payback period and will definitely trend downwards over the next ten years. Until the payback period reaches less than ten years, battery storage may not be financially desirable from an energy production standpoint.

RE5 Mounting Options

Once the size of the renewable energy system is determined, the school site can be evaluated for PV panels. Determining if there is adequate space for the PV modules and equipment is the next most important consideration after sizing considerations. (See also BP19 and BP20.) PV panels may be used as shading devices or building integrated as roof material and power production. The PV system can be mounted a number of different ways on the school property. Examples of different mounting options are shown in Figures 5-52 and 5-53.

The most used location is on the roof of the school buildings. An example of this mounting option from the Richard J. Lee Elementary school is shown in Figure 5-52. Roof-mounted PV systems are typically used for the larger systems necessary to complete the zero energy equation, as roof areas are large spaces that are not being used for other purposes. At the time of building construction, minimizing the amount of non-solar rooftop equipment will maximize the available area for installing a solar PV system in the future. See BP19–BP20 for information on determining and maximizing the required roof area for PV installation (Pickerel 2016).

Also important is determining whether the roof installation carries a warranty, and if the warranty includes contract terms involving solar installations.

The type of roof system used can affect the cost of solar installations. To host a solar PV system, a roof must be able to support the weight of PV equipment and the system should be mounted so as to minimize the impacts of wind loads and maintain solar access. One reason that flat roof PV systems are only tilted at 10 degrees is to minimize wind loading on the roof and PV system. It also minimizes the shading of the PV panels on other PV panels. See BP21–BP23 for more information on roof durability and maintaining solar access.

Covering parking areas may provide another location for siting PV systems in schools. In addition in hot sunny climates, parking canopies created by PV panels can serve a dual purpose of shading cars, which reduces fuel consumption from air-conditioning, and power generation (Figure 5-53).

Ground-mounted PV systems are seen in larger PV power generation systems but are only an option where the site can provide adequate real estate without jeopardizing other functions such as athletic fields and parking. PV systems require considerable space for panels and equipment. A rough rule of thumb is 2.5 acres for a 500 kW system, depending on shading factors, module efficiency, location, and orientation.

Additionally, assessing the potential PV system size and corresponding energy production output can inform building design and result in optimized system sizing at a later date.

Figure 5-52 (RE5) Roof-mounted PV system.
Photo reproduced by permission of Stantec

Figure 5-53 (RE5) PV canopy-mounted PV system.
Photo by Dennis Schroeder, NREL Image 48750

NREL's PV Watts and System Advisor Model (SAM) are online, interactive tools that can be used to explore system sizing and output potential (NREL n.d., NREL 2010).

When establishing the location for the PV panel arrays, shading must be considered. Shading studies take into account obstructions from trees, adjacent buildings, towers, power lines, or even rooftop HVAC equipment or antennas. Minimal shading at all times is best, but essential during the middle day peak generation period. The arrays should be oriented for peak solar energy harvesting. See also BP17.

RE6 *Interconnection Considerations*

PV systems for commercial use fall into two categories: sell all, where the energy produced is connected to a utility grid and sold to a utility company, i.e., not consumed at the site; and net metered, where the energy produced is consumed at the site and any excess is not compensated by the utility company. Both system types are metered to determine the amount of renewable energy produced. With a sell all system, excess energy produced during a grid failure must be controlled. Inverters should be programmed to limit power output to the school demand energy use during times of grid failure.

The interconnection point is where the renewable energy system connects to the commercial power system. For a sell all system this is at the utility transformer, either a dedicated one or the same utility transformer used for the school service. When contemplating a sell all PV system for a zero net energy school, involve the utility company early, as soon as the system size is known. The transformer size for the school service will need to be increased to accept the PV power generated on site and if not addressed in the planning stages, can result in a too small transformer being installed. The larger transformer may also impact fault currents and impedance on the schools electrical power distribution systems. If the school site is using a net metered system, the point of interconnection is usually made at the main switchboard for the school. The switchboard will need to be upsized in order 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 school demand load and PV load, plus 20%.

Standoff mounting is often used for slant roof-top mounted solar systems. These 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 pounds per square foot; however, they can be designed to coincide with the roof structure. Be cautious that the thermal integrity of the roof is not compromised with the PV system.

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. 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 10° to minimize uplift. 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. Roofs may require fall protection railings for roof mounted equipment. Access to the roof should be more than a vertical ladder with roof hatch. Full walk-up stair access should be provided.

Roof mounted systems should be planned around the replacement of the panels at 25-year life, and for the roof replacement. The roof selection should be made with consideration that 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.

Rack mounting for panels are typically used for ground mounted systems that do not use tracking. Rack mounting is not common on smaller projects and is commonly used for large utility scale generation projects over 1MW.

A discussion of wind turbines as a renewable energy system are not included in this guide. While in Kansas, Iowa, South Dakota, Oklahoma, Nebraska, and parts of Texas wind power generates a significant portion of electricity produced—more than 20% of power production in some cases (Jossi 2017)—these are utility-grade turbines beyond the capabilities of most school systems to maintain. Wind turbines large enough to produce power for a zero energy school are inappropriate for school properties in urban and suburban areas.

RE7 Net Metering Options

With a net metered, grid connected system, PV power is produced and used by the facility first, before the facility imports energy from the utility grid, and before the facility exports PV energy to the grid. Net metering or net energy metering (NEM), allows owners of PV power generation systems to "send" that energy when it is generated, for "use" at a later date. A typical PV single line diagram is shown in Figure 5-54. The diagram illustrates a net metered system. For example, if you have a PV system that generates power during the day in excess of your load, then you may send the excess power in the form of credits that can be applied in the future. Often the credits, if they remain after a 12-month period, are converted to a monetary credit according to the utility rate tariff.

Annual net metering allows power credits that are generated and exported during weekend or summer months when a school is lightly loaded, to be used during the school year and when the building is fully engaged. Net metering uses a bidirectional meter that measures power flowing in two directions—from the PV power generation system to the utility grid, and from the utility grid to the customer's electrical load. For a zero energy elementary or high school of the sizes being modeled for this design guide, PV systems might range in size from 600 kW DC to 1000 kW DC. With systems this large, utility fault current and impedance studies are commonly required to minimize negative impacts to the grid. With battery storage systems, the inverter or charge controller will regulate the battery charging during the day when PV power is being produced. In addition, the inverter must disconnect any electrical panel boards that have PV or battery inputs from the utility for stand-alone operation much like an emergency generator system.

Check with the latest public utility commission, state laws, and utility rules governing renewable energy systems in your jurisdiction for the current status of net metering policies. PV system sizes affect application fees and sometimes, utility rates. PV systems will be larger for extreme climate zones and possibly fall into a different regulatory category. Implementation of PV systems and net metering are highly location specific across the US. Utilities may be concerned about the effect of PV system inverters on the grid, which may act to destabilize the grid from the intermittent nature of renewable power generation. The issue of flicker in power grids connected to PV systems comes from rapidly moving clouds across PV panels, which results in uncontrolled power generation. Inverters are increasingly being required to limit excess energy exported to the grid, and to shut down under unstable conditions.

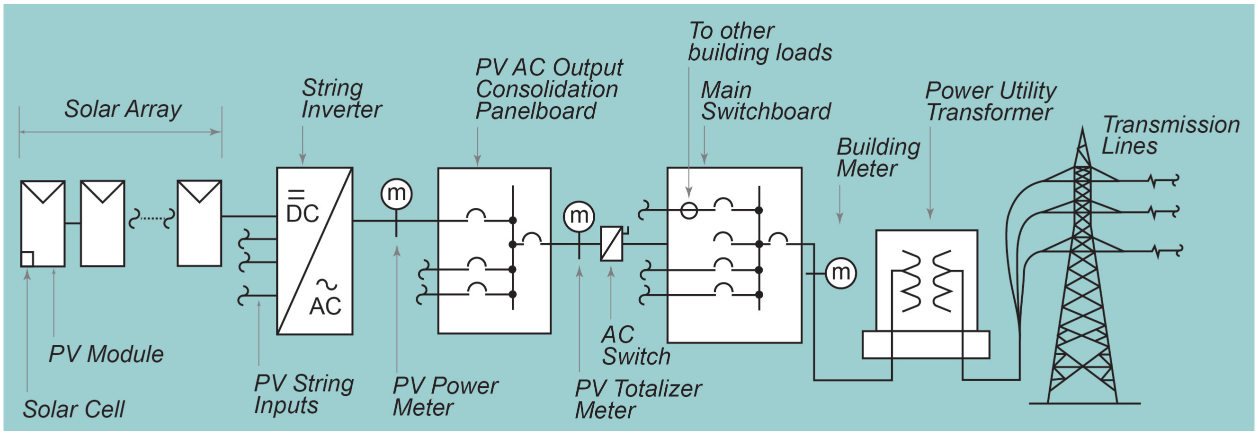

Figure 5-54 (RE7) Typical PV single-line diagram.

RE8 Utility Considerations

Coordinate with the local utility company and the school district to determine the proposed contract demand for the project. This will be based on the design team's load calculation for the school from the energy model with all loads considered, such as HVAC, lighting, plug, kitchen, IT, and exterior lighting.

Initiate discussion with the local utility company as soon as the decision is made to build a zero energy school to understand the grid connection and public utilities 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 if 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:

- With a zero energy school, 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 school building's utility transformer?
- What will the utility pay for excess power exported to the grid?
- How will having a PV system affect the school's electricity rate?
- When do they require the filing of a report on the planned construction with their distribution department?

It is important to get answers in writing. Staff change, PUC rules and regulations 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.

RE9 Utility Rates

Questions to ask regarding utility rates include the following:

- What is the rate type: time of use, flat rate, peak demand charges, uninterruptible, or interruptible rate?
- 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 summer and winter? Time of day?
- Is there a minimum contract kWh 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

RE10 Purchasing Options

Determine whether to purchase the PV system outright or to enter into a power purchase a agreement (PPA) with a solar developer, who will furnish, install, and maintain the PV system for you under a lease or lease purchase agreement.

Caution: If you go with a lease or purchase agreement, remember to maintain ownership of the renewable energy certificates (RECs).

Determine school system maintenance staff capabilities and current and projected maintenance work load for providing ongoing maintenance for the PV system. Consider contracting with the PV installer for an ongoing maintenance contract. Decide if you want to include a Performance Bond 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.

RE11 Purchasing the System

Write the technical specs and request for proposal (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 the one available from the Solar Energy Industry Association (SEIA 2017).

Negotiate and bid the system, including doing homework on the warranty and guarantee offered, the PV products, the technologies, the 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:

- Are they accredited with electrical contracting license in your state, with adequate liability insurance?
- Do they have workers compensation insurance and are they Occupational Safety and Health Administration (OHSA) 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?
- Is the system performance estimates included for daily, weekly, monthly, and annually?
- Are they members of industry associations?
- How many similarly sized systems have they installed?
- Are they experienced in working with your local utility company?
- Will any of the work be subcontracted to another firm?
- What specific equipment are they proposing for your project?
- Does it 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?

RE12 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 for PV systems
- Safety considerations for wind turbines

- 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 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 of a typical school
    - Solar irradiance
    - Weather station
    - Carbon reduction for school
    - Impact on natural environment
    - Carbon trading for students
    - 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
    - School owned
    - Private-public partnerships
    - Bidding methods
    - Included with construction documents
    - Included as stand-alone contract
    - Bid with construction versus as post building completion

RE13 Commissioning the System

Once the system is installed, provide independent commissioning of the PV system to verify performance, grounding, over current protection, and overall functionality. Perform a reconciliation of predicted energy production versus actual 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 PV system to peak operating performance.

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FRIENDS SCHOOL OF PORTLAND

CLIMATE ZONE 6A

EUI
11.7

Cumberland, ME

Independent School District

Built on undeveloped land outside of the city, the Friends School was designed for both zero energy operation and Passivhaus certification. These goals were inspired by the Quaker values of simplicity and stewardship.

Because it was financed through a capital campaign and a mortgage, the project had a hard cost cap, which required careful oversight by the project team. An integrated design approach was used with each decision analyzed against its impact on energy use.

Compromises were made for the low cost, including a kitchenette in place of a full-service kitchen. And rather than building both a meeting room and a gymnasium, the gymnasium construction was deferred until phase 2. However, other features were incorporated that had nothing to do with energy, such as the custom-milled white pine used as benches in the meeting room and the undulating ceiling in that same room.

Perhaps the most successful outcome of the project is low total cost to operate the building. In the first year, that cost was only $0.82/ft^2. Small changes are expected to lower that cost even further.

For more information about this school, visit the U.S. DOE Commercial Buildings Resource Database: https://buildingdata.energy.gov/cbrd/search/resources/k12casestudy.

Friends School of Portland.

Construction of meeting room.

Photos courtesy of ncob photo

Project Data	Building Envelope
Site area: 21 acres	Roof type: Ventilated truss
Conditioned gross area: 15,000 ft^2	Overall R-value: R-91
No. of floors: 2	Wall construction: Wood frame
Grade levels: Pre-K–8th grade	Insulation type: Dense packed cellulose (framed cavities) and 4 in. polyisocyanurate.
Occupancy: Standard	Overall R-value: R-47
Context: Rural	Foundation insulation R-value: R-28
No. of students: 125	Sub slab insulation R-value: R-48
Year completed: 2010	Window type: Triple glazed
Financing model: Capital campaign and mortgage	Window assembly U-factor: 0.15
PV financing: Purchase power agreement	Solar heat gain coefficient: 0.62
Construction cost: $196/ft^2	Airtightness: 0.32 ACH50
Total cost: $37,750,000	
Energy Data	**Project Team**
Predicted EUI: 9.45 kBtu/ft^2·yr	Architect: Kaplan Thomson Architects
Predicted RE: 8.88 kBtu/ft^2·yr	Engineers: Allied Engineering Company, Casco Bam Engineering, Bartlett Engineering, Blais Civil Engineers
Predicted net EUI: 9.6 kBtu/ft^2·yr	Contractor: Warren Construction Group
Actual EUI: 11.72 kBtu/ft^2·yr	***Note:*** *ACH50 = air changes per hour at 50 Pa pressure*
Actual RE: 2.05 kBtu/ft^2·yr	
Actual net EUI: 3.67 kBtu/ft^2·yr	
Certifications: Passivhaus	
Building Systems	
HVAC systems: Mini-split air-source heat pumps	
Ventilation: Operable windows and energy recovery ventilation	
RE type and size: 36 kW PV system	

Appendix A—Envelope Thermal Performance Factor

A

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 2017), and expanded U-factor, C-factor, and F-factor tables are presented in Appendix A of ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2016).

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.

Table A-1 Opaque Construction Options

Roof Assemblies	
Insulation Above Deck	
R	*U*
20 c.i.	0.048
25 c.i.	0.039
30 c.i.	0.032
35 c.i.	0.028
40 c.i.	0.025

Metal Building	
19 +10 FC	0.041
19 +11 Ls	0.037
25 + 8 Ls	0.037
25 + 11 Ls	0.031
30 +11 Ls	0.029
25+11+11 Ls	0.026

Walls, Above Grade	
Steel Framed	
R	*U*
7.6 c.i.	0.123
15.2 c.i.	0.071
13 + 7.5 c.i.	0.064
13 + 8.0 c.i.	0.062
13 + 10.0 c.i.	0.052
13 + 12.0 c.i.	0.047
13 + 18.8 c.i.	0.035

Metal Building	
13	0.124
16 + 6.5 c.i.	0.077
16 + 9.8 c.i	0.062
30	0.052
25 + 10	0.047
25 + 13 c.i.	0.035

Mass Walls	
7.6 c.i.	0.123
15.0 c.i.	0.076
19.6 c.i.	0.062
20.0 c.i.	0.060
28.0 c.i.	0.046
39.2 c.i.	0.034

Slabs	
R-in (Vertical)	*F*
Unheated	
0	0.73
15 - 36	0.480
30 - 54	0.400

Heated—Fully Insulated	
7.5	0.64
15	0.44
20	0.373

Note: All information in this appendix is in Inch-Pound (I-P) units. For slabs, the "in." refers to the depth of the vertical slab edge insulation. See ANSI/ASHRAE/IES Standard 90.1 for additional explanation. All units used in the table are defined in the Abbreviations and Acronyms of the guide.

c.i. = continuous insulation
F = slab edge heat loss coefficient per foot of perimeter, Btu/h·ft°F
FC = filled cavity
Ls = liner system
R = thermal resistance, h·ft^2·°F/Btu
R-in = R-value followed by the depth of insulation in inches
U = thermal transmittance, Btu/h·ft^2·°F

Appendix B— International Climatic Zone Definitions

B

The following tables show the climate zone definitions that are applicable to any location. The information is from ANSI/ASHRAE Standard 169-2013, A3 Climate Zone Definitions. Weather data is needed in order to use the climate zone definitions for a particular city.

Table B-1 International Climate Zone Definitions

CZ	Name	Thermal Criteria
0	Extremely hot	10,800 < CDD50°F
1	Very hot	9000 < CDD50°F ≤ 10,800
2	Hot	6300 < CDD50°F ≤ 9000
3	Warm	CDD50°F ≤ 6300 and HDD65°F ≤ 3600
4	Mixed	CDD50°F ≤ 6300 and 3600 < HDD65°F ≤ 5400
5	Cool	CDD50°F ≤ 6300 and 5400 < HDD65°F ≤ 7200
6	Cold	7200 < HDD65°F ≤ 9000
7	Very cold	9000 < HDD65°F ≤ 12600
8	Subarctic/arctic	12600 < HDD65°F

CDD50°F = Cooling degree-day to a base temperature of 50°F
HDD50°F = Heating degree-day to a base temperature of 50°F

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 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 (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
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, °F
Summer or high sign period	=	April through September in the Northern Hemisphere and October through March in the Southern Hemisphere.
Winter or cold season	=	October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.

Humid (A) Definition—Locations That are Not Marine (C) and Not Dry (B)

Appendix B

Advanced Energy Design Guide for K–12 School Buildings Achieving Zero Energy

This guide was prepared under ASHRAE Special Project 139.

Advanced Energy Design Guide for Zero Energy K-12 Schools—Achieving Zero Energy is the first in a series of guides for achieving zero energy and is tailored to the design and creation of zero energy schools. It builds on the popular 50% design guide series with new and updated recommendations on energy efficiency along with guidance about on-site renewable energy sources. The Guide establishes a set of energy performance goals for achieving zero energy. The goals are provided for all ASHRAE climate zones, in both site and source energy.

Strategies on how to achieve these energy targets are provided throughout the guide and include setting measurable goals, hiring design teams committed to that goal, using simulation throughout the design and construction process, and being aware of how process decisions affect energy usage.

As in previous guides, the how-to tips address specific project aspects—building and site planning, envelope, daylighting, electric lighting, plug loads, kitchens and food service, water heating, HVAC, and renewable energy generation. Each section contains multiple tips that move the design incrementally toward the zero energy goal.

Finally, case studies and technical examples show how the energy goals are achievable at typical construction budgets as well as demonstrate the technologies in real-world applications.

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