ZERO ENERGY

ACHIEVING ZERO ENERGY

Advanced Energy Design Guide for Multifamily Buildings



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

Advanced Energy Design Guide for Multifamily 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

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

This Guide was primarily written by the six committee members of ASHRAE Special Project 143 (SP-143) representing ASHRAE, The American Institute of Architects (AIA), Illuminating Engineering Society (IES), U.S. Green Building Council (USGBC), and the U.S. Department of Energy (DOE).

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The project committee's efforts were guided by the AEDG Steering Committee under the leadership of Presidential Member Tom Phoenix. It consists of members from the AEDG partnering organizations (ASHRAE, AIA, IES, USGBC) with support from DOE. These members provided the direction and guidance to complete the Guide and assembled a team of top-notch experts willing to work together to produce this Guide. And while this book took longer to produce as a result of complications created by the pandemic, the steering committee kept the committee focused during unusual circumstances and were a source of constant encouragement during the process. A special mention is due Brendan Owens, formerly with USGBC, for his many years of contribution, support, and encouragement as part of the AEDG Steering Committee and for the development of the AEDGs, including his support of this Guide at the start of the project.

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

Finally, this Guide would not have been possible without the dedication of Lilas Pratt, ASHRAE staff. Her organizational skills and dedication to taking ideas, thoughts, and draft text from the committee and bringing it together are what really make this Guide a single book. 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 multifamily residential buildings and shifts those buildings from consumers to producers of energy. It should provide confidence that zero energy is possible today and is not a dream. Together we can change the way buildings use energy.

Paul Torcellini
Chair, Special Project 143
August 2021

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Abbreviations and Acronyms

AC	alternating current
A/E	architectural/engineering
AEDG	Advanced Energy Design Guide
AFF	above finished floor
AFUE	annual fuel utilization efficiency, dimensionless
ANSI	American National Standards Institute
ASHP	air-source heat pump
BIPV	building-integrated photovoltaic
BOD	Basis of Design
BP	Advanced Energy Design Guide code for “building and site planning”
Btu	British thermal unit
CEE	Consortium for Energy Efficiency
CFL	compact fluorescent lamp
cfm	cubic feet per minute
c.i.	continuous insulation
CMAR	construction manager at risk
COP	coefficient of performance, dimensionless
Cx	commissioning
CxP	commissioning provider
CZ	climate zone
DC	direct current
DOAS	dedicated outdoor air system
DOE	U.S. Department of Energy
DX	direct expansion
ECM	electronically commutated motor
EER	energy efficiency ratio, Btu/W·h
EIFS	exterior insulation and finish system
ELT	entering load fluid temperature
EN	Advanced Energy Design Guide code for “envelope”
EPA	United States Environmental Protection Agency
EPS	expanded polystyrene
ERV	energy recovery ventilator
EUI	energy use intensity

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fc	footcandle
GSHP	ground-source heat pump
Guide	*Advanced Energy Design Guide for Multifamily Buildings—Achieving Zero Energy*
HID	high intensity discharge
HSPF	heating seasonal performance factor, Btu/W•h
HV	Advanced Energy Design Guide code for "HVAC systems and equipment"
HVAC	heating, ventilating, and air conditioning
IAQ	indoor air quality
IEER	integrated energy efficiency ratio, Btu/W·h
IES	Illuminating Engineering Society
in.	inch
in. w.c.	inches of water column
IPLV	integrated part-load value, dimensionless
ISCOP	integrated seasonal coefficient of performance
ISMRE	integrated seasonal moisture removal efficiency
kBtu/h	thousands of British thermal units per hour
kW	kilowatt
kWh	kilowatt-hour
LD	Advanced Energy Design Guide code for "lighting design"
LED	light-emitting diode
LLLC	luminaire-level lighting control
LPA	lighting power allowance, W/ft^2
LPD	lighting power density, W/ft^2
N/A	not applicable
NEMA	National Electrical Manufacturers Association
NFRC	National Fenestration Rating Council
NPLV	nonstandard part-load value
NREL	National Renewable Energy Laboratory
OPR	Owner's Project Requirements
PL	Advanced Energy Design Guide code for "plug loads and power distribution systems"
PV	photovoltaic
QA	quality assurance
R	thermal resistance, $h•ft^2•°F/Btu$
RE	Advanced Energy Design Guide code for "renewable energy"
REC	renewable energy certificate
RFP	request for proposals
rh	relative humidity
SCT	saturated condensing temperature
SEER	seasonal energy efficiency ratio, Btu/W·h
SHGC	solar heat gain coefficient, dimensionless
U	thermal transmittance, $Btu/h•ft^2•°F$
uPVC	unplasticized polyvinyl chloride
UV	ultraviolet
VRF	variable refrigerant flow
VSD	variable-speed drive
VT	visible transmittance, dimensionless
W	watt
WH	Advanced Energy Design Guide code for "domestic water heating"
WSHP	water-source heat pump
WWR	window-to-wall ratio
XPS	extruded polystyrene

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Foreword: A Message to Building Owners and Managers

My grandfather was a builder in Minneapolis and was a big inspiration to me. He taught me the value of craftsmanship and reminded me that every detail should be completed thoughtfully and with the understanding that it would be on display for the next 100 years. My grandfather didn't know about building sustainably, but the long-term thinking he imparted to me became part of my ethos as a green builder, developer, and educator.

Growing up in Minnesota, I was struck at an early age by the proliferation of wind turbines across the great prairies and the idea that our homes and businesses could be powered by a free clean resource. As I grew older, developments in solar photovoltaics decreased the costs significantly while increasing the efficacy of these systems. I remain awed that light leaving the sun eight minutes before can cleanly power our buildings. My inspiration today is to be an innovator and early adopter in net zero building and beyond, just like many of you.

When I started my building company, I wasn't sure what a green building was, but I knew I wanted to integrate sustainable technologies like wind, solar, batteries, and insulation into my buildings to protect their occupants for the next 100 years. I learned everything I could about building sustainably through Energy & Environmental Building Alliance (EEBA), ASHRAE, the United States Environmental Protection Agency (EPA), the U.S. Department of Energy (DOE), U.S. Green Building Council (USGBC), International Living Future Institute (ILFI), and the National Labs education and programs. I'm a self-described green building geek and think I have read all the Advanced Energy Design Guides. It's my great honor to write the foreword to this latest design guide, and I hope you'll be inspired in your own innovation journey.

When we look at the history of innovation, it is one of scrappy competitors wielding disruption like a pickax—steadily chipping away at the old order. Ten years ago, Tesla was a nobody in an industry defined by legacy players. Today, the legacy players can't keep up. Tesla's market cap is almost five times Ford and GM combined.

A similar story has played out across industries. Airbnb "happened" to hospitality, Uber "happened" to transportation, Netflix "happened" to Hollywood, Robinhood "happened" to stock trading, and so on. But somehow, construction has remained a stubborn exception. Industry incumbents have clung to their old ways. But any safety they still feel in this paradigm is a false sense of security.

I'm not sure I could have said that with confidence even just two years ago. But 2020 changed everything.

As the SARS-CoV-2 pandemic raged, Americans turned to their houses as the last line of defense. As the worst wildfires in history torched the west coast, millions wished for better air

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filtration systems to protect their families. As hurricanes slammed into coastal states, millions saw the need for new power sources, alternatives to gas generators, and homes built for resiliency and a carbon-neutral future.

American homes have always been monsters of energy consumption, typically accounting for 20% of U.S. greenhouse gas emissions.[1] But the situation has grown more dire during the pandemic. Americans spent about an extra $6 billion on at-home power consumption from April to July 2020.[2] Demand for homes and new construction has skyrocketed, suggesting that current trends in home energy use will continue as working from home becomes the new normal for millions.

Someone once said that innovation happens gradually, then suddenly. Well, suddenly consumers are primed for exactly what we offer: efficient, healthy, high-performance net zero homes. They are fleeing cities for the suburbs, but they're bringing green values with them. They're fleeing retirement facilities for traditional housing, but they're bringing health concerns with them. They're abandoning corporate skyscrapers for home offices, but they still crave the same modern and sustainable features.

We're here to tell them that they can have it all. They can have what I call the triple zero: zero health impact, zero net energy, and zero carbon.

Yesterday, building owners and developers could ignore net zero and beyond building with ease. Today, if they adopt it, they do so with reluctance. But tomorrow, they'll adopt it because their survival depends on it.

The residential zero energy market continues to grow across the United States and Canada, according to the EEBA TEAM ZERO *Zero Energy Residential Buildings Study*.[3] The new report documents an increase in total zero energy projects to 27,965 units from the previous 22,146 units in 2018. These single-family and multifamily units are working to achieve zero energy performance in design, construction, and/or operation, with multifamily projects comprising 75% of the total zero energy residential inventory. With code requirements ratcheting up across the country, if you're not building zero energy today, you will need to be prepared to do so soon.

As innovators and early adopters, our goal is not to vanquish old players—it's to vanquish old ways. We know this won't happen without a push. GM would never have gone electric if Tesla hadn't forced its hand.

And that's why innovation is a virtue—because it is the precursor to widespread adoption. Without it, change is impossible, a healthier planet is impossible, and healthier homes for all our families are impossible.

If my grandfather were around today, I know he'd be working alongside me to build greener and healthier homes—homes that are sustainable and forward-looking enough to stand for a century or more. That is the task before us. We aren't just building homes for the future; we are building the future of homes. And that's a legacy we can all be proud of.

Aaron C. Smith
Energy & Environmental Building Alliance (EEBA), TEAM ZERO,
and GreenSmith Builders

Aaron C. Smith is the CEO of EEBA and TEAM ZERO, nonprofit associations dedicated to advancing sustainable residential construction and creating a community where all can come together to learn, share, and collaborate toward a future that is net zero, zero carbon, and zero health impacts. Smith is also the CEO of GreenSmith Builders, an investor, developer and builder of healthy, electric, resilient, and decarbonized single-family and multifamily homes.

1. B. Goldstein, D. Gounaridis, and J.P. Newell, "The carbon footprint of household energy use in the United States," *Proceedings of the National Academy of Sciences* 117(32) (August 2020):19122-30, https://doi.org/10.1073/pnas.1922205117.
2. S. Maas, "Working from Home's Impact on Electricity Use in the Pandemic," *The Digest* No. 12 (December 2020), www.nber.org/digest-202012/working-homes-impact-electricity-use-pandemic.
3. TEAM ZERO, *Zero Energy Residential Buildings Study: 2019-2020 Inventory of residential projects on the path to zero in the U.S. and Canada*, downloadable from www.eeba.org/netzero/inventory.

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Introduction

1

Buildings account for roughly 40% of total energy consumption in the United States and globally (EIA 2019). This Guide provides insight on how to achieve a zero energy building at a cost that is comparable to buildings built to typical energy codes in use today.

Zero energy multifamily building can provide increased resilience and utility cost stability and contribute to reduced or eliminated utility costs for tenants and property owners. The majority of zero energy multifamily projects also eliminate combustion appliances within the units, which improves indoor air quality (IAQ) significantly and results in healthier homes. Beyond the energy savings and health benefits, more and more families are looking for housing that reduces their climate impacts. Zero energy homes provide a means to demonstrate and live a commitment to sustainability and can attract higher rental rates.

Zero energy buildings are designed first to significantly reduce energy consumption and then to meet remaining loads with renewable resources, ideally located on site. These buildings are usually connected to the utility grid to receive energy whenever renewable energy production is insufficient to meet required loads and to return energy to the grid when renewable energy production exceeds the loads.

For multifamily buildings that exceed four to six stories, on-roof renewables may not be enough to offset 100% of on-site energy use but often can offset energy consumption for common spaces. For shorter multifamily buildings, on-roof renewables may be enough to offset, on an annual basis, both common loads and tenant loads, resulting in dramatically reduced tenant energy costs.

GOALS OF THIS GUIDE

This Guide demonstrates that zero energy multifamily buildings are attainable and provides design teams with strategies for achieving energy savings goals that are financially feasible, operationally workable, and readily achievable. The Guide offers direction for designing and constructing zero energy multifamily buildings in all climate zones through recommendations, strategies, and solution packages. Like the zero energy Advanced Energy Design Guides (AEDGs) for small to medium offices and K-12 school buildings that preceded this Guide, absolute energy targets are provided rather than a percentage of energy reduction from a designated baseline.

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Energy efficiency and renewable energy technologies are rapidly improving, and technologies that did not make sense financially or technically a few years ago are feasible today. As a result of this progress, the zero energy goal can be achieved, not only for new buildings but also for existing buildings subjected to the deep retrofit process. Providing buildings with a pathway to zero energy will help lead to a fundamental shift from buildings as consumers of energy to buildings as producers of energy.

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

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

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

ZERO ENERGY DEFINITION

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

> An energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy.

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

Target EUI information is provided in both site energy and source energy. Either can be used to calculate the energy balance of a project. While there are many factors that determine which metric (site or source) to use when calculating the energy balance, a general explanation of the difference between the two follows:

- *Site energy* refers to the number of units of energy consumed on the site and typically metered at the property line or the utility meter.
- *Source energy* refers to the total amount of energy required to produce and transmit a given amount of energy of each fuel type to the site.

Each step from energy extraction to actual consumption has energy losses. Source energy takes into account the efficiency of the production and transport process. It is calculated by multiplying the site energy of each fuel source by a factor specific to that fuel. For example, for electri-

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cal 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-site renewable energy generation is multiplied by these same factors, to give credit for the total avoided source energy consumption. These specific factors will change over time as the grid evolves. Additional discussion on the grid can be found in Chapter 2 of this Guide.

This Guide focuses on the design decisions needed to achieve energy goals and accommodate renewable energy on site, which is the last step needed to achieve a zero energy building. In many situations, renewable energy is limited by site constraints, local regulations, and utility restrictions. Regardless of the limitations, the energy efficiency of a building has a large impact because it reduces the renewable energy needed, whether that energy is produced on site or somewhere else. The goal for the building is to achieve energy use targets in order to create a zero energy ready building. Renewable energy may then be added on site, if available, or procured off site, if desired. In dense urban areas, the recommendations and strategies in this Guide can still be used to create ultra-efficient low-energy buildings that help support zero energy communities.

BENEFITS OF A ZERO ENERGY BUILDING

SOUND FISCAL MANAGEMENT

Zero energy buildings reduce energy consumption and mitigate the risk of future energy cost volatility. Reduced energy consumption leads to reduced energy bills as compared to traditional buildings and to energy costs that are a smaller and more manageable percentage of operational budgets. Utilities and utility rate structures will not remain static as the generation mix and distribution systems change. Investing in energy efficiency and renewable energy minimizes the risk associated with fluctuations in utility prices and provides protection against potential future carbon taxes or regulatory emissions limitations.

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

OCCUPANT SATISFACTION

Occupant satisfaction is complex, but some aspects of satisfaction, such as physical and visual comfort, access to daylighted spaces, views to the outdoors, and natural ventilation, are achieved through effective building design and operation as discussed throughout this Guide. IAQ is one of the most important factors for occupant satisfaction in housing, making it a critical focus for zero energy multifamily building design. There are synergies and co-benefits between designing for zero energy and high IAQ.

Many factors contribute to increased IAQ, from materials selection, exhaust design, and HVAC system selection to air-sealing and compartmentalization. References that provide additional guidance on IAQ strategies and occupant satisfaction that are beyond the scope of this Guide include the following:

- *Residential Indoor Air Quality Guide: Best Practices for Home Design, Construction, Operation, and Maintenance* (ASHRAE 2018)

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- *Energy Savings Plus Health: Indoor Air Quality Guidelines for Multifamily Renovations* (EPA 2021)
- ASHRAE Standard 55-2020, *Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2020)
- ASHRAE Guideline 10-2016, *Interactions Affecting the Achievement of Acceptable Indoor Environments* (ASHRAE 2016)

ENVIRONMENTAL STEWARDSHIP

Completing a zero energy or zero energy ready multifamily building demonstrates leadership and a clear commitment to sustainability and environmental stewardship. Investing in a zero energy building is one of the most impactful things an owner can do to improve communities, protect natural resources, and mitigate climate change (Terrapin 2015). This commitment can also provide market differentiation and a possible competitive advantage.

SCOPE

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

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

This Guide cannot specifically address all possible configurations of buildings. The recommendations therefore primarily apply to multifamily buildings covered by ANSI/ASHRAE/IES Standard 90.1 (ASHRAE 2019) up to twenty floors. While the recommendations may be applicable to taller buildings, the energy loads for buildings over 20 floors are more dominated by the vertical transportation (elevators), which changes the EUI targets for such buildings. This Guide covers buildings with independent tenant living spaces with units ranging from one to three bedrooms, where each unit has a kitchen space, bathroom(s), bedroom(s), and living spaces. A first floor containing common meeting spaces, a workout room, and staff/management offices or containing low-energy-density mixed-use spaces such as light retail and leased offices is also covered. The Guide also includes consideration of vertical transportation and laundry facilities, as well as energy management systems and controls. The Guide does not consider specialty spaces with extraordinary heat generation, large ventilation requirements, food service, pools, vehicle or other maintenance areas, domestic water well pumping, sewerage disposal, medical equipment as found in skilled nursing facilities, or smaller residential buildings not covered by ASHRAE/IES Standard 90.1.

Much of the Guide may also be applicable to buildings undergoing complete or partial renovation, additions, and/or changes to one or more building systems; however, upgrading existing exterior building envelopes as required to achieve the low EUIs needed to reach zero energy can often be challenging. With that in mind, owners should seize opportunities to move buildings toward zero energy whenever significant changes are made to their facilities. Any time a design decision is made is an opportunity to save energy. Changes may include replace-

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ment of a boiler, replacing light fixtures, or simply painting the space. Design decisions can be made that will reduce the energy impact of the building. One of the icons next to the how-to strategies in Chapter 5 (and described later in this chapter) indicates strategies that are particularly well suited for existing buildings to be renovated or modernized. See the How to Use This Guide section of this chapter for a description of the icons used in the Guide.

While this Guide focuses on reducing energy consumption in a building, there are also other important aspects of sustainability. Acoustics, IAQ, water efficiency and quality, landscaping, access to views, and effective space planning are just some of the other benefits of an effective design. The objective is to create a zero energy building that is cost-effective and also designed with all these parameters in mind.

DEVELOPING THE GUIDE

To establish reasonable energy targets for achieving zero energy performance in all climate zones, a prototypical multifamily building was modeled and analyzed using hourly building simulations. The prototype building was carefully assembled to represent multifamily building construction, with information drawn from several sources. Typical floor plan layouts for a market-rate multifamily building are shown in Figure 1-1. While floor plans vary considerably, this diagram was configured so that horizontal and vertical circulation were internalized to maximize exterior exposure for the living space.

The EUIs were verified not to exceed the amount of renewable solar energy that could be generated by photovoltaic (PV) panels reasonably accommodated on the roof or on the site of the four-story prototype building. The EUI targets shown in Figure 1-2 are not intended to be prescriptive requirements but rather to be achievable design starting points that can be cost-effectively attained. Further optimization through building simulation and integrated design is recommended to reach the lowest possible EUI for each project striving for zero energy. Additional information on leveraging simulation and analysis in the design process is provided in Chapter 4.

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

The recommendations are the result of numerous building energy simulation analyses using a four-story prototype multifamily building, shown in Figure 1-3. Specifically, the simulations used a four-story building with three stories of residential units and one story of commercial and common spaces. Simulation analyses explored the energy impacts of various envelope, HVAC, water heating, lighting, and plug load systems and configurations. Additional sensitivity analyses determined the EUI impact of additional residential stories, as well as an exploration of how EUI is impacted by varying the density of residential units per floor to reflect different market categories of multifamily buildings. More information on the simulation specifics used in this Guide are detailed in the Energy Modeling for the Multifamily AEDG sidebar in this chapter.

HOW TO USE THIS GUIDE

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

Chapter 2, Principles for Success, identifies the main principles fundamental for success in implementing a zero energy building, including the importance of zero energy and how to be successful in delivering a zero energy building through an integrated process and a hierarchy of decision making. The chapter also touches on adapting to future needs.

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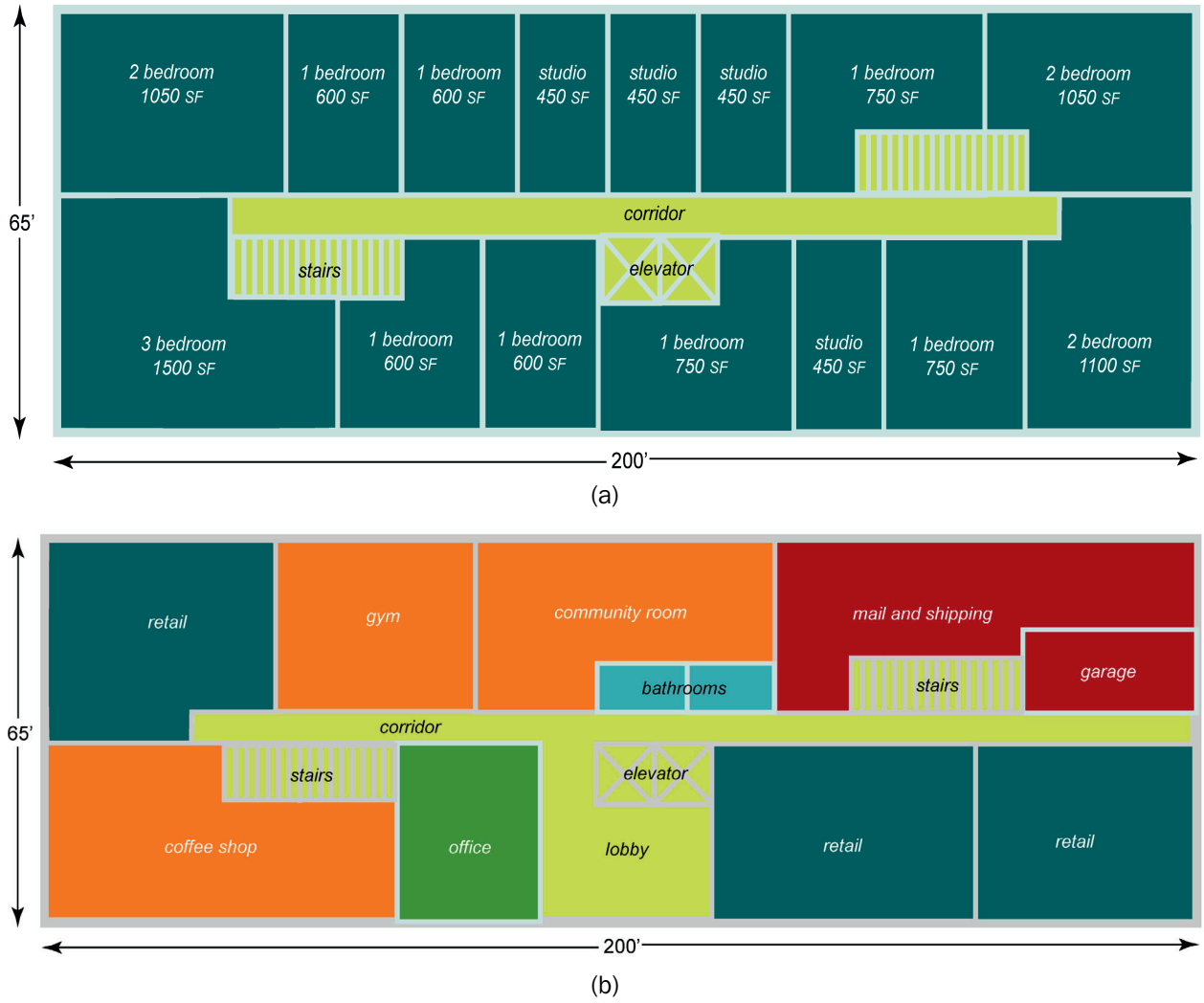


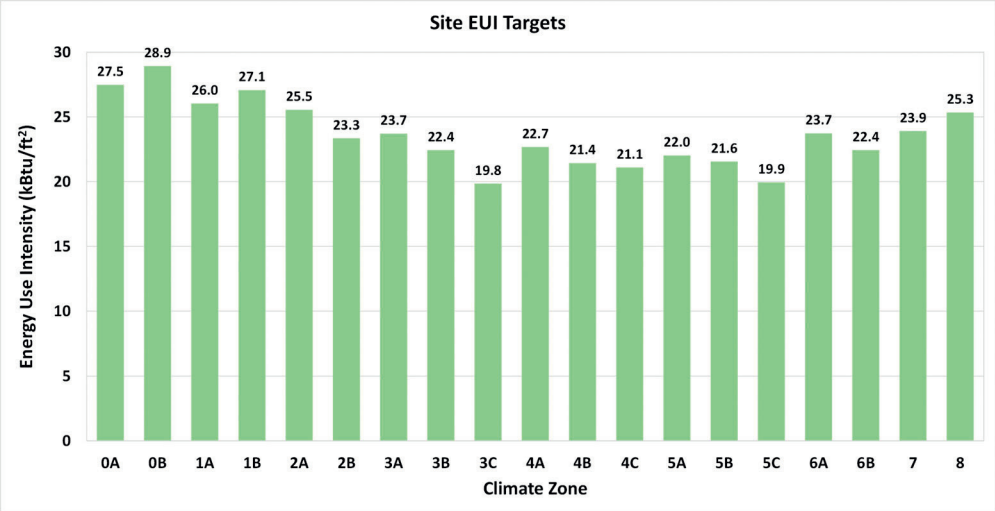
Figure 1-1 Typical Multifamily Floor Plans: (a) Residences and (b) Lobby

Chapter 3, A Process for Success, outlines how to achieve a zero energy building from a process standpoint and provides guidance on how to navigate the design and construction process in order to achieve zero energy. The chapter outlines how to determine a target EUI and provides recommended EUI targets in both site and source energy. Commissioning, occupant engagement, and maintaining zero energy after occupancy are also discussed.

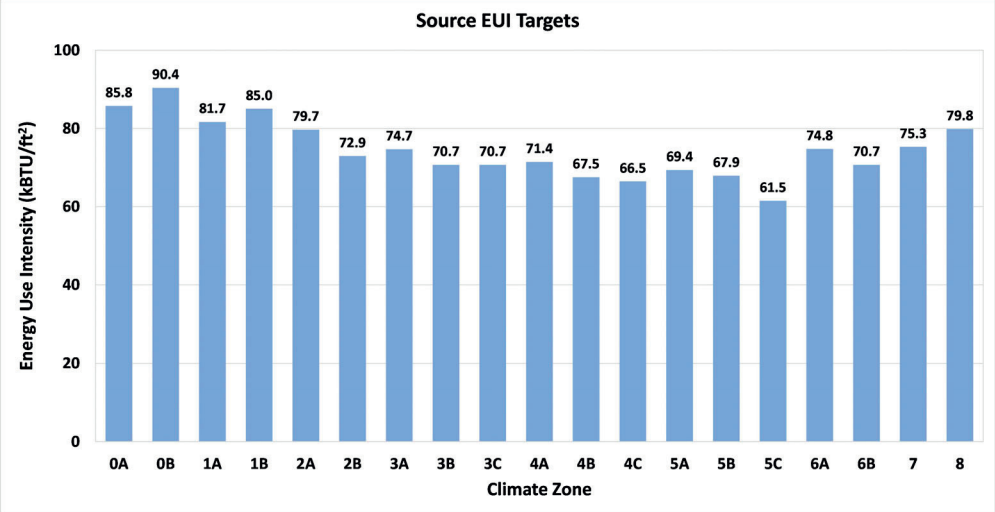
Chapter 4, Leveraging Analysis to Drive Success, provides information on how to incorporate building simulation into the design process. The chapter summarizes the modeling processes needed to evaluate different energy efficiency measures and to predict whether or not a project is likely to achieve the desired level of energy performance. The chapter emphasizes how energy modeling should be used to get the right information to the design team at the right time of the design process.

Chapter 5, How-To Strategies, provides specific strategies and recommendations regarding the design, construction, and operation of zero energy buildings. The chapter has suggestions on how to implement best design practices, how to avoid problems, and how to achieve the energy targets advocated in this Guide. The chapter is organized into easy-to-follow how-to strategies by system type, including building and site planning (BP), envelope (EN), lighting design (LD), plug loads and power distribution systems (PL), domestic water heating (WH), HVAC systems and equipment (HV) and renewable energy (RE).

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(a)



(b)

Figure 1-2 EUI Comparison by Climate Zone: (a) Site and (b) Source

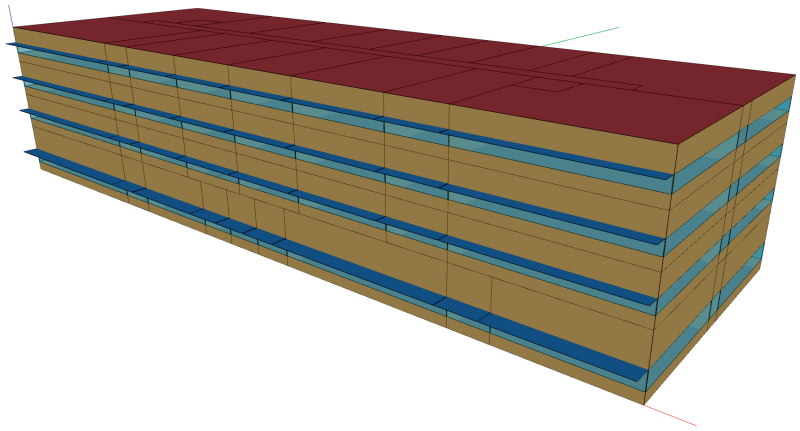


Figure 1-3 Multifamily Prototype Building
Courtesy of National Renewable Energy Laboratory

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Energy Modeling for the Multifamily AEDG

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

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

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

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

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

- OpenStudio: https://openstudio.net/
- OpenStudio documentation: http://nrel.github.io/OpenStudio-user-documentation/
- Building Component Library: https://bcl.nrel.gov/
- Measures: https://github.com/NREL/OpenStudio-EMS-Measures
- Parametric Analysis Tool: http://nrel.github.io/OpenStudio-user-documentation/reference/parametric_analysis_tool_2/
- Zero Energy Buildings Resource Hub: www.zeroenergy.org

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Often energy efficiency saves on energy costs, but many energy efficiency strategies have other attributes that add value to the design. Four of these attributes are flagged in the Guide. Icons in Chapter 5 highlight strategies that contribute to the four different attributes. These icons and attributes are as follows:

- **Grid Alignment:** Many energy efficiency strategies can reduce electrical grid demand as well as help the utility grid manage grid-level peak demand issues. This is sometimes referred to as *grid alignment*.
- **Energy Resilience:** Energy efficiency strategies can be used to help a building respond to and recover from an interruption—often a utility grid issue such as a power outage from a weather-related event. A resilient building can more quickly return to normal operations once grid operation is restored or can operate at some level without the utility grid.
- **Capital Cost Savings:** In some cases, energy efficiency strategies can be implemented such that they save capital costs or up-front costs for the entire building budget.
- **Building Retrofit Strategies:** While this Guide was formulated for new construction, many design strategies can also be used for retrofit applications on existing buildings.

Appendices provide additional information:

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

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

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

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

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

REFERENCES AND RESOURCES

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

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

ASHRAE. 2018. *Residential indoor air quality guide: Best practices for home design, construction, operation, and maintenance*. Peachtree Corners, GA: ASHRAE.

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

ASHRAE. 2020. ANSI/ASHRAE Standard 55-2020, *Thermal environmental conditions for human occupancy*. Peachtree Corners, GA: ASHRAE.

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

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

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

EPA. 2021. *Energy savings plus health: Indoor air quality guidelines for multifamily renovations*. EPA Publication No. 402K21002. Washington, DC: United States Environmental Protection Agency. www.epa.gov/indoor-air-quality-iaq/indoor-air-quality-guidelines-multifamily-building-upgrades-printable-file.

NREL. n.d. Zero energy buildings resource hub. United States: National Renewable Energy Laboratory and U.S. Department of Energy. www.zeroenergy.org.

Terrapin. 2015. *The economics of biophilia: Why designing with nature in mind makes financial sense* [revised publication of 2012 first edition]. NY: Terrapin Bright Green, LLC. www.terrapinbrightgreen.com/report/economics-of-biophilia/.

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