PNNL-30547

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Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Abstract

This study investigates the technical feasibility of achieving zero energy (ZE) new residential and commercial buildings with national model energy codes. The approach and analysis are intended to provide guidance, inform goal setting, and direct future code development. ZE buildings are typically very energy efficient and grid connected. They use on-site renewable energy systems and export energy to the grid that is equal to or greater than the source energy delivered to the building annually. The study analysis establishes the efficiency gap that exists between a reference energy code and the ZE target on an annual site energy use basis. It applies the Pacific Northwest National Laboratory (PNNL) Building Energy Codes Program process for determining the Progress Indicator (PI) metric that quantifies the national efficiency advancements made between each 3-year energy code publication cycle and the progression of energy advancements. It examines the historical rate of change of the PI metric and gauges it against the future advancements needed to achieve a ZE goal by 2030. The assessment includes benchmarks of site energy-use reductions achievable with advanced efficiency measures and potential offsets associated with on-site rooftop solar photovoltaic systems. The results indicate that future efficiency advancements need to improve at a rapid rate relative to past achievements. The assessed beyond-code measures and rooftop solar offsets make substantial gains toward filling the gap but do not result in zero site energy for newly constructed U.S. buildings. Thus, a ZE code will need to account for additional energy-use reduction strategies that might include increased efficiency improvements, integrative design solutions, reduced plug and process loads, and off-site renewable energy procurement.

Executive Summary

This study was conducted by Pacific Northwest National Laboratory (PNNL) in support of the Department of Energy's efforts to advance model energy codes. It assesses the energy efficiency gap that exists between model energy codes[1] and a zero energy (ZE) performance target for newly constructed residential and commercial buildings in the United States. A common definition for a ZE building is "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."[2] In this report, the discussion focuses on building site energy to align it with the basis used to assess code advancements. Thus, in this context, ZE refers to a building that is zero energy on an annual basis at the site level.

This report provides a high-level overview of the historical achievement of energy codes and future trajectory needed to achieve ZE new buildings by 2030. The study provides a national-scale analysis to quantify the performance of energy code compliant buildings and the advancements needed for ZE. In addition, the study defines and applies advanced, beyond-code measures and considers rooftop solar photovoltaics (PV) to quantify the ability of tangible market-ready technologies to fill the performance gap.

This study follows the progress indicator (PI) process to analyze the impact of historical and potential future code requirements. PI is a PNNL-developed methodology and metric created specifically for the purpose of quantifying the progress of model energy codes.[3] It uses whole-building simulation analysis based on representative building types in U.S. climates zones. Site energy use intensities are developed for each building type and weighted by their relative square footage of new construction to estimate the aggregated national energy use under the model energy code baseline. In the study, the PI values are presented relative to a historical baseline, which is the 2006 International Energy Conservation Code (IECC) for residential buildings (IECC-R) and American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2004 for commercial buildings. The ZE performance gap is determined relative to a reference baseline model code, such as the 2018 IECC and the ASHRAE Standard 90.1-2019.

The advanced measures considered for residential buildings characterize buildings compliant with the Passive House Institute U.S. (PHIUS) Standard.[4] Passive house concepts include superinsulation, airtight envelopes, high-performance windows, and managing solar gain. The approach minimizes energy loads to achieve ambitious yet technically feasible performance

[1] While advanced codes can be considered model codes, in this document, the term "model energy code" refers to the current published version of the International Energy Conservation Code-Residential and ASHRAE Standard 90.1, because those documents are referenced by the Energy Conservation and Production Act as modified by the Energy Policy Act of 1992 as the minimum requirements for states adopting energy codes. https://www.govinfo.gov/content/pkg/USCODE-2011-title42/pdf/USCODE-2011-title42-chap81-subchapII.pdf.

[2] NIBS, 2015; https://www.energy.gov/sites/default/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf.

[3] Thornton, BA, MI Rosenberg, EE Richman, W Wang, Y Xie, J Zhang, H Cho, VV Mendon, RA Athalye, and B Liu. 2011. Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010. PNNL-20405, Pacific Northwest National Laboratory, Richland, Washington.

[4] https://www.phius.org/phius-certification-for-buildings-products/project-certification/phius-2018-getting-to-zero

targets. The advanced measures considered for commercial buildings comprise a subset of the measures studied in ASHRAE Research Project 1651 – *Development of Maximum Technical Achievable Energy Targets for Commercial Buildings* (RP-1651).[5] For our application, we selected 17 of the 30 measures identified. This subset was chosen based on engineering judgment, which considered existing market share, current cost-effectiveness, and future market opportunity. In addition, the published ASHRAE RP-1651 data indicate that the selected subset comprises approximately 90% of the identified commercial building energy-saving technical potential.

To develop the national on-site rooftop solar photovoltaic (PV) generation potential for newly constructed buildings, two approaches were followed. The first approach utilized PVWatts[6] and was based on the building code prototype models' geometries, the U.S. climate zone locations' solar resources, and national new construction weighting factors. The second approach utilized published data characterizing the U.S. rooftop solar PV generation technical potential.[7] To apply the data, PNNL disaggregated and normalized it to align with the building types regulated by each of the model energy codes (IECC-R and ASHRAE 90.1) then scaled it based on national new construction floor area data.

Figure ES. 1 and Figure ES. 2 indicate the energy use reductions required to achieve ZE by 2030. The figures show the impact of the advanced measures amended to the baseline code (black dashed lines), as well as the energy-use offset attributed to rooftop solar (yellow dashed line). For residential codes, Figure ES. 1 shows four historical code development cycles and four future cycles (2021, 2024, 2027, and 2030). For commercial codes, Figure ES. 2 encompasses five historical code development cycles and three future cycles (2022, 2025, and 2028). The data indicate that performance advancements must improve more rapidly than what has been achieved historically. This is indicated by the steeper slope of the ZE future code trend (green dashed line) compared to the slope of the historical code trend (brown dashed line). The figure data reveal that the required rate of efficiency advancements must nearly double that achieved historically to meet the ZE goal. Specifically for residential codes, historical achievements reduce the normalized energy use index (NEUI) by 26% over four code cycles (about 6% per cycle). The needed future efficiency improvements must achieve a NEUI reduction of 46% over four code cycles (about 11% per cycle). Similarly, for commercial codes, historical achievements reduce the NEUI by 36% over five code cycles (about 7% per cycle). The necessary future efficiency improvements require achieving a NEUI reduction of 33% over three code cycles (11% per cycle).

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[5] Glazer, Jason. 2016. *ASHRAE 1651-RP Final Report: Development of Maximum Technically Achievable Energy Targets for Commercial Buildings – Ultra Low Energy Use Building Set*. GARD Analytics, Inc, and ASHRAE, Atlanta, GA.

[6] Dobos, AP. 2014. *PVWatts 5 Manual*. NREL/TP-6A20-62641.

[7] Gagnon, P, R Margolis, J Melius, C Phillips, and R Elmore. 2016. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment*. NREL/TP-6A20-65298, National Renewable Energy Laboratory, Golden, Colorado.

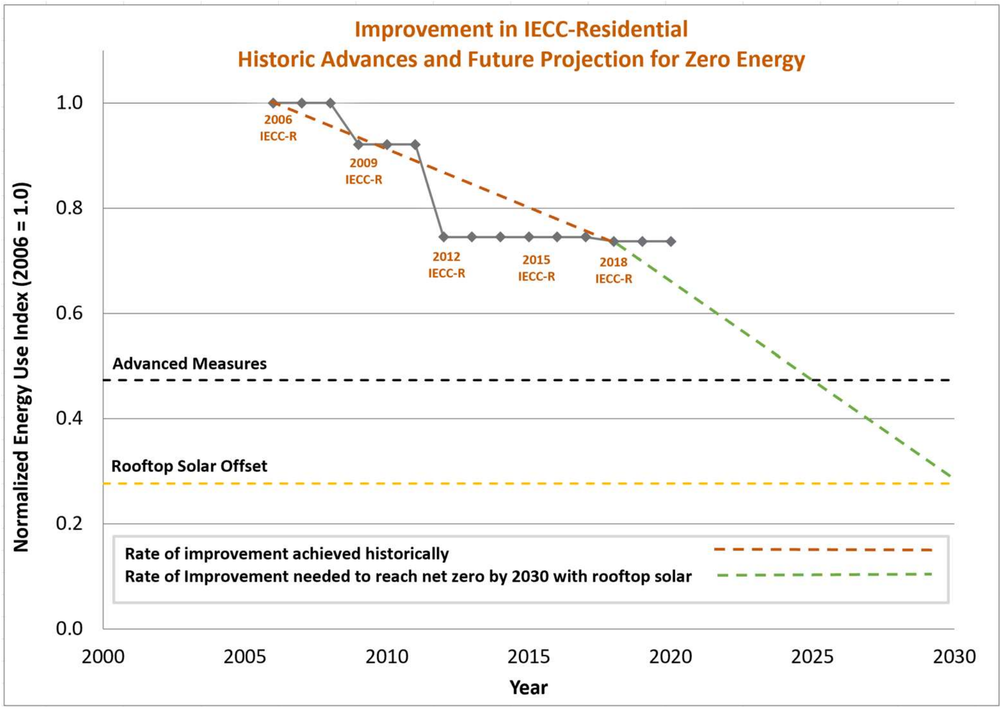

Figure ES. 1 Historical and Needed Advances to Achieve Zero Energy Residential Buildings with Model Energy Codes

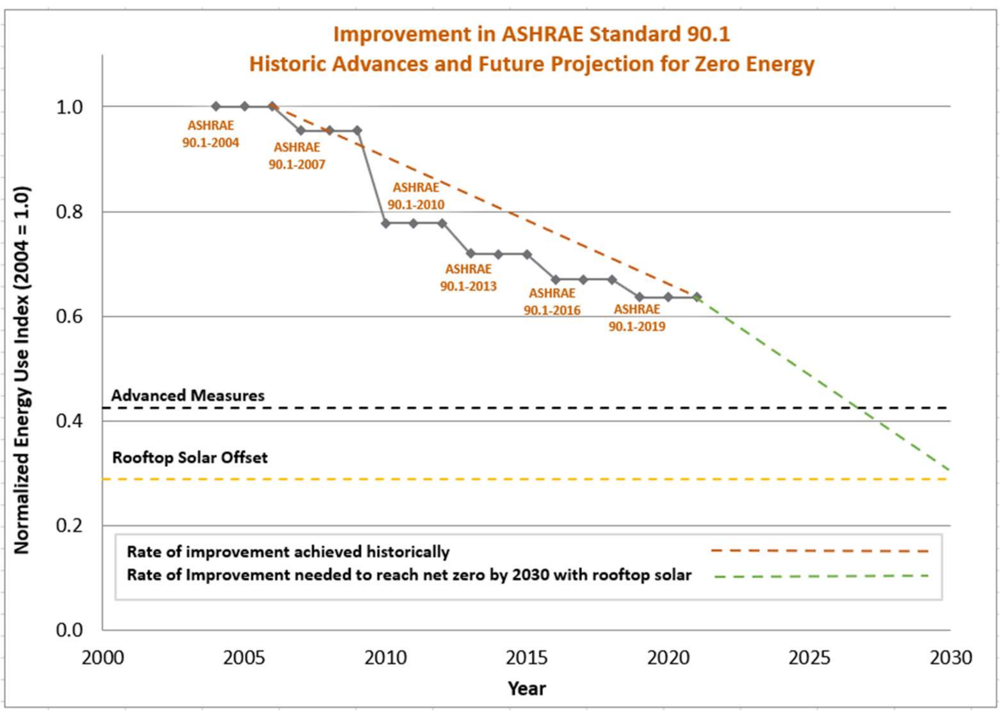

Figure ES. 2. Historical and Needed Advances to Achieve Zero Energy Commercial Buildings with Model Energy Codes

Table ES. 1 summarizes the site energy use reductions determined from the analysis relative to the referenced baseline model code. As indicated, the advanced measures reduce the baseline code site energy use by 36% and 33% for residential and commercial buildings, respectively. The rooftop solar offsets the baseline code site energy use by 38% and 48% for residential and commercial buildings, respectively.[8] These measures will push model codes substantially closer to ZE, filling about 75–80% of the gap. Strategies to fill the remaining gap might include additional efficiency improvements, integrative design solutions, reduced plug and process loads, and off-site renewable energy procurement.

Table ES. 1. The Efficiency Gap to Achieve ZE Model Energy Codes [9]

	Residential (IECC 2018)		Commercial (ASHRAE 90.1-2019)	
	Code cycle	Filling the gap	Code cycle	Filling the gap
Advanced Measures	2021–2030 (four code cycles)	36%	2022–2028 (three code cycles)	33%
Rooftop Solar Offset		38%		48%
Remaining Gap		27%		19%

As noted, to meet the 2030 ZE target timeline, the identified energy code advancements must occur over three or four code cycles. Model energy codes are starting to incorporate requirements for renewable energy resources, albeit at nominal levels. For example, addendum *BY* to ASHRAE 90.1-2019 adds an on-site renewable energy system rated capacity requirement of 0.25 W/ft^2 based on the conditioned floor area for all floors up to the three largest floors. However, to reach the energy offset values cited in this study, much larger PV system capacities are required. Based on this study's assessment of suitable roof area based on the prototype models' geometries, the cited energy offset for rooftop PV corresponds to an overall average PV system capacity of 5 W/ft^2 for commercial buildings based on total conditioned floor area. For residential buildings, the cited energy offset associated with the rooftop solar corresponds to an average PV system capacity of 3 W/ft^2.

Another important aspect of ZE model energy code development is the establishment of code mechanisms that support demonstrating compliance. Needed progressions include moving away from the popular prescriptive compliance path and further developing the performance-based compliance path, which offers design flexibility, supports innovative low-energy solutions, and substantiates achievement of established performance targets. In conjunction with this, the performance metric used to demonstrate compliance must consider total building energy use,

[8] The rooftop PV estimated offset value reflects the net generation potential determined for residential or commercial buildings at the national level. Specifically, for each building type analyzed, the on-site renewable exported energy that exceeds the building's annual delivered energy is credited to offset the energy use of other buildings that have annual delivered energy that is greater than their on-site renewable exported energy.

[9] ZE gap values stated for residential code total 101% due to rounding errors.

including plug and process loads not regulated by energy code. Doing so supports the establishment of a target value equaling zero and achievement of the ZE goal.

Acknowledgments

The authors would like to acknowledge the Building Technologies Office (BTO) of the Department of Energy's Office of Energy Efficiency and Renewable Energy for supporting this research and development effort. The authors thank Jeremy Williams, BTO Program Specialist, for his guidance on the project and commitment to meeting the goals of the Building Energy Codes Program. The authors would also like to recognize Passive House Institute U.S. for their supporting work that underlies the beyond-code efficiency measure packages utilized in the residential building analysis.

Acronyms and Abbreviations

AFUE	annual fuel utilization efficiency
AHS	American Housing Survey
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
CFM	cubic feet per minute
CO_2	carbon dioxide
COP	coefficient of performance
CZ	climate zone
DOE	Department of Energy
DT	delta temperature
DX	direct expansion
EER	energy efficiency ratio
EIA	Energy Information Agency
EPD	equipment power density
ERI	Energy Rating Index
EUI	energy use intensity
HSPF	heating seasonal performance factor
HVAC	heating, ventilation, and air conditioning
IECC	International Energy Conservation Code
IECC-R	International Energy Conservation Code Residential
JFC	justified first cost
lidar	light detection and ranging
LPD	lighting power density
MEC	model energy code
MECS	Manufacturers Energy Consumption Survey
NEUI	normalized energy use index
NREL	National Renewable Energy Laboratory
PHIUS	Passive House Institute U.S.
PI	Progress Indicator
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
QA	quality assurance
QC	quality control
RECS	Residential Energy Consumption Survey
RP	research project

SAT	supply air temperature
SEER	seasonal energy efficiency ratio
VRF	variable refrigerant flow
W	watts
WUFI	*Wärme-und Feuchtetransport instationär*
ZE	zero energy
ZER	Zero Energy Ready

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1.0 Introduction

Energy codes are intended to minimize energy use in buildings, resulting in increased cost savings for building owners and occupants, decreased power demands, and reduced environmental impacts. They have significantly increased building efficiency over the last 39 years since the first national energy code[1] was published in 1975 (ASHRAE 1975). The main approach for achieving improved performance involves providing minimum requirements for the energy-efficient design and construction of buildings, where the most cost-effective opportunities exist. For building energy codes to continue progressing, the next generation will need to provide a path and assure a measurable trajectory toward achieving zero energy (ZE) buildings.

A ZE building, according to the common definition used by the Department of Energy (DOE), is "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" (National Institute of Building Sciences, 2015). Building industry professionals may refer to a building's ZE status based on its site energy use rather than source energy use or on a timescale smaller than one year, so a clear definition must begin any discussion of ZE status. Other terms may be used interchangeably with ZE, such as net zero energy or zero net energy. For all ZE buildings, the key concept is to reduce the building's energy use through energy-efficient design and operation, and to then meet the building's reduced energy needs with renewable energy generation, which commonly comes from on-site solar photovoltaic (PV) systems. A building's zero source energy status requires converting site energy to source energy using conversion factors defined by source type. The factors account for the energy consumed in the extraction, processing, and transport of primary fuels used in power generation, as well as energy losses in transmission and distribution of the energy delivered.

Many U.S. cities and states are establishing performance targets to move their building sector toward ZE status or specifying design requirements to support the construction of ZE buildings within their jurisdiction. In 2009, the State of Washington passed legislation requiring the state energy code to achieve a 70% reduction in annual net energy consumption compared to the 2006 Washington State energy code by 2031. The Government of the District of Columbia (2017) has a net-zero energy compliance path defined in their current energy code, which makes it easier for projects pursuing ZE status to demonstrate code compliance. Starting in 2020, the Title-24 2019 state energy code in California requires new residential projects to install solar photovoltaics to offset or zero out electricity uses, excluding space conditioning and water heating.[2]

This study investigates the technical feasibility of achieving ZE new residential and commercial buildings with national model energy codes.[3] Model energy codes are developed by industry

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[1] The term "energy code" is used within this report as a generic term that includes ASHRAE 90.1 (a standard), the International Energy Conservation Code, and other forms of building energy standards, guidelines, laws, rules, etc.

[2] https://www.energy.ca.gov/sites/default/files/2020-11/2020%20-%20CEC%20-%20Solar%20PV%20Systems_ADA.pdf

[3] While advanced codes can be considered model codes, in this document, the term "model energy code" refers to the International Energy Conservation Code-Residential and ASHRAE Standard 90.1, because those documents are referenced by Energy Conservation and Production Act as modified by the Energy Policy Act of 1992 as the minimum requirements for states adopting energy codes.

partners, and new updates are published every three years. They are adopted by states and local jurisdictions and form the basis for their minimum building energy requirements. The analysis and results are intended to provide guidance, inform goal setting, and direct future code development. The report describes the methodology and presents results characterizing the energy efficiency gap that exists between the baseline model energy code[4] and a ZE performance target for newly constructed buildings in the United States. The assessment includes a comparison of the rate of efficiency improvements achieved historically and the trajectory needed to achieve a ZE 2030 target for residential and commercial energy codes.

The report is organized as follows. Section 2.0 of the report discusses the role of building energy codes in advancing efficiency. It introduces the Progress Indicator (PI) methodology and metric, developed by Pacific Northwest National Laboratory (PNNL), which is used to quantify efficiency improvements.

Section 3.0 describes the analysis techniques applied to assess the efficiency gap associated with current residential and commercial model energy codes. It includes an overview of the beyond-code measures evaluated and the approach for determining the potential energy use offset from on-site rooftop PV.

Section 4.0 presents the study analysis results, including graphics depicting historical code achievements, potential gains from advanced measures and PV, and the remaining efficiency gap for achieving ZE. Data tables are provided that summarize the progression of efficiency values underlying the analysis, as well as efficiency measure energy and cost savings. A metric that indicates measure cost-effectiveness is also provided.

Section 5.0 outlines key steps on the path for model energy codes to achieve the ZE goal. The activities involve the transformation of code development procedures and mechanisms. Section 6.0 highlights the report findings and conclusions.

The report appendices include the analysis technical details. Data underlying the PI process are provided. Methodology details are supplied for the residential and commercial beyond-code measure analysis and rooftop PV assessment. In addition, reference tables compare current code to advance code measure efficiency values by climate zone.

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https://www.govinfo.gov/content/pkg/USCODE-2011-title42/pdf/USCODE-2011-title42-chap81-subchapII.pdf.

[4] For the study, the baseline referenced code is the 2018 International Energy Conservation Code-Residential and ASHRAE Standard 90.1-2019.

2.0 The Role of Building Energy Codes in Advancing Efficiency

In the United States, nearly 6 million commercial buildings and 115 million residential households consume about 39% of the total energy consumption and 70% of electricity (EIA 2019). Because buildings typically exist for decades, and in many cases even centuries, energy codes represent a unique opportunity to assure buildings are designed and constructed to minimum acceptable levels of energy performance, which has lasting impacts for years to come. Addressing energy efficiency during new construction and major renovation also can be accomplished at an expense far less costly than later upgrades, which can also result in significant disruption to the building's occupants and operations. Establishing and improving energy code requirements over time help typical design and construction practices remain on par with current and cost-effective technologies and assure more efficient, healthier, and affordable living and working environments for future generations.

2.1 Addressing Building Efficiency with Energy Codes

In 1975, the first national model energy code— American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) Standard 90-75—was developed that covered both low-rise residential buildings and commercial and high-rise multifamily buildings (ASHRAE 1975). ASHRAE Standard 90-75 and its successor were eventually codified in the 1983 Council of American Building Officials model energy code (MEC) (Crowder et al. 1998). The development of ASHRAE Standard 90 (now called Standard 90.1) and the MEC continued in parallel through the 1980s and early 1990s. In 1994, the regional code groups combined efforts to form the International Code Council (ICC) and delivered the first edition of the International Building Code in 1997, which addresses residential and commercial building design and construction, with new additions released every 3 years. Since then, the ICC publications have expanded to include a set of 15 code-related documents, which address plumbing, mechanical, fuel gas, existing buildings, green construction, and other topics. The set also includes the International Energy Conservation Code (IECC), which addresses energy efficiency requirements for residential and commercial buildings. The commercial portion of the IECC permits using the ASHRAE 90.1 Standard, which specifies the minimum requirements for energy-efficient design for most buildings, except low-rise residential buildings.

The DOE plays a role in the advancement of building energy codes as mandated and defined by federal statute, namely the Energy Conservation and Production Act as modified by the Energy Policy Act of 1992. The statute directs DOE to review the technical and economic basis for voluntary building energy codes and participate in the industry review process, including seeking adoption of all technologically feasible and economically justifiable energy efficiency measures. The statute identifies ASHRAE Standard 90.1 as the national model energy standard for commercial buildings (and multifamily residential buildings over three floors) and the IECC as the national energy standard for low-rise residential buildings (including one- and two-family detached and attached buildings, duplexes, townhouses, row houses, and low-rise multifamily buildings not greater than three stories).[5] After a code's revision, the statute directs the

[5] While advanced codes can be considered model codes, in this document, the term "model energy code" refers to the current published version of the International Energy Conservation Code-Residential and ASHRAE Standard 90.1, because those documents are referenced by the Energy Conservation and Production Act as modified by the Energy Policy Act of 1992 as the minimum requirements for states

Secretary of Energy to make a determination, not later than 12 months after such a revision, whether the revised code would improve energy efficiency in commercial buildings and to publish a notice of such determination in the *Federal Register* (42 U.S.C. 6833(b)(2)(A)). The statute also directs DOE to provide technical assistance and support to states for energy code implementation. The most recent model energy codes for which a determination has been published are the 2018 IECC for low-rise residential buildings and ASHRAE Standard 90.1-2019 for commercial and high-rise multifamily buildings.[6]

2.2 Tracking Advances with the Progress Indicator

PNNL supports DOE in their efforts to advance the MECs, provide technical assistance, and support state implementation of energy codes. With each new code edition, DOE is required by statute to issue a determination as to whether the updated edition will improve energy efficiency. This quantitative assessment of energy-use reduction helps inform and encourage states and local jurisdictions to update their energy codes. To perform this quantitative assessment and measure the progress of codes, PNNL developed the PI metric and underlying analysis process. [7] It uses whole-building simulation analysis based on representative building types across all U.S. climate zones. Site energy use intensities are developed for each building type and weighted by the relative square footage of new construction to estimate the aggregated national energy use under the MEC baseline. In the PI process, the baseline condition of each of the model code prototypes for each climate location represents a minimally code-compliant building. Because the model codes are continually maintained and published every 3 years, the prototype building models are as well.

The study applies the PI process to assess the energy efficiency gap for achieving ZE site-energy buildings by 2030. The reference code baseline is 2018 IECC for residential and ASHRAE Standard 90.1-2019 for commercial buildings. The analysis includes evaluating the reference code baseline and an amended model that exceeds the reference baseline by adding advanced energy efficiency measures. The analysis is performed for a representative set of building types using the EnergyPlus simulation software (DOE 2018). The building prototype models[8] include 32 residential[9] and 16 commercial building models. The prototypes are simulated in 16 U.S. cities that represent the 16 U.S. climate zones defined by ASHRAE Standard 169 (ASHRAE 2013).

The building prototypes modeled are listed in

Table 1 along with their building floor areas and contributions to total new construction area. As indicated, the floor area associated with residential new building construction is more than double that of commercial buildings. Based on average growth trends, the annual new U.S. floor

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adopting energy codes. https://www.govinfo.gov/content/pkg/USCODE-2011-title42/pdf/USCODE-2011-title42-chap81-subchapII.pdf.

[6] https://www.energycodes.gov/determinations

[7] Thorton et al. 2011.

[8] More details about the energy code building simulation prototype models can be found at https://www.energycodes.gov/development/commercial/prototype_models https://www.energycodes.gov/development/residential/iecc_models

[9] The two core residential building types, single family and low-rise multifamily, form the basis for 32 variations that account for different heating systems and foundation types typically found in residential new construction.

area is made up of approximately 2.8 billion square feet for residential (U.S. Census 2020) and 1.3 billion square feet for commercial (Lei et al. 2020).

Table 1. Residential and Commercial Model Code Prototype Building Models

Building Category	Model Code Prototype Characteristics			
	Building Type	Floor Area (ft^2)	Floors	Average New Construction Floor Area (% or ft^2/year)
Residential	Single Family	2,377	2	80%
	Low-Rise Multifamily	21,610	3	20%
	Total	2,768,857,300		100%
Commercial	Apartment – High rise	84,352	10	7.2%
	Apartment – Mid rise	33,741	4	10.3%
	Hospital	241,501	5	3.4%
	Hotel – Large	122,120	6	3.2%
	Hotel – Small	43,202	4	1.2%
	Office – Large	498,588	12	2.9%
	Office – Medium	53,628	3	3.8%
	Office – Small	5,502	1	2.8%
	Out-Patient Health Care	40,946	3	2.6%
	Restaurant – Quick Service	2,501	1	0.2%
	Restaurant – Full Service	5,502	1	0.7%
	Retail – Stand-alone	24,692	1	8.2%
	Retail – Strip Mall	22,500	1	2.8%
	School – Primary	73,959	1	3.6%
	School – Secondary	210,887	2	8.2%
	Warehouse	52,045	1	13.9%
	Not represented			25.0%
	Total	1,287,090,200		100%

The geometric form of each prototype building is intended to represent a typical building of the corresponding building type. Figure 1 illustrates the 3D rendering of the prototype buildings, including their shape, size, number of floors, and window configuration. The prototypes are used to simulate building energy performance and associated energy costs in 16 U.S. cities that represent the 16 U.S. climate zones as designated by ASHRAE Standard 169 (ASHRAE 2013). The climate zones and their associated locations are presented in Appendix A.

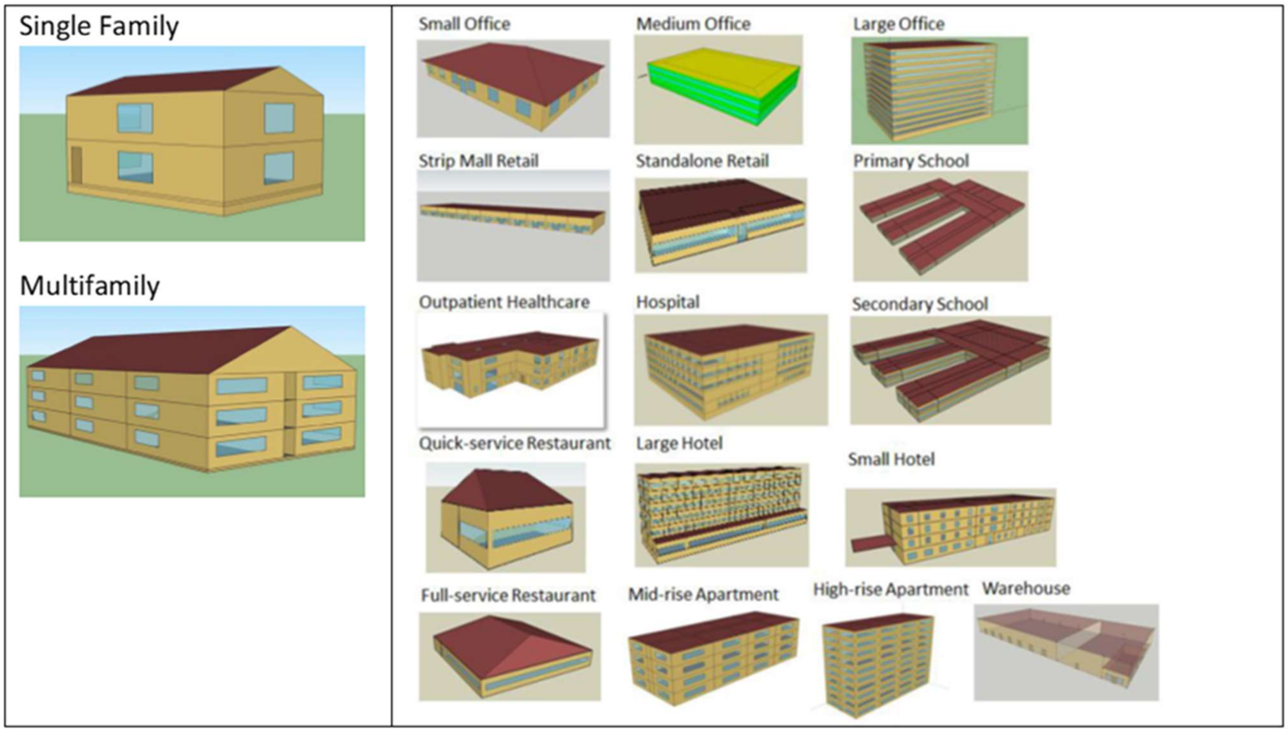

Figure 1. 3D Rendering of Residential and Commercial Prototype Building Models

Variations of the prototype models are created to match the model code requirements that vary by climate zone, such as wall insulation. The prototypes characterize a cross-section of common building types and climate zones, representing about 80% of new residential and commercial floor area.[10] Evaluating the PI metric involves using the building simulation models to determine the prototypes' annual site energy use and costs. To evaluate the PI value at the national level, the prototype annual energy costs are scaled using floor-area weighting factors defined for each building type and climate-related geographic regions developed from recent construction data.[11,12] The weighting factors used in the analysis are presented in Appendix B. Most of the new construction floor area occurs in climate zones 2, 3, 4, and 5. In these regions, the new residential floor space equals 21%, 29%, 22%, and 19%, respectively. For commercial buildings, the distribution of floor area is 19%, 26%, 25%, and 22%, respectively.

To evaluate the PI value at the national level, the prototype annual energy costs are scaled using floor-area weighting factors defined for each building type and climate-related geographic

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[10] The residential and commercial building prototype models used to inform code development can be accessed from https://www.energycodes.gov/development.
[11] The residential building weighting factors are developed by PNNL by applying U.S. housing starts and building permit data reported monthly by the U.S. Census Bureau and the U.S. Department of Housing and Urban Development.
[12] The commercial building weighting factors are developed by PNNL from data acquired from the Dodge Data & Analytics database. See Lei et al. 2020.

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[13] The residential building weighting factors are developed by PNNL by applying U.S. housing starts and building permits data reported monthly by the U.S. Census Bureau and the U.S. Department of Housing and Urban Development.

[14] The commercial building weighting factors are developed by PNNL from data acquired from the Dodge Data & Analytics database. See Lei et al. 2020.

3.0 Assessing the Efficiency Gap

This section explains how the PI process is applied to assess the site energy efficiency gap associated with the referenced baseline code and the ZE goal. It examines the rate of change of the PI metric across historical code cycles to gauge the rate of change needed to meet the ZE goal by 2030. It also provides efficiency data tables that show the progressive improvement in prescriptive requirements across historical code cycles and compares them to the advanced measures.

Of course, achieving ZE buildings cannot be accomplished with efficiency alone. ZE solutions involve coupling high-efficiency buildings with renewable energy generation to offset their annual energy need. Thus, this analysis includes the estimated energy offsets associated with on-site rooftop PV system energy generation based on the prototype buildings' geometries and the solar resources associated with representative cities in each of the 16 climate zone sites. The analysis also quantifies the national PI value resulting from the adoption and implementation of advanced efficiency measures not yet included in the reference baseline code to gauge the level of aggressiveness needed to fill the efficiency gap. In the analysis, the PI values are presented relative to a historical baseline, which is the 2006 IECC for residential buildings and ASHRAE Standard 90.1-2004 for commercial buildings. The reference baselines for assessing the ZE performance gap are the 2018 IECC and ASHRAE Standard 90.1-2019.

3.1 Quantifying Energy Code Advancements

In the PI process, the baseline condition of each of the model code prototypes for each climate location represents a minimally code-compliant building. Because the model codes are continually maintained and published every 3 years, the prototype building models are as well. Thus, the prototype models reflect code requirements associated with a specific code cycle. At the start of a new code cycle, the current code prototype models are updated to reflect the new addenda approved since the previous code cycle was published.

The PNNL building prototype modeling framework comprises the core set of prototype models and parametric analysis capabilities, which accommodates modeling past code cycles and adding new requirements as indicated in energy code addenda. This built-in backward compatibility minimizes potential discrepancies, such as those that might arise due to the use of different simulation software versions. In this study, for residential buildings, we utilized the PNNL framework to determine the PI metric for the IECC residential 2006 code cycle through 2018. For commercial buildings, we applied it to evaluate the PI metric for the ASHRAE 90.1-2004 code cycle through 2019. The parametric capabilities of the framework were also utilized to modify the code baseline conditions to analyze the impact of advanced efficiency improvements that go beyond code. In this study, the building prototypes are simulated using EnergyPlus 9.0 (DOE 2018).

3.2 Applying Advanced Measures to Assess Impact

Two sets of advanced measures were applied to the current code building prototype models to assess their potential to reduce the ZE efficiency gap. The measure set applied to residential prototypes represents new building construction that meets the Passive House Institute U.S. (PHIUS) performance standard, which targets low-energy design. The measure set applied to the commercial prototypes creates new building constructions that incorporate market-ready advanced measures not yet incorporated into code. More details are presented below about the selection and customization of these sets of measures.

3.2.1 Residential Application of Advanced Measures

PHIUS is a refined climate-specific passive building standard based on the European Passive House standard, includes limited prescriptive requirements, and explicitly limits heating and cooling loads through performance-based requirements (PHIUS 2018). The established criteria are based on optimized modeling studies that account for location, building size, and occupant density (Wright and Klingenberg 2015).[15,16] PNNL worked collaboratively with PHIUS to develop the PHIUS 2018 (PHIUS 2018) efficiency characterizations to apply to the model code prototypes, which are customized for each of the 16 IECC-R climate zone locations. To develop the advanced measure solutions, PHIUS followed their standard modeling procedures, which includes utilizing WUFI Passive, a heat and moisture building simulation software tool.[17] The PHIUS models were developed using the key building characteristics of the PNNL residential prototypes, including exterior dimensions, orientation, site shading, foundation type, number of bedrooms, number of bathrooms, window-to-wall area, space conditioning system types, and water heater type. PHIUS modeled a subset of the 32 residential prototype variations in the 16 IECC-R climate zone locations, which captured about 80% of the single-family building floor area and 50% of the low-rise multifamily building floor area.[18] PNNL mapped the PHIUS solutions to the residential model code prototype EnergyPlus models and followed the PI process to determine the nationally weighted PI representing PHIUS-2018 compliant new construction. Appendix C provides more information about the residential building advanced measure analysis underlying the associated PI value.

3.2.2 Commercial Application of Advanced Measures

The advanced measures applied to the commercial building prototypes comprise a subset of the measures analyzed in an ASHRAE research project led by Glazer (Glazer 2016). Research Project 1651—Development of Maximum Technical Achievable Energy Targets for Commercial Buildings (RP-1651)—investigates the energy efficiency potential of commercial buildings achievable in the near future. The RP-1651 study analyzed 30 measures selected from a master list of nearly 400 measures, consisting of commonly used and cutting-edge technologies. The cost of the measure was not considered in its selection.

The RP-1651 study followed a process similar to that for the model code PI. In RP-1651 study, the advanced measures were applied to the ASHRAE 90.1-2013 code-compliant commercial building models across representative U.S. climate locations. Performance was simulated using

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[15] In this study, the PHIUS-compliant buildings achieved an overall reduction in site energy use of 38% compared to the 2018 IECC reference baseline buildings.

[16] https://www.phius.org/phius-certification-for-buildings-products/project-certification/phius-2018-getting-to-zero

[17] WUFI Passive is a user-friendly building energy modeling software tool that combines passive building energy modeling with hygrothermal analysis, which assesses potential moisture issues. More information about WUFI Passive can be found at https://www.phius.org/software-resources/wufi-passive-and-other-modeling-tools/wufi-passive-3-2

[18] The single-family prototypes captured two foundation types (slab and crawlspace) and two base heating systems (gas furnace and heat pump). The crawl space results were assumed indicative of the nonheated basement results and included the weighting factor for this foundation type. The multifamily prototypes captured one foundation type (slab) and two base heating systems (gas furnace and heat pump).

EnergyPlus. The simulation-determined baseline and technical potential annual performance values were weighted, based on new construction data, to determine and compare overall commercial building performance at the national scale.

For this study, 17 of the 30 measures analyzed in RP-1651 were evaluated. This measure subset was selected using engineering judgment based on their perceived higher current market share, as well as the fact that the ASHRAE study results indicate that they comprise approximately 90% of the identified energy-saving technical potential. The subset was amended to the 16 commercial building prototypes representing the ASHRAE 90.1-2019 reference baseline model code and simulated using EnergyPlus v9.0. Measures in the RP-1651 study were modeled using Python scripts. The scripts and other supporting materials, distributed along with the published RP-1651 report, are publicly available and accessible from the ASHRAE publications website. For this study, we incorporated the scripts into the PNNL simulation framework and analyzed their impact relative to current MEC. Additional details regarding the commercial building advanced measure analysis are provided in Appendix D.

3.3 Assessing the On-Site Rooftop Solar Offset Potential

Two approaches are followed to determine the national on-site rooftop solar PV generation potential for residential and commercial buildings. The first approach utilizes the prototype building model geometry to estimate the roof area suitable for rooftop PV. The second approach uses observational data collected by light detection and ranging (LiDAR) sensing that characterizes a sample of the U.S. building stock to estimate the roof area suitable for rooftop PV. Because the two approaches utilize two different means for estimating roof area suitable for PV installation by orientation, similar results will increase the confidence of the value determined for the potential on-site energy-use offset attributed to rooftop PV.

3.3.1 PV Potential Based on Prototype Buildings Analysis

In the first approach, the suitable roof area for PV collector installation is determined based on the building azimuth and roof geometry as depicted by the building code prototype models. The PV on-site generation potential is assessed for each building type in the U.S. climate zone locations. The annual renewable energy generation is calculated using PVWatts Version 6.[19]

For slanted or flat roof geometries, a roof area adjustment factor of 80%[20] is applied to account for shading and roof obstructions that limit the viable roof area. For prototypes with slanted roofs, the collectors are assumed to be roof mounted on the south, east, and west roof orientations. Panels are installed on the plane of each rooftop face, and the collector-to-suitable roof area is assumed to be 98% of the roof plane. For prototypes with flat roofs, the collector tilt angle is set at 20 degrees, and 70%[21] of the flat roof area is assumed to be viable for collectors to account for spacing between rows. Thus, 56% and 78% of the considered roof area is identified as suitable for PV collectors for the flat and sloped roof orientations, respectively. With the north orientations excluded for sloped roofs, the percent of total building roof area (including the north area) deemed suitable for PV development is approximately 40% for residential code prototype buildings and 55% for commercial code prototype buildings, based on the prototypes'

[19] Dobos 2014. Tool accessible at https://pvwatts.nrel.gov/.

[20] This assumption is consistent with the value assessed based on LiDAR data (Gagnon et al. 2016).

[21] Ibid

geometries. These percentages are approximate to those determined for existing buildings (Gagnon et al. 2016).[22]

The annual PV energy generation determined for each prototype and climate zone was scaled using the new construction weighting factors to evaluate the national offset potential. Some additional analysis considerations are outlined below. Further details are provided in Appendix F.

- Three out of the sixteen commercial prototypes have sloped gable roofs, not flat roofs. These are the small office, quick service restaurant, and full service restaurant.
- The two residential prototypes have sloped gable roofs.
- All prototypes with sloped roofs have a long east-west axis, resulting in south- and north-facing roof areas.
- The default PVWatt input values are utilized in the analysis. They include a PV system efficiency of 16%, inverter efficiency of 98%, and DC-to-AC size ratio of 1.2.

3.3.2 PV Potential Based on Building Stock Analysis

In the second method, we evaluated the solar generation potential based on published data (Gagnon et al. 2016). The published research reports the rooftop PV technical potential for all U.S. buildings. The study uses LiDAR data observed for 128 cities and their surrounding areas. The study uses the LiDAR data to estimate the appropriate roof area for PV system installation after accounting for roof tilt, orientation, contiguous roof area, shading, and obstructions. Statistical models were applied to extrapolate the LiDAR data to determine the national technical potential for on-site rooftop PV. The generation estimate was disaggregated into three building footprint size categories (small, medium, and large).

To use the published data for our application, we supplemented it with U.S. floor area and building characteristics survey data. We used the survey data[23] to allocate U.S. floor area across three categories: buildings associated with (1) residential codes, (2) commercial codes, and (3) industry. Using survey micro data, we further disaggregated the floor-area data into floor height categories, which supported the assignment of floor areas to the three building footprint categories. This enabled cross-referencing of the U.S. rooftop PV generation potential data to the residential and commercial energy code building floor-area categories of interest in this report. Further details underlying the two approaches for estimating the rooftop PV energy offsets are provided in Appendix F.

3.4 Comparison of Prescriptive Requirements

To gain further insights into past code achievements and future code requirements that support the design of ZE buildings, minimum efficiency levels associated with the past, current, and beyond-code measures are presented below. Table 2 presents efficiency values for the five

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[22] The Gagnon study reports viable roof area as a function of three building footprint categories. These values were applied to each prototype, as well as their new construction weighting factor, to determine the aggregated weighted values representing residential and commercial new construction.

[23] The data sources include Energy Information Agency (EIA) Annual Energy Outlook, the Residential Energy Consumption Survey (RECS), the Commercial Energy Consumption Survey (CBECS), the Manufacturers Energy Consumption Survey, and the American Housing Survey.

residential IECC code cycles (2006–2018) alongside those utilized in the beyond-code PHIUS analysis. Two sets of additional benchmarks are also provided, including the national program requirements for: (1) the DOE Zero Energy Ready Homes (ZER Homes) and (2) the ENERGY STAR Certified Homes (Energy Star Homes). The ZER Homes program recognizes builders that apply the program attributes to increase efficiency, improve indoor air quality, and make homes ZE ready, which implies that they are at least 40% to 50% more efficient than a typical new home. The Energy Star Homes program supports builder branding and assures that certified homes are at least 10% better than those built to code, achieving a 20% performance improvement on average. As noted in Table 2, some efficiency requirements remain the same across all climate zones, while those affecting building thermal resistance and air tightness are variable. For the latter, data are provided for climate zone 4A, which has mixed warm/cool, and humid conditions. The energy efficiency values for all climate zones are presented for current code and the PHIUS beyond-code cases in Appendix F. The Table 2 values indicate that the PHIUS package has a better envelope with highly thermally resistant (lower U-value) walls and ceilings, high-performance windows, and lower air leakage compared to the current energy code. In addition, the PHIUS design includes a markedly higher cooling system efficiency. As noted in Appendix C, the PHIUS package also includes energy-efficient appliances.

Table 3 presents efficiency values for the six ASHRAE 90.1 code cycles (2004–2019) alongside those utilized in the beyond-code measures analysis. The list includes a sampling of code-compliant mechanical system equipment efficiencies. Values are provided for the beyond-code measures if relevant. As noted in Table 3, some efficiency requirements remain the same across all climate zones, while those affecting building thermal resistance vary based on climate zone. The overall building interior lighting levels also vary based on building type due to differences in occupant tasks and associated light levels. The table values indicate that the beyond-code package includes a significantly better envelope and windows. The overall installed lighting power density is lower, and the cooling equipment is also more efficient.

The beyond-code measures data listed in Table 2 and Table 3 indicate the progressive improvement in measure performance levels over historical code cycles. The tables include the values associated with beyond-code measures, including the advanced measures. As indicated in Figure 2 and Figure 3, the packages provide impactful efficiency improvements toward filling the efficiency gap, reducing it by approximately 30% and 20% for residential and commercial buildings, respectively.

Table 2. The Efficiency Progression of Residential Building Measures

Climate Zone	Measures		Units	Energy Efficiency Values							
				IECC					Beyond-Code Measures (PHIUS)	ZER Homes	Energy Star
				2006	2009	2012	2015	2018			
All	Lighting		Relative lms/W (%)	-	50	75	75	90	100	80% installed are ES	80% installed are ES
All	Cooling		SEER	13.1	13.3	13.3	13.4	13.4	21.9	15	13
All	Heating	Gas Furnace	AFUE	79.8	79.8	79.8	79.8	79.8	90	90	95
All		Heat Pump	HSPF	8.1	8.1	8.1	8.2	8.2	8.2	9	8.5
CZ 4	Floor		U-value	0.047	0.047	0.047	0.047	0.047	0.047		
CZ 4	Foundation	Slab	U-value	0.100	0.100	0.100	0.100	0.100	0.048	R-10, 2 ft	R-10, 2 ft
CZ 4		Crawl space	U-value	0.065	0.065	0.065	0.065	0.065	0.049	0.065	0.065
CZ 4	Envelope	Walls	U-value	0.082	0.082	0.057	0.06	0.06	0.027	0.06	0.057
CZ 4		Ceiling	U-value	0.03	0.03	0.026	0.026	0.026	0.016	0.026	0.026
CZ 4		Windows	U-value	0.40	0.35	0.35	0.35	0.32	0.26	0.3	0.30
CZ 4			SHGC	NR	NR	0.40	0.40	0.40	0.31	0.25	0.40
CZ 4	Air leakage		ACH50	8.00	7.00	3.00	3.00	3.00	0.33	2.5	3

CZ is climate zone.

Table 3. The Efficiency Progression of Commercial Measures

Prototype	Climate Zone	Measures		Efficiency Units	Energy Efficiency Values, Weighted U.S.						
					ASHRAE Standard 90.1						FS Beyond Code
					2004	2007	2010	2013	2016	2019	
All	All	Lighting		Relative lighting power density (LPD)	1	1	0.9	0.82	0.79	0.79	0.26
All	All	Cooling	Packaged RTUs (< 65,000 Btu/h)	Energy efficiency ratio (EER)	11.3	12.0	13.0	14.0	14.0	14.0	15.9
All	All	Cooling	Air-cooled chillers (< 150 tons)	Energy efficiency ratio (EER)	9.6	9.6	9.6	10.1	10.1	10.1	
All	All	Cooling	Water-cooled chillers (300–600 tons)	kW/ton	0.58	0.58	0.58	0.56	0.56	0.56	0.43
All	All	Heating	Warm-air furnace, gas (< 225,000 Btu/h)	Eff.	0.80	0.80	0.80	0.80	0.80	0.81	0.81
All	All	Heating	Boilers, hot water, gas (> 2,500 kBtu/h)	Eff.	0.80	0.80	0.82	0.82	0.82	0.82	
Med Office	4A	Envelope (medium office in CZ 4A)	Roof, above deck	U-value	0.063	0.048	0.048	0.037	0.032	0.032	0.007
Med Office	4A	Envelope (medium office in CZ 4A)	Floor	U-value	0.322	0.322	0.322	0.322	0.033	0.033	
Med Office	4A	Envelope (medium office in CZ 4A)	Walls	U-value	0.124	0.064	0.064	0.064	0.064	0.064	
Med Office	4A	Envelope (medium office in CZ 4A)	Windows + frame	U-value	0.57	0.55	0.55	0.42	0.38	0.37	0.09
Med Office	All	Lighting	Exterior lighting	W	14,338	14,338	7,922	7,922	5,237	5,237	1751
Med Office	All	Lighting	Interior lighting	LPD	1	1	0.9	0.82	0.79	0.64	0.26
Med Office	All	Lighting	Task lighting	LPD	0	0	0	0	0	0	0.18

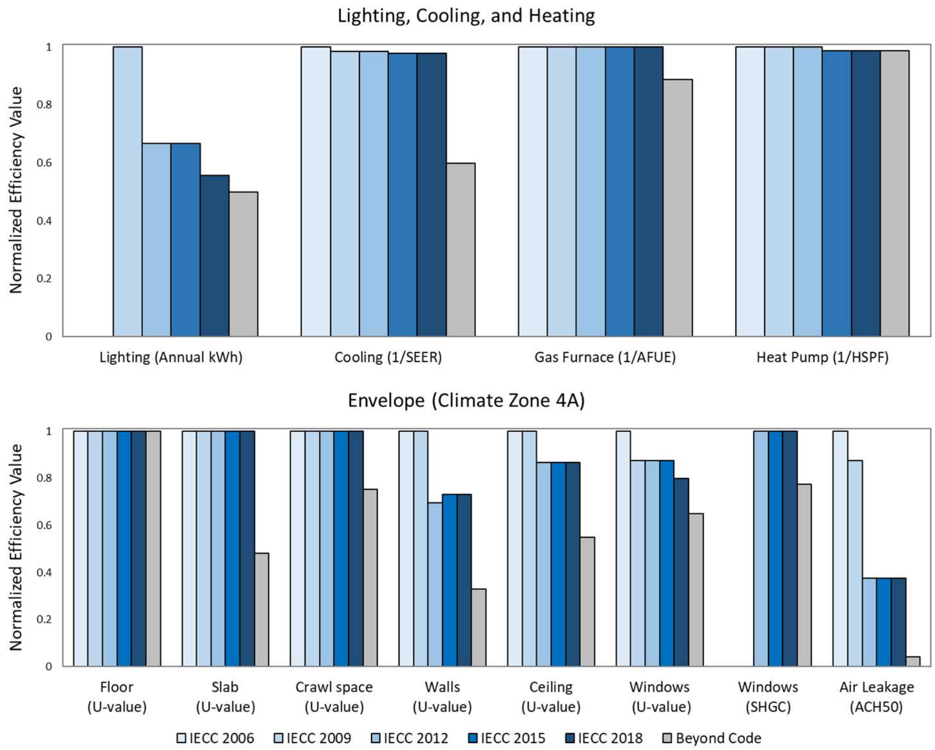

Figure 2. Normalized Performance Values for Residential Building Measures

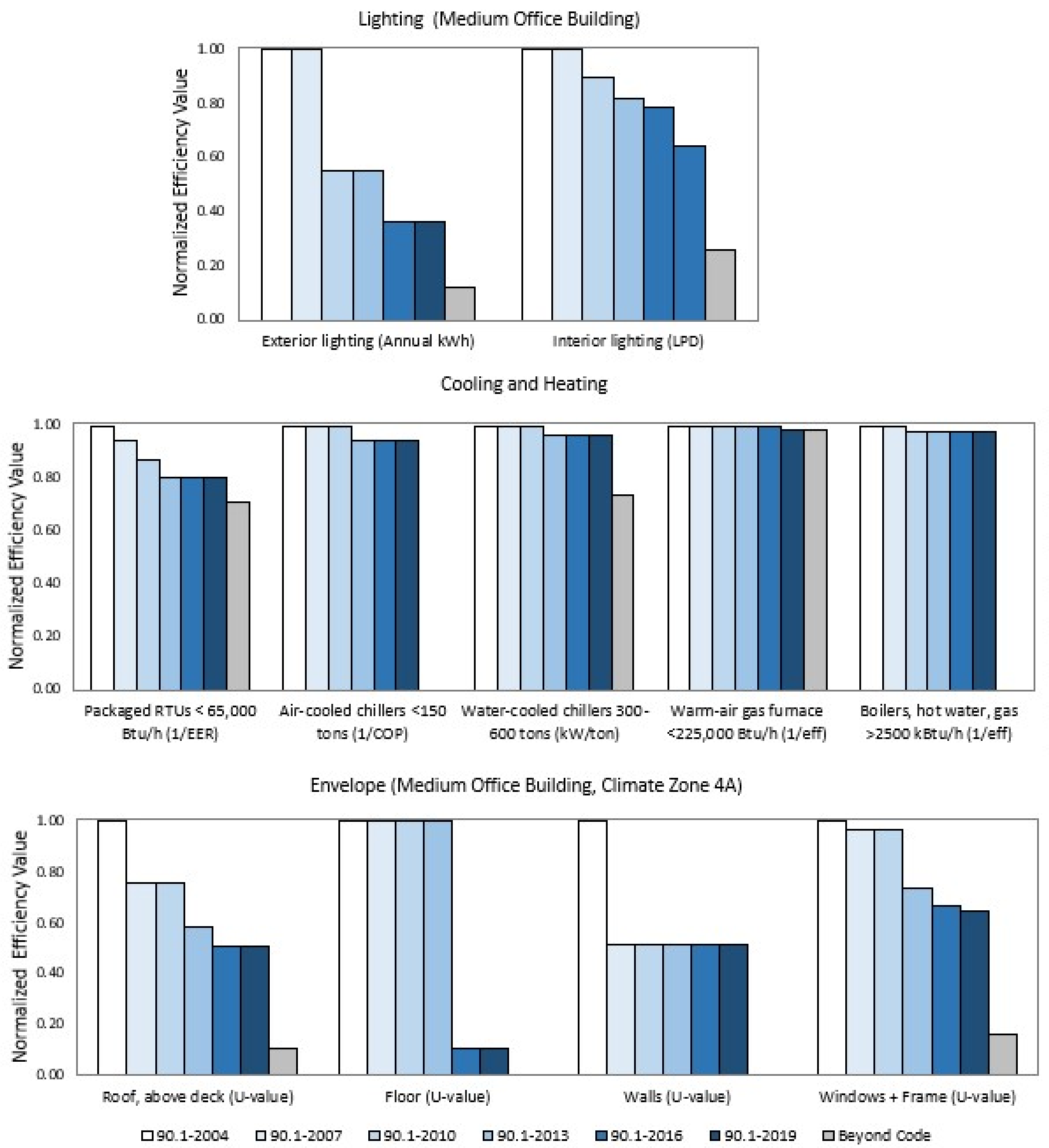

Figure 3. Normalized Performance Values for Commercial Building Measures

4.0 Results

This section presents the prototype building simulation analysis results that quantify the historical advances achieved in MECs, as well as the additional performance impact of advanced measures and rooftop solar. Results are presented by climate zone, as well as at the national level. The analysis and results are intended to provide guidance for future model code development and aid in the establishment of code-cycle performance goals.

4.1 Energy and Cost Savings

For each climate zone and building type, the energy savings and associated annual energy cost savings relative to the referenced baseline model code were determined for individually applied measures and for the package of measures. Table 4 and Table 5 present the average annual energy savings determined from the performance analysis for residential and commercial new buildings, respectively. For each measure, the cost savings is the weighted average value based on the floor area attributed to each building type constructed in the climate zone. For residential buildings, the advanced measure package results in annual energy savings that range from 40% to 52% of baseline energy use. In general, the measure savings vary across climate zones. For example, reducing plug loads results in the highest savings in hot climates due to the associated reduction in cooling loads. In cold climates, however, reducing plug loads results in a heating penalty and reduced annual savings. For commercial buildings, the beyond-code measure package results in annual energy savings that range from 30% to 53% of baseline energy use. The measure savings also vary across climate zones although more moderately than the residential measures, with lighting and heating, ventilation, and air conditioning (HVAC) equipment efficiency measures having the largest impact.

The advanced measures applied to the reference baseline residential prototypes indicate substantial energy use reductions can be achieved with passive measures. These measures, which include increasing envelope insulation, shading windows with blinds and overhangs, and reducing air leakage, result in savings ranging from 16% to 39% of baseline energy use. Plug load energy use reductions result in notable savings, ranging from 8% to 29%. This may indicate that the underlying assumptions dictating baseline plug load energy use need to be updated to reflect typical loads, which will be investigated in future work.[1] Increased efficiency in heating and cooling systems comprise 5% to 14% savings, with the highest savings occurring in the warmest climate zones.

For commercial buildings, the highest savings are achieved from mechanical system efficiency improvements, which range from 7% to 31%, with the greater savings achieved in warmer climates. Improvements in lighting efficiency and the addition of fixture-level daylighting controls provide savings ranging from 8% to 16% across the climate zones. Envelope improvements result in 2% to 8% savings, with higher savings achieved in the coldest climates. As indicated in Table 5, no modifications to insulation levels were applied to climate zone 3C, which is a moderate climate with low space conditioning loads.

Table 6 and Table 7 provide the energy cost savings determined from the analysis for residential and commercial buildings, respectively. The assumed costs of energy for the residential code analysis are based on values used in the 2018 IECC residential energy code

[1] The plug loads for the 2018 IECC-R model code prototype buildings are based on the appliance and miscellaneous load characterizations developed for Building America (Hendron and Engebrecht 2010)

cost savings determination, which are \$0.13/kWh for electricity and \$1.08/therm for natural gas. The assumed commercial energy costs are consistent with values used in the ASHRAE 90.1-2019 commercial MEC savings determination, which equal \$0.106/kWh and \$0.98/therm. For residential buildings, the PHIUS measure package results in annual energy cost savings that range from \$0.33/ft^2 to \$0.77/ft^2. The package cost savings are highest in the coldest climates and lowest in the moderate climates. The widest range of cost savings occurs for the envelope and air infiltration measures. For commercial buildings, the beyond-code measure package results in annual energy cost savings that range from \$0.29/ft^2 to \$0.46/ft^2. The measure savings are most significant for high-efficiency cooling equipment in the warmer climate zones and for demand control ventilation in the colder climates.

A justified first cost (JFC) approach, which has been applied in previous PNNL code studies (Taylor and Mendon 2016), was utilized in this analysis to inform code development cost-effectiveness considerations for the beyond-code measures. JFC signifies the first cost that exactly balances costs and benefits over the life of the measure. Once the market price reflects the JFC, measure implementation or adoption in the energy code can be economically justified. JFC is a useful concept to apply when first costs are not known or vary regionally, which may be the case for future considerations, new technologies, or builders with different purchase volumes. The JFC can be defined in terms of many different economic test metrics, such as simple payback period or life-cycle cost analysis. For this study, a life-cycle cost approach is followed to determine the JFC and is consistent with the underlying economic assumptions used in code development. The economic parameters, their values, and resulting JFC curves are presented in Appendix H.

The JFC values for the beyond-code measures listed in Table 8 and

Table 9 have been normalized based on residential and commercial floor-area values, respectively. Indicated in each table is the percent of new construction floor area that the measure applies to based on the total new construction floor area for the building sector. The values provided can be utilized in conjunction with new code proposals informed by the beyond-code efficiency measures described in Appendix F and Appendix G. The data can be utilized by code-making bodies, industry stakeholders, and policy makers to identify the technologies ripe for adoption and those that may be promising in future code cycles.

Table 4. Feasibility Study Beyond-Code Residential Measure Energy Savings

Measures		Efficiency Units	Energy Savings Relative to IECC 2018 Referenced Baseline														
			CZ1A	CZ2A	CZ2B	CZ3A	CZ3B	CZ3C	CZ4A	CZ4B	CZ4C	CZ5A	CZ5B	CZ6A	CZ6B	CZ7	CZ8
All		NA	45%	47%	52%	45%	44%	40%	42%	46%	40%	46%	45%	45%	46%	46%	47%
Foundation	Slab	U-value	12%	9%	9%	7%	6%	2%	6%	6%	5%	4%	5%	3%	4%	2%	1%
	Crawl space	U-value															
Envelope	Walls	U-value	1%	7%	6%	6%	4%	5%	8%	9%	7%	12%	11%	12%	14%	14%	19%
	Ceiling	U-value															
	Window	U-value															
		SHGC															
Shading		NA	3%	2%	4%	1%	2%	2%	2%	2%	2%	1%	1%	1%	1%	1%	0%
Air Leakage		ACH50	6%	9%	8%	10%	6%	7%	10%	9%	10%	14%	11%	16%	14%	18%	19%
Lighting		kWh/year	6%	5%	4%	4%	4%	4%	4%	4%	3%	2%	3%	2%	2%	2%	1%
Plug Loads		kWh/year	29%	26%	29%	24%	29%	25%	20%	23%	19%	16%	19%	14%	15%	11%	8%
Cooling		SEER	12%	9%	9%	7%	6%	2%	6%	6%	5%	4%	5%	3%	4%	2%	1%
Heating	Gas Furnace	AFUE	2%	3%	3%	4%	3%	3%	3%	4%	4%	5%	4%	5%	5%	5%	6%
	Heat Pump	HSPF															

Table 5. Feasibility Study Beyond-Code Commercial Measure Energy Savings

FS Advanced Measures		Efficiency Units	Energy Savings Relative to ASHRAE 90.1-2019 Referenced Baseline															
			CZ1A	CZ2A	CZ2B	CZ3A	CZ3B	CZ3C	CZ4A	CZ4B	CZ4C	CZ5A	CZ5B	CZ5C	CZ6A	CZ6B	CZ7	CZ8
	All Measures		35%	34%	36%	39%	33%	30%	45%	33%	34%	47%	36%	35%	53%	34%	47%	50%
Envelope	Roof, above deck	U-value	1%	1%	1%	2%	1%	0%	3%	2%	2%	4%	4%	3%	4%	4%	4%	6%
	Windows	U-value	1%	1%	1%	2%	1%	0%	3%	2%	2%	4%	2%	2%	4%	4%	3%	4%
Lighting	Exterior lighting	W	2%	2%	2%	2%	2%	2%	2%	1%	2%	1%	1%	1%	1%	1%	1%	1%
	Interior lighting	LPD	7%	8%	9%	7%	7%	7%	6%	7%	5%	7%	5%	5%	7%	7%	3%	3%
	Task lighting	LPD	1%	1%	2%	1%	1%	2%	1%	1%	1%	0%	1%	1%	1%	1%	1%	0%
	Daylighting	kWh/year	2%	2%	3%	2%	2%	2%	1%	2%	1%	1%	1%	1%	1%	1%	1%	1%
Plug Loads	Office equipment	Equipment power density (EPD)	5%	5%	5%	4%	5%	7%	3%	4%	4%	2%	4%	3%	2%	2%	2%	1%
HVAC	Fans	W/cubic feet per minute (CFM)	3%	3%	3%	2%	3%	3%	2%	2%	2%	1%	2%	2%	1%	2%	1%	1%
	Ducts	W/CFM	2%	3%	3%	2%	2%	2%	2%	2%	1%	1%	2%	2%	1%	2%	1%	1%
	Chillers	COP	8%	7%	5%	5%	4%	3%	3%	3%	1%	2%	2%	1%	2%	2%	2%	1%
	Chillers	Delta temperature (DT), supply air temperature (SAT) (varies, $/ft^2)	4%	3%	1%	2%	2%	1%	2%	3%	2%	2%	3%	0%	1%	2%	1%	1%
	HE packaged direct	EER	14%	11%	11%	7%	8%	5%	4%	6%	2%	3%	4%	2%	3%	3%	2%	1%

expansion (DX)																	
HE Heat pump	EER, COP	10%	9%	8%	11%	8%	2%	10%	10%	8%	15%	10%	8%	15%	9%	9%	12%
Variable refrigerant flow (VRF) system	EER, COP	16%	16%	11%	15%	11%	12%	18%	9%	14%	21%	15%	17%	26%	17%	25%	27%
Demand control ventilation	CO_2 limit	3%	4%	2%	5%	3%	0%	6%	6%	5%	10%	8%	8%	12%	10%	11%	19%
Indirect evaporative pre-cooling	Effectiveness	1%	2%	9%	2%	6%	2%	1%	5%	1%	1%	3%	0%	1%	2%	1%	1%

Table 6. Feasibility Study Beyond-Code Residential Measure Cost Savings

Measures		Efficiency Units	Energy Cost Savings Relative to 2018 IECC ($/ft^2 floor area per year)														
			CZ1A	CZ2A	CZ2B	CZ3A	CZ3B	CZ3C	CZ4A	CZ4B	CZ4C	CZ5A	CZ5B	CZ6A	CZ6B	CZ7	CZ8
All		NA	0.413	0.450	0.566	0.445	0.399	0.328	0.430	0.451	0.388	0.502	0.469	0.495	0.499	0.569	0.766
Foundation	Slab	U-value	0.019	0.021	0.021	0.024	0.022	0.021	0.022	0.022	0.021	0.022	0.022	0.022	0.024	0.025	0.032
	Crawl space	U-value	0.035	0.020	0.020	0.021	0.020	0.020	0.021	0.022	0.020	0.021	0.022	0.021	0.019	0.021	0.022
Envelope	Walls Ceiling Window	U-value U-value U-value SHGC	0.009	0.055	0.057	0.034	0.027	0.029	0.074	0.062	0.056	0.096	0.084	0.100	0.105	0.139	0.261
Shading		NA	0.024	0.018	0.058	0.019	0.018	0.019	0.020	0.021	0.022	0.020	0.022	0.020	0.020	0.019	0.016
Air leakage		ACH50	0.060	0.075	0.071	0.069	0.042	0.035	0.086	0.059	0.065	0.111	0.075	0.123	0.101	0.173	0.258
Lighting		kWh/year	0.053	0.050	0.052	0.050	0.049	0.046	0.048	0.050	0.046	0.047	0.048	0.045	0.047	0.044	0.044
Plug loads		kWh/year	0.266	0.270	0.344	0.302	0.299	0.260	0.238	0.300	0.258	0.279	0.292	0.265	0.286	0.250	0.250

Cooling		SEER	0.113	0.088	0.101	0.064	0.049	0.019	0.059	0.052	0.031	0.036	0.039	0.026	0.018	0.010	-0.005
Heating	Gas furnace	AFUE	0.020	0.028	0.025	0.032	0.025	0.025	0.036	0.033	0.033	0.045	0.038	0.047	0.044	0.057	0.081
	Heat pump	HSPF	0.019	0.020	0.019	0.020	0.019	0.019	0.020	0.021	0.020	0.020	0.020	0.019	0.020	0.019	0.020

Table 7. Feasibility Study Beyond-Code Commercial Measure Cost Savings

FS Advanced Measures		Efficiency Units	Energy Cost Savings Relative to ASHRAE 90.1-2019 ($/ft^2 floor area per year)															
			CZ1A	CZ2A	CZ2B	CZ3A	CZ3B	CZ3C	CZ4A	CZ4B	CZ4C	CZ5A	CZ5B	CZ5C	CZ6A	CZ6B	CZ7	CZ8
All Measures			0.398	0.406	0.431	0.387	0.461	0.350	0.332	0.347	0.463	0.246	0.409	0.281	0.376	0.361	0.361	0.377
Envelope	Roof, above deck	U-value	0.008	0.012	0.011	0.016	0.016	0.010	0.000	0.017	0.015	0.010	0.024	0.020	0.031	0.027	0.032	0.055
	Windows	U-value	0.017	0.016	0.014	0.005	0.005	0.009	0.000	0.022	0.013	0.007	0.023	0.010	0.032	0.028	0.031	0.046
Lighting	Exterior lighting	W	0.025	0.022	0.023	0.021	0.021	0.023	0.021	0.022	0.022	0.021	0.022	0.021	0.021	0.020	0.021	0.023
	Interior lighting	LPD	0.098	0.116	0.120	0.106	0.106	0.100	0.096	0.090	0.120	0.079	0.104	0.096	0.116	0.112	0.105	0.117
	Task lighting	LPD	0.012	0.015	0.020	0.015	0.015	0.014	0.023	0.011	0.019	0.014	0.011	0.016	0.013	0.013	0.013	0.012
	Daylighting	kWh/year	0.024	0.031	0.034	0.026	0.026	0.027	0.026	0.023	0.035	0.021	0.025	0.026	0.025	0.027	0.026	0.031
Plug Loads	Office equipment	EPD	0.073	0.069	0.070	0.061	0.061	0.058	0.083	0.055	0.066	0.059	0.051	0.065	0.054	0.057	0.054	0.051
HVAC	Fans	W/CFM	0.044	0.038	0.038	0.035	0.035	0.035	0.032	0.031	0.042	0.028	0.031	0.035	0.034	0.038	0.037	0.039
	Ducts	W/CFM	0.032	0.036	0.037	0.033	0.033	0.032	0.027	0.026	0.042	0.022	0.029	0.033	0.032	0.037	0.037	0.040
	Chillers	COP	0.170	0.139	0.097	0.079	0.079	0.079	0.049	0.056	0.053	0.024	0.039	0.039	0.043	0.035	0.040	0.018
	Chillers	DT, SAT (varies, $/ft2)	0.074	0.053	0.021	0.041	0.041	0.020	0.016	0.035	0.067	0.020	0.040	0.052	0.017	0.045	0.018	0.022
	HE packaged DX	EER	0.182	0.140	0.122	0.090	0.090	0.077	0.049	0.059	0.079	0.025	0.045	0.048	0.051	0.041	0.047	0.028
	HE heat pump	EER, COP	0.129	0.104	0.091	0.074	0.074	0.065	0.024	0.053	0.068	0.026	0.045	0.033	0.035	0.029	0.019	0.000
	VRF system	EER, COP	0.245	0.235	0.145	0.147	0.147	0.115	0.136	0.129	0.038	0.086	0.076	0.067	0.143	0.062	0.155	0.097
	Demand control ventilation	CO_2 limit	0.035	0.048	0.025	0.041	0.041	0.019	0.001	0.040	0.032	0.018	0.056	0.038	0.083	0.066	0.086	0.146
	Indirect evaporative pre-cooling	Effectiveness	0.020	0.024	0.124	0.033	0.033	0.071	0.022	0.018	0.081	0.013	0.020	0.050	0.017	0.039	0.020	0.023

Table 8. Justified First Cost Beyond-Code Residential Measures

Measures		Efficiency Units	Measure Life (Years)	Floor Area Impacted	Justified First Costs Relative to 2018 IECC ($/ft2 floor area)														
					CZ1A	CZ2A	CZ2B	CZ3A	CZ3B	CZ3C	CZ4A	CZ4B	CZ4C	CZ5A	CZ5B	CZ6A	CZ6B	CZ7	CZ8
All Measures			15	100%	5.5	6.0	7.6	6.0	5.4	4.4	5.8	6.0	5.2	6.7	6.3	6.6	6.7	7.6	10.3
Foundation	Slab	U-value	30	49%	0.4	0.4	0.4	0.5	0.5	0.4	0.5	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.7
	Crawl space	U-value	30	26%	0.7	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Envelope	Walls	U-value	30	100%	0.2	1.1	1.2	0.7	0.6	0.6	1.5	1.3	1.2	2.0	1.7	2.1	2.2	2.9	5.4
	Ceiling	U-value																	
	Windows	U-value																	
		SHGC																	
Shading		NA	20	100%	0.4	0.3	0.9	0.3	0.3	0.3	0.3	0.3	0.4	0.3	0.4	0.3	0.3	0.3	0.3
Air Leakage		ACH50	20	100%	1.0	1.2	1.2	1.1	0.7	0.6	1.4	1.0	1.1	1.8	1.2	2.0	1.6	2.8	4.2
Lighting		kWh/year	10	100%	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.5	0.5	0.5	0.5	0.4	0.5	0.4	0.4
Plug Loads		kWh/year	10	100%	2.6	2.7	3.4	3.0	2.9	2.6	2.3	3.0	2.5	2.7	2.9	2.6	2.8	2.5	2.5
Cooling		SEER	15	100%	1.5	1.2	1.4	0.9	0.7	0.3	0.8	0.7	0.4	0.5	0.5	0.3	0.2	0.1	-0.1
Heating	Gas Furnace	AFUE	15	49%	0.3	0.4	0.3	0.4	0.3	0.3	0.5	0.4	0.4	0.6	0.5	0.6	0.6	0.8	1.1
	Heat Pump	HSPF	15	45%	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Table 9. Justified First Cost Beyond-Code Commercial Measures

Measures		Efficiency Units	Measure Life (Years)	Floor Area Affected	Justified First Cost Relative to ASHRAE 90.1-2019 ($/ft² floor area)															
					CZ1A	CZ2A	CZ2B	CZ3A	CZ3B	CZ3C	CZ4A	CZ4B	CZ4C	CZ5A	CZ5B	CZ5C	CZ6A	CZ6B	CZ7	CZ8
	All measures		21	100%	9.26	9.48	9.32	8.50	10.13	6.89	6.72	7.40	10.60	4.69	9.25	6.09	8.06	9.69	8.89	9.97
Envelope	Roof, above deck	U-value	25	100%	0.18	0.28	0.25	0.36	0.36	0.23	0.01	0.40	0.36	0.24	0.55	0.48	0.32	0.72	0.63	0.74
	Windows	U-value	25	100%	0.40	0.36	0.33	0.12	0.12	0.21	0.00	0.52	0.31	0.16	0.54	0.24	0.25	0.75	0.66	0.72
Lighting	Exterior lighting	W	30	100%	0.71	0.62	0.66	0.61	0.61	0.65	0.60	0.63	0.63	0.61	0.63	0.60	0.61	0.60	0.56	0.59
	Interior lighting	LPD	30	100%	2.80	3.31	3.43	3.02	3.02	2.87	2.76	2.58	3.45	2.27	2.98	2.74	3.49	3.32	3.21	3.00
	Task lighting	LPD	10	80%	0.10	0.13	0.17	0.12	0.12	0.12	0.19	0.10	0.16	0.12	0.09	0.14	0.11	0.11	0.11	0.11
	Daylighting	kWh/year	15	100%	0.32	0.41	0.45	0.34	0.34	0.36	0.34	0.31	0.46	0.28	0.33	0.34	0.39	0.33	0.36	0.35
Plug Loads	Office equipment	EPD	10	100%	0.62	0.59	0.60	0.53	0.53	0.50	0.71	0.47	0.57	0.51	0.44	0.55	0.51	0.46	0.49	0.46
HVAC	Fans	W/CFM	25	100%	1.01	0.89	0.88	0.80	0.80	0.81	0.73	0.72	0.97	0.65	0.73	0.81	0.92	0.79	0.87	0.87
	Ducts	W/CFM	30	100%	0.92	1.02	1.06	0.95	0.95	0.91	0.78	0.75	1.21	0.64	0.83	0.93	1.11	0.92	1.05	1.06
	Chillers	COP	25	23%	3.94	3.22	2.26	1.84	1.84	1.83	1.14	1.30	1.22	0.55	0.91	0.90	0.60	1.00	0.82	0.94
	Chiller controls	DT, SAT optimized	15	9%	0.98	0.70	0.28	0.54	0.54	0.27	0.21	0.46	0.88	0.26	0.53	0.69	0.02	0.22	0.60	0.24
	HE packaged DX	EER	15	78%	2.41	1.86	1.61	1.20	1.20	1.02	0.64	0.77	1.04	0.33	0.60	0.63	0.37	0.68	0.54	0.62
	HE heat pump	EER, COP	15	85%	1.70	1.38	1.20	0.98	0.98	0.86	0.32	0.69	0.90	0.35	0.59	0.44	0.39	0.46	0.38	0.25
	VRF system	EER, COP	25	77%	5.70	5.47	3.37	3.41	3.41	2.66	3.15	3.01	0.88	2.01	1.77	1.55	1.38	3.31	1.43	3.60
	Demand control ventilation	CO_2 limit	15	99%	0.46	0.63	0.33	0.54	0.54	0.25	0.01	0.52	0.42	0.24	0.75	0.51	0.54	1.09	0.87	1.14
	Indirect evaporative pre-cooling	Effective ness	15	100%	0.26	0.31	1.64	0.43	0.43	0.94	0.29	0.24	1.07	0.18	0.27	0.66	0.14	0.23	0.51	0.27

4.2 Assessing the Efficiency Gap

Figure 4 and Figure 5 indicate historical MEC progress for U.S. buildings and the advancements needed to achieve ZE new construction by 2030. The slope of the brown dashed line and the green dashed line indicate the rate of advancement of historical code and that required to achieve ZE by 2030, respectively. The black dashed line indicates the normalized energy use index (NEUI) achieved after amending the referenced baseline code (2018 IECC for residential and 90.1-2019 for commercial) with the advanced measures considered. The yellow dashed line indicates the energy offset potential associated with rooftop solar. The value is the average determined from two different assessment methods. For the residential solar offset, method one (prototype roof area analysis) and method two (LiDAR roof area analysis) resulted in offset NEUI values of 0.28 and 0.27, respectively. For the commercial solar assessment, method one and method two resulted in offset NEUI values of 0.32 and 0.26, respectively. In this study, we refer to the difference in NEUI values between the black (advanced measure NEUI) and yellow (solar offset) dashed lines as the "efficiency gap." This gap can be filled through increased efficiency, additional solar offsets, or reductions in unregulated loads. Table 10 list these NEUI benchmarks indicated in Figure 4 and quantifies the ZE efficiency gap relative to historical code, 2006 IECC. Table 11 provides the efficiency gap value relative to the referenced baseline code, 2018 IECC.

For residential buildings, Figure 4 indicates that the rate of historical efficiency gains (slope of dashed brown line) must be exceeded in future code development (slope of green dashed line) if ZE buildings are to be achieved by 2030. In the figure, the rate and magnitude of needed advancements assume that the full rooftop solar energy offset potential is realized. As indicated in Figure 4 and Table 10, the rooftop solar offset potential is significant (reducing NEUI by 0.28) and slightly exceeds the energy-use reductions achieved historically in energy codes from 2006 to 2018 (reducing NEUI by 0.26). The advanced measures reduce the NEUI by 0.26, equaling the offset attributed to historical code improvements. However, a further reduction in NEUI, equaling 0.20, is required to fill the efficiency gap. Relative to 2018 IECC performance, the advanced measures reduce baseline energy use by 36%, rooftop solar offsets the baseline energy use by 38%, and the remaining efficiency gap is 27%, as indicated in Table 11.[34]

For commercial buildings, Figure 5 indicates that the rate of historical efficiency gains must also be exceeded moving forward if ZE buildings are to be achieved by 2030. In the figure, the rate and magnitude of relative advancement assume that the full rooftop solar energy offset potential is realized. As indicated in Figure 5 and Table 10, the rooftop solar offset is significant (reducing NEUI by 0.30) but less than the energy-use reductions achieved historically in energy code from 2004 to 2019 (reducing NEUI by 0.36). Amending the advanced measures to ASHRAE 90.1-2019, reduce the NEUI by 0.21. However, a further reduction in NEUI equaling 0.13 is required to fill the commercial code efficiency gap. Relative to ASHRAE 90.1-2019 performance, the advanced measures reduce the baseline energy use by 33%, rooftop solar offsets the baseline energy use by 48%, and the remaining efficiency gap is 19%, as indicated in Table 11.

[34] ZE gap values stated for the residential code total 101% due to rounding errors.

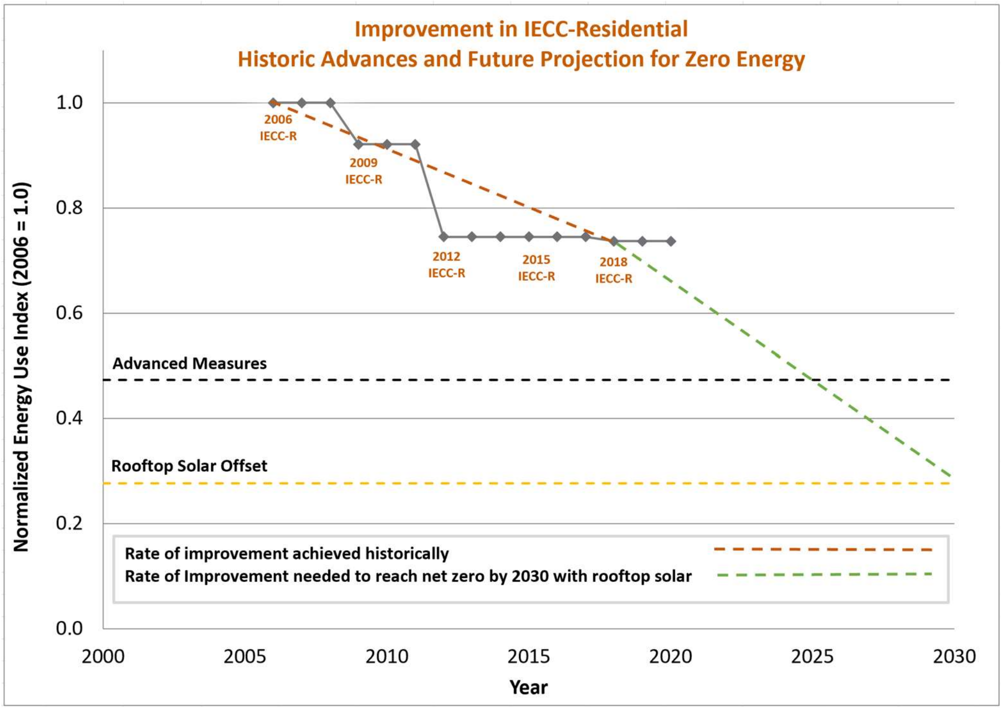

Figure 4. Historical and Needed Advances to Achieve Zero Energy Residential Buildings with Model Energy Codes

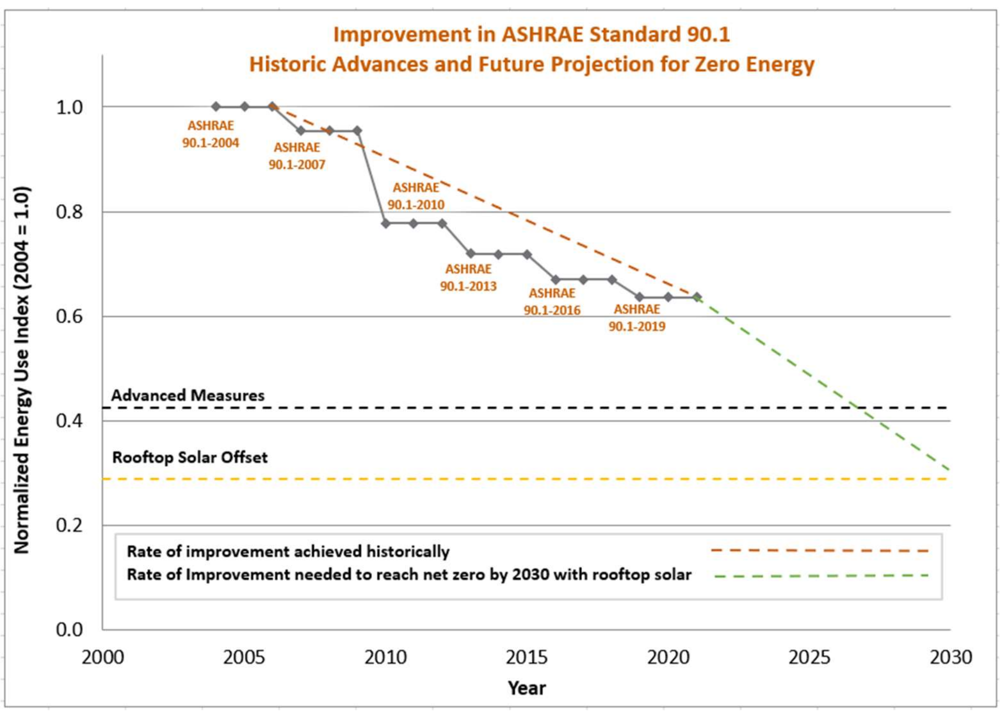

Figure 5. Historical and Needed Advances to Achieve Zero Energy Commercial Buildings with Model Energy Codes

Table 10. Historical and Future Energy Code Advancement

Efficiency Gap Relative to Historical Code 2006 IECC Residential and ASHRAE 90.1-2004 Commercial						
	Residential			Commercial		
	Code cycle	NEUI Value	NEUI Reduction Relative to 2006 IECC	Code cycle	NEUI Value	NEUI Reduction Relative to 90.1-2004
Reference Baseline Code	2018 IECC (four code cycles)	0.74	26%	90.1 2019 (five code cycles)	0.64	36%
Advanced Measures	2021–2030 IECC (+four code cycles)	0.47	26%	90.1 2022–2028 (+three code cycles)	0.42	21%
Rooftop Solar Offset		0.28	28%		0.29	29%
Efficiency Gap		0.20	20%		0.13	13%

Table 11. The Efficiency Gap to Achieve ZE Model Energy Codes

Efficiency Gap Relative to Reference Code 2018 IECC-R and ASHRAE 90.1-2019				
	Residential (IECC 2018)		Commercial (ASHRAE 90.1-2019)	
	Code cycle	Filling the gap	Code cycle	Filling the gap
Advanced Measures	IECC 2021–2030 (four code cycles)	36%	90.1 2022–2028 (three code cycles)	33%
Rooftop Solar Offset		38%		48%
Efficiency Gap		27%		19%

5.0 Discussion

The efficiency gap analysis reveals the on-site energy use impact of current code adoption, beyond-code measures, and on-site rooftop PV, as well as the remaining gap that must be filled to achieve ZE buildings by 2030. The Table 10 data indicate that the rate of efficiency improvements needed in model code to achieve ZE by 2030 requires residential advancements to double what has been achieved historically. Specifically, future energy-use reductions of 46% must be achieved over four residential code cycles—with an average of 11% per cycle—versus historical energy-use reductions of 26% achieved over four code cycles, with an average of 5% per cycle. Commercial advancements also must occur at a rate double that achieved historically. Namely, future energy-use reductions of 34% must be achieved over three commercial code cycles—with an average of 11% per cycle—versus historical energy-use reductions of 36% achieved over five code cycles, with an average of 7% per cycle. Based on the code baselines referenced in this study, these advancements must occur over the residential code development cycles that include IECC-R 2021, 2024, 2027, and 2030. For commercial buildings, the advances must occur over the commercial code development cycles that include ASHRAE 90.1 2022, 2025, and 2028.

The national-level building performance improvements quantified in this study indicate that the efficiency gap for achieving ZE newly constructed buildings with energy codes can be filled as follows.

- Residential
  - 36% with the PHIUS 2018 efficiency improvements
  - 38% with rooftop solar
  - 27% with additional efficiency measures, plug and process load reductions, and renewable energy offsets
- Commercial
  - 33% with market-ready measures not yet included in model codes
  - 46% with rooftop solar
  - 21% with additional efficiency measures and renewable energy systems.

The analysis establishes the significance of on-site energy use offsets from renewable energy resources and the importance of addressing their requirement in model energy codes. In the study, the offset attributed to rooftop solar for residential buildings slightly exceeds that achieved through historical code efficiency advances. For commercial buildings, the potential offset attributed to rooftop solar is 80% of historical code advances. Model energy codes are starting to incorporate requirements for renewable energy resources, albeit at nominal levels. For example, addendum *BY* to ASHRAE 90.1-2019 adds an on-site renewable energy system rated capacity requirement of 0.25 W/ft^2 based on the conditioned floor area for all floors up to the three largest floors. However, to reach the energy offset values cited in this study, much larger PV system capacities are required. Based on the Method one rooftop PV assessment (based on prototype building geometry and orientation), the average PV system design capacity is about 5 W/ft^2 for commercial buildings based on total conditioned floor area. For residential buildings, the cited energy offset associated with the rooftop solar corresponds to an average PV system capacity of 3 W/ft^2.

The assessed beyond-code measures and rooftop solar offsets make substantial gains toward filling the gap but do not result in zero site energy for newly constructed U.S. buildings. Thus, a ZE code will need to account for additional energy-use reduction strategies that might include: increased efficiency improvements, integrative design solutions, reduced plug and process loads, and off-site renewable energy procurement. Addressing such provisions in model energy codes will require enhancing code development procedures and considering new code compliance mechanisms. Many of the supporting activities underlying such a transformation have been described in detail as part of PNNL's commercial code road map (Rosenberg et al. 2015) and apply to both residential and commercial energy codes. Necessary progressions include moving away from the popular prescriptive compliance path and further developing performance compliance approaches, which offers design flexibility, supports innovative low-energy solutions, and substantiates the achievement of established performance targets. A summary is provided below of the underlying activities needed to support the ZE goal for model energy codes.

1. Expand the scope of regulated loads.

The efficiency of appliances and equipment is addressed by federal standards. Currently, more than 60 products, representing 90% of home energy use and 60% of commercial energy use, are subject to these standards.[35] However, as indicated in the beyond-code measure analysis, the energy use and cost savings associated with reduced equipment and plug loads in buildings can be substantial. Efforts are currently underway to expand the scope of regulated loads (not covered by federal standards) in energy codes, which will support ZE achievement. Defining performance compliance metrics in codes that account for all energy use, including regulated and unregulated loads, is also needed.[36]

2. Incorporate requirements for renewable energy resources.

Model energy codes are beginning to incorporate requirements for renewable energy resources, albeit at nominal levels and with restrictions applied to limit trade-offs against efficiency. As efficiency requirements increase in support of established ZE targets for code, the renewable requirements will need to increase as well. As previously cited in this study, nominal requirements are being considered, but much larger system capacities are required to meet the ZE goal.

3. Update performance-based compliance targets over the next code cycles to align with meeting ZE codes by 2030.

The performance-based compliance method in current commercial energy code, utilized in ASHRAE 90.1-2019 as described in Appendix G, is based on predicting performance relative to an ASHRAE 90.1-2004 code-compliant baseline using building simulation analysis. Such an approach supports upholding established relative performance targets. To achieve ZE new

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[35] Accessed at https://www.energy.gov/sites/prod/files/2017/01/f34/Appliance%20and%20Equipment%20Standards%20Fact%20Sheet-011917_0.pdf on September 14, 2020.

[36] For example, the ANSI/RESNET 301 Standard addresses lighting and appliance energy efficiency for credit in the RESNET Energy Rating Index (ERI), which is a performance-based compliance option in residential model code. Currently, refrigerators, dishwashers, clothes washers and dryers, and ceiling fans are minimum rated features where a rated home can gain ERI credit for these high-efficiency appliances. The remaining appliance loads (TVs, entertainment, cooking, etc.) are not minimum rated features and thus are not allowed to be used for ERI credit. Involving most if not all appliance loads toward ZE credit in the energy codes will help drive market transformation of high-efficiency appliances.

buildings by 2030, the targets will need to be specified and aligned with ZE goals over the three code cycles preceding 2030.

For residential buildings, there are two performance-based options in the 2018 IECC. Section R405 is a performance compliance pathway considering regulated loads only (heating, cooling, water heating, mechanical ventilation) where a proposed home must show less energy consumption than that of a standard reference home. Section R406 is the Energy Rating Index (ERI) pathway utilizing the ANSI/RESNET 301 Standard where the ERI of the proposed home must be less than specified targets in the IECC. A home with an ERI of 0 is considered a ZE home. The upcoming 2021 IECC will contain Appendix RB: Zero Energy Residential Buildings to specify the ERI compliance requirements for ZE buildings.

Thus, aligning ASHRAE 90.1 Appendix G and IECC-R ERI performance-based compliance pathways with ZE targets will support progressive advancement toward the 2030 goal.

4. Include prescriptive packages for all appropriate building types.

The introduction of prescriptive packages, which are pre-selected complementary combinations of measures, provides additional flexibility for designers and builders within a prescriptive-based compliance approach while achieving a desired level of performance. They are particularly suitable for smaller or simpler buildings, providing these building types with an interim solution to achieve more integrative design solutions following a prescriptive approach.

5. Create automated software for implementing updated performance approach to help increase its use.

Automated performance software is currently used to provide for making trade-offs between code requirements. Continuing to develop automated performance software will allow simpler buildings to have more flexibility in developing compliant designs and streamline compliance activities. Performance software developers will likely participate.

6. Review code cost-effectiveness policies.

Cost-effectiveness is the criterion typically used in code development for considering new code requirements. Yet, some measures provide additional benefits that are not revealed using fixed, average energy costs, including improved occupant comfort, better space utilization, and demand flexibility in response to a grid signal. While energy code directives do allow for the consideration of societal benefits, methods to quantify impact are missing in code development. Methods and benefit criteria must be developed and introduced into the code development process for quantifying environmental externalities, non-energy benefits like productivity, improved green market value, and improved energy resilience.

7. Move away from the prescriptive component-based compliance approach.

As compliance methods advance, they will increasingly support integrative solutions and streamlined compliance procedures, which will initially be achieved through design packages and ultimately with performance-based solutions developed through automated software. As software tools become available, simpler to use, and include enhanced capabilities, the prescriptive component approach will no longer be widely utilized or necessary.

8. Establish outcome-based codes for new and existing buildings.

Outcome-based codes link actual building performance to desired performance targets. A major benefit of an outcome-based approach is that all building energy use is considered. Establishing appropriate performance targets may prove challenging. Building energy-use benchmarking of actual building performance is a vital step in energy management, which could become an extension of energy codes. Current activities in mandatory building benchmarking will help set the stage for future outcome-based codes. Outcome-based codes must not only apply to newly occupied buildings. Future efforts can focus on establishing requirements for existing and new buildings and be combined with requirements focused on building design to assure the realization of high-performing, low-energy buildings.

6.0 Conclusions

The reference baseline code and beyond-code efficiency improvements considered in this study serve to define a tangible means for reducing building energy use to meet 2030 ZE goals. In addition, quantifying their impact helps gauge the level of aggressiveness and types of modifications needed in model energy codes moving forward.

To meet the 2030 ZE target timeline, the identified energy code advancements must occur over three or four code cycles. The analysis reveals that the market-ready technologies analyzed that are not yet in codes can make a significant contribution to filling the efficiency gap. The energy savings offset attributed to rooftop solar is of equal impact. Addressing efficiency and on-site renewables at the levels identified in the study will not completely fill the gap, but these measures will move model codes significantly closer, filling about 75–80% of the gap. Thus, a ZE code will need to account for additional energy-use reduction strategies that might include greater efficiency improvements, integrative design solutions, reduced plug and process loads, and off-site renewable energy procurement.

To fill the efficiency gap, residential and commercial energy code advancements must occur at a rate double that achieved historically. Specifically, residential code efficiency advancements must average 11% per cycle over four code cycles (2021, 2024, 2027, and 2030), while historical achievements have averaged 5% per cycle (relative to the 2006 historical baseline). Commercial efficiency advancements must average 11% per cycle over three code cycles (2022, 2025, and 2028) while historical achievements have averaged 6% per cycle (relative to the 2004 historical baseline). These on-site energy use reduction targets assume that the rooftop solar energy offsets quantified in the study are achieved. The offsets are equivalent to solar PV system installation capacities of about 5 W/ft^2 for commercial code buildings based on total conditioned floor area and 3 W/ft^2 for residential code buildings.

Filling the efficiency gap and including renewable energy provisions in model energy codes will require enhancing code development procedures and considering new code compliance mechanisms. Required progressions include moving away from the popular prescriptive compliance path and further developing performance compliance approaches, which offers design flexibility, supports innovative low-energy solutions, and substantiates the achievement of established performance targets. In addition, total building energy use must be reflected in performance compliance metrics. Such an approach supports establishing a ZE target to demonstrate compliance.

7.0 References

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Appendix A – Climate Data

Each of the eight climate zones (1–8) and three moisture regimes (A = Moist, B = Dry, C = Marine) defined by the International Energy Conservation Code (IECC) and American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) are provided in Table A.1. The Pacific Northwest National Laboratory (PNNL) residential model code prototype buildings are simulated with the IECC-R climate zone locations. The PNNL commercial model code prototype buildings are simulated with the ASRHAE 90.1 climate zone locations.[1]

Table A.1. Model Code U.S. Climate Zone Locations

Climate Zone	Climate Zone Type	Thermal Condition	IECC - R		ASHRAE 90.1	
			Representative Location	Average Solar Insolation (kWh/ft² day)	Representative Location	Average Solar Insolation (kWh/ft² day)
1AT	Very Hot-Humid	9000 < CDD50°F	Honolulu, HI	0.55	--	
1A	Very Hot-Humid	9000 < CDD50°F	Miami, FL	0.54	Honolulu, HI	0.55
2A	Hot-Humid	6300 < CDD50°F £ 9000	Houston, TX	0.50	Tampa, FL	0.54
2B	Hot-Dry	6300 < CDD50°F £ 9000	Phoenix, AZ	0.61	Tucson, AZ	0.61
3A	Warm-Humid	4500 < CDD50°F £ 6300	Memphis, TN	0.48	Atlanta, GA	0.49
3B	Warm-Dry	4500 < CDD50°F £ 6300	El Paso, TX	0.61	El Paso, TX	0.61
3C	Warm-Marine	HDD65°F £ 3600	San Francisco, CA	0.52	San Diego, CA	0.53
4A	Mixed-Humid	CDD50°F £ 4500 and HDD65°F £ 5400	Baltimore, MD	0.45	New York, NY	0.43
4B	Mixed-Dry	CDD50°F £ 4500 and HDD65°F £ 5400	Albuquerque, NM	0.60	Albuquerque, NM	0.60
4C	Mixed-Marine	3600 < HDD65°F £ 5400	Salem, OR	0.39	Seattle, WA	0.37
5A	Cool-Humid	5400 < HDD65°F £ 7200	Chicago, IL	0.42	Buffalo, NY	0.40
5B	Cool-Dry	5400 < HDD65°F £ 7200	Boise, ID	0.48	Denver, CO	0.53
5C	Cool-Marine	5400 < HDD65°F £ 7200	--		Port Angeles, WA	0.38
6A	Cool-Humid	7200 < HDD65°F £ 9000	Burlington, VT	0.41	Rochester, MN	0.43
6B	Cool-Dry	7200 < HDD65°F £ 9000	Helena, MT	0.43	Great Falls, MT	0.43
7	Very Cold	9000 < HDD65°F £ 12600	Duluth, MN	0.41	International Falls, MN	0.40
8	Sub-Arctic	12600 < HDD65°F	Fairbanks, AK	0.29	Fairbanks, AK	0.29

[1] The residential prototype climate zone location weather files can be accessed at https://www.energycodes.gov/development/residential/iecc_models. The commercial climate zone location weather files can be accessed at https://www.energycodes.gov/development/commercial/prototype_models.

Appendix B – New Construction Floor Area Weighting Factors

The construction weights applied to the prototype buildings are used to aggregate simulation results to represent national new construction performance. The prototype simulation energy results are aggregated as energy use intensity (EUI) per dwelling unit and then converted to EUI per square foot based on the conditioned area.

The residential new construction floor area weighting factors used in this study are presented in Table B.1. They were developed by Pacific Northwest National Laboratory (PNNL) from U.S. new construction permit data for 2019 recorded by the Census Bureau.[1] The permit data are weighted according to the prototype floor area in developing the weight factors. The residential single-family prototype is a two-story building with 2,376 ft^2 for each dwelling unit. The residential multifamily prototype is a three-story building with six dwelling units on each floor. The size of each dwelling unit is 1,200 ft^2. The single-family residential prototypes comprise a suite of 16 sub-models with four foundation types and four heating system types. The conditioned area per dwelling unit is larger for the heated basement foundation case. The basement adds another floor level of conditioned area, which contributes 1,188 ft^2 (2,376 ft^2/2) to each dwelling unit. For the multifamily residential prototype, there are 18 dwelling units in the three-story building. The heated basement consists of the 1,200 ft^2 below each dwelling unit plus the area below the breezeway. Dividing by 3 (the number of stories) adds an additional 443 ft^2 to each dwelling unit. In addition, for single-family residences in tropical semi-condition designations such as Hawaii, the conditional space is cut in half, making the conditioned area 1,188 ft^2 per dwelling unit.

The data presented in Table B.1 are "re-weighted" values derived from the methodology described above and account for the residential prototype climate-zone combinations utilized in the study. This subset of buildings represents approximately 80% of the total residential floor space that the prototypes characterize. They exclude single-family buildings with heated basements and multifamily buildings with crawl spaces or heated basements.

Table B.1. Residential New Construction Floor Area Weighting Factors

	1A	1AT	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8	All
Single Family	2.1	0.2	15.0	2.8	15.7	6.4	1.2	13.3	0.6	2.7	8.7	5.7	3.5	1.1	0.6	0.0	79.5
Multifamily	0.5	0.1	3.4	0.4	2.5	2.2	0.5	3.9	0.1	1.1	2.8	1.4	1.1	0.2	0.2	0.0	20.5
Weights by Zone	2.5	0.3	18.3	3.2	18.2	8.6	1.7	17.3	0.7	3.8	11.5	7.1	4.6	1.3	0.8	0.0	100.0

The commercial new construction floor area weighting factors used in this study are presented in Table B.2. They were developed by PNNL from the Dodge Data & Analytics database (formerly McGraw Hill) for the years 2003–2018. The new construction floor area data from the database are applied to the prototypes and climate zones, which resulted in the new construction-area-based weighting factors reported in the table. The weighting factors do not take into account the floor area associated with buildings not represented by the prototypes. Approximately 75% of the total new construction floor area reported can be mapped to and

[1] https://www.census.gov/construction/chars/highlights.html

represented by the model code prototype building types. More details about the commercial weighting factor development is documented in a PNNL report (Lei et al. 2020).

Table B.2. Commercial New Construction Floor Area Weighting Factors

	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8	All
Large Office	0.11	0.54	0.07	0.54	0.26	0.23	1.13	0.00	0.24	0.48	0.15	0.00	0.09	0.00	0.01	0.00	3.86
Medium Office	0.14	0.78	0.19	0.73	0.45	0.16	0.95	0.03	0.17	0.88	0.31	0.00	0.17	0.03	0.02	0.00	5.01
Small Office	0.11	0.77	0.15	0.70	0.27	0.05	0.58	0.03	0.09	0.67	0.21	0.00	0.13	0.02	0.02	0.00	3.80
Stand-alone Retail	0.29	1.79	0.31	1.78	0.85	0.12	1.92	0.08	0.26	2.37	0.54	0.01	0.49	0.06	0.06	0.01	10.94
Strip Mall	0.16	0.63	0.14	0.70	0.42	0.09	0.66	0.02	0.09	0.61	0.12	0.00	0.06	0.01	0.01	0.00	3.71
Primary School	0.13	0.98	0.12	0.94	0.36	0.04	0.88	0.03	0.12	0.77	0.23	0.00	0.16	0.05	0.02	0.00	4.83
Secondary School	0.26	1.86	0.19	2.16	0.77	0.14	1.98	0.07	0.27	2.18	0.51	0.01	0.37	0.09	0.06	0.01	10.92
Hospital	0.09	0.75	0.11	0.63	0.32	0.10	0.92	0.03	0.13	0.95	0.23	0.01	0.20	0.03	0.03	0.00	4.52
Outpatient Health Care	0.05	0.54	0.09	0.53	0.17	0.04	0.62	0.02	0.10	0.80	0.20	0.00	0.18	0.03	0.03	0.00	3.42
Full Service Restaurant	0.03	0.18	0.03	0.17	0.08	0.01	0.16	0.01	0.02	0.19	0.04	0.00	0.03	0.00	0.00	0.00	0.97
Quick Service Restaurant	0.01	0.07	0.01	0.06	0.02	0.00	0.06	0.00	0.00	0.07	0.02	0.00	0.01	0.00	0.00	0.00	0.33
Large Hotel	0.18	0.71	0.10	0.56	0.55	0.09	0.82	0.02	0.13	0.65	0.19	0.00	0.14	0.04	0.02	0.00	4.22
Small Hotel	0.03	0.30	0.02	0.27	0.11	0.02	0.30	0.01	0.03	0.27	0.10	0.00	0.08	0.03	0.02	0.00	1.59
Non-Refrigerated Warehouse	0.53	3.53	0.63	2.77	2.23	0.18	3.69	0.05	0.54	3.14	0.82	0.00	0.37	0.03	0.04	0.00	18.56
High-rise Apartment	1.44	1.19	0.08	0.57	0.63	0.29	3.26	0.00	0.49	1.36	0.19	0.00	0.11	0.01	0.00	0.00	9.64
Mid-rise Apartment	0.36	2.24	0.27	1.78	1.18	0.49	3.02	0.03	0.71	2.22	0.73	0.01	0.57	0.05	0.04	0.00	13.69
Weights by Zone	3.94	16.85	2.52	14.89	8.67	2.06	20.94	0.43	3.39	17.60	4.59	0.05	3.17	0.49	0.38	0.03	100.00

Appendix C – Residential Building Advanced Measure Analysis

In this study, we used the Pacific Northwest National Laboratory (PNNL) residential prototype building models to evaluate the impact of advanced efficiency measures that in combination result in a design solution that meets the Passive House Institute U.S. (PHIUS) standard for residential buildings. The performance of each prototype variation modeled was scaled to the national level and compared to the performance achieved by current code—the 2018 International Energy Conservation Code-Residential (IECC-R)—to evaluate the ability of advanced measures to fill the efficiency gap for achieving net zero energy (ZE) buildings by 2030. The modeling methodology followed to model and scale the residential building performance is explained in detail below.

C.1 Residential Prototypes

A suite of 32 residential prototypes has been developed by PNNL to conduct performance assessments of energy code requirements based on the IECC-R, which is the model energy code for one- and two-family dwellings, townhomes, and low-rise multifamily residential buildings. The residential representations characterized by the prototypes are summarized in Table C.1 and modeled in EnergyPlus™ version 9 (DOE 2018) in the IECC-R 16 U.S. climate zone locations noted in Appendix A.

Table C.1. Residential Prototypes

No.	Building Type	Foundation Type	Heating System Type
1	Single Family	Vented Crawlspace	Electric Resistance
2	Single Family	Vented Crawlspace	Gas Furnace
3	Single Family	Vented Crawlspace	Heat Pump
4	Single Family	Vented Crawlspace	Oil Furnace
5	Single Family	Heated Basement	Electric Resistance
6	Single Family	Heated Basement	Gas Furnace
7	Single Family	Heated Basement	Heat Pump
8	Single Family	Heated Basement	Oil Furnace
9	Single Family	Slab	Electric Resistance
10	Single Family	Slab	Gas Furnace
11	Single Family	Slab	Heat Pump
12	Single Family	Slab	Oil Furnace
13	Single Family	Unheated Basement	Electric Resistance
14	Single Family	Unheated Basement	Gas Furnace
15	Single Family	Unheated Basement	Heat Pump
16	Single Family	Unheated Basement	Oil Furnace
17	Low-Rise Multifamily	Vented Crawlspace	Electric Resistance

18	Low-Rise Multifamily	Vented Crawlspace	Gas Furnace
19	Low-Rise Multifamily	Vented Crawlspace	Heat Pump
20	Low-Rise Multifamily	Vented Crawlspace	Oil Furnace
21	Low-Rise Multifamily	Heated Basement	Electric Resistance
22	Low-Rise Multifamily	Heated Basement	Gas Furnace
23	Low-Rise Multifamily	Heated Basement	Heat Pump
24	Low-Rise Multifamily	Heated Basement	Oil Furnace
25	Low-Rise Multifamily	Slab	Electric Resistance
26	Low-Rise Multifamily	Slab	Gas Furnace
27	Low-Rise Multifamily	Slab	Heat Pump
28	Low-Rise Multifamily	Slab	Oil Furnace
29	Low-Rise Multifamily	Unheated Basement	Electric Resistance
30	Low-Rise Multifamily	Unheated Basement	Gas Furnace
31	Low-Rise Multifamily	Unheated Basement	Heat Pump
32	Low-Rise Multifamily	Unheated Basement	Oil Furnace

For this study, we modeled the six residential prototypes listed in Table C.2 in the 16 U.S climate zone locations. Using parametric analysis, the characteristics of the base prototype models were modified to reflect different levels of efficiency. The different cases analyzed included five model energy code cycles (IECC 2006, IECC 2009, IECC 2012, IECC 2015, and IECC 2018) and the beyond-code measures case representing a PHIUS-compliant building.

Table C.2. Residential Prototypes Used in This Study

No.	Building Type	Foundation Type	Heating System Type
1	Single Family	Slab	Heat Pump
2	Single Family	Slab	Gas Furnace
3	Single Family	Vented Crawlspace	Heat Pump
4	Single Family	Vented Crawlspace	Gas Furnace
5	Low-Rise Multifamily	Slab	Heat Pump
6	Low-Rise Multifamily	Slab	Gas Furnace

Each EnergyPlus model input file (idf) was generated from a single template, which is based on a PNNL-developed program called GPARM written in the PERL programming language. This framework provides the flexibility to combine multiple parameters to create unique run combinations from a single starting point. The parameters include model specification ranging from building geometry, shading options, internal loads, envelope efficiency, HVAC system type, efficiency, and exterior loads. The input parameters utilized to create the PHIUS modification to the IECC base model are listed in Table C.3.

Table C.3. PHIUS Parameters

Input Parameters	
I. Foundation	a. Slab Insulation
	b. Crawl Space Insulation
II. Envelope	a. Exterior Wall Insulation
	b. Roof Insulation
	c. Window U and SHGC
III. Window Shading	
IV. Envelope Air Leakage	
V. Lighting	
VI. Plug Loads	
VII. Cooling Efficiency	
VIII. Heating Efficiency	Gas Furnace
	Heat Pump

The efficiency values associated with the above parameters were established by PHIUS and shared with PNNL. To develop the values, PHIUS applied their internal analysis procedures to develop compliant solutions for the prototypes selected for the study in each of the 16 climate zone locations. Each compliant solution met the PHIUS standard requirements, which include (1) limits on heating and cooling loads (both peak and annual), (2) limits on overall source energy use, and (3) air tightness and other prescriptive quality assurance requirements.[1] Specifically, PHIUS created WUFI Passive[2] models of the select residential prototype cases to determine the optimal efficiency combinations that meet the PHIUS standard design criteria. These criteria are presented in Table C.4.The efficiency values underlying the PHIUS design solutions were incorporated by PNNL into the corresponding EnergyPlus code prototype models. The PNNL analysis included analyzing each PHIUS measure individually and as a package of measures. The PNNL PHIUS model results were compared to the IECC 2018 case to assess their impact on current codes and ability to fill the efficiency gap to achieve ZE buildings.

[1] Additional details regarding PHIUS certification can be found at https://www.phius.org/PHIUS+2018/PHIUS+%20Certification%20Guidebook%20v2.0_final.pdf

[2] WUFI Passive is a user-friendly building energy modeling software tool that combines passive building energy modeling with hygrothermal analysis, which assesses potential moisture issues. More information about WUFI Passive can be found at https://www.phius.org/software-resources/wufi-passive-and-other-modeling-tools/wufi-passive-3-2

Table C.4. PHIUS Criteria for Advanced Case Efficiencies

Single Family																
Climate Zone	1A	1A,T	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Annual heating demand (kBTU/sq.ft yr	1	1	1.4	1	3.3	2	2.5	5	3.7	5.7	7.1	6	7.5	8	9.4	11.7
Annual cooling demand (kBTU/sq.ft yr)	25.9	23.4	16.2	16.5	11	11.5	4.1	5.3	7	1	3.2	3	1.4	1.2	1	1
Peak heating load (kBTU/hr sq.ft)	1	1	1.7	1.3	3.3	1.7	1.2	4	2.9	4.3	4.7	4	4.3	5.1	5.8	7.3
Peak cooling load (kBTU/hr sq.ft)	3.5	3.3	3.5	5.6	3	3.8	1.3	3	3.1	2.5	2.8	3.1	2.7	1.7	2.2	0.9
Multifamily																
Climate Zone	1A	1A, T	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Annual heating demand (kBTU/sq.ft yr	1	1	1	1	2.4	1.7	1.9	3.7	3	4.1	5.2	4.5	5.5	6	6.9	7.9
Annual cooling demand (kBTU/sq.ft yr)	26	22.5	15.8	13.5	10	8.5	2	4.2	4.4	1	2.3	1.2	1	1	1	1
Peak heating load (kBTU/hr sq.ft)	0.1	0	1.6	1.2	2.8	1.6	1	3.3	2.5	3.6	3.9	3.3	3.5	4.3	7.3	5.6
Peak cooling load (kBTU/hr sq.ft)	3	2.9	2.9	4.7	2.5	3	1	2.4	2.4	2	2.2	2.4	2.1	1.6	0.9	0.7

Details of the beyond-code measures as modeled in EnergyPlus are described below.

- Foundation: Two foundation types—slab-on-grade and crawlspace—are included in the analysis. The insulation of the foundation was modeled per the PHIUS specifications with insulation on the slab/floor.
- Envelope: The exterior wall and roof insulation and window properties of the advanced case were modeled with insulation levels per PHIUS specifications. Roof is assumed to be a gabled roof with a slope of 4/12. It has insulation entirely above the roof deck and has asphalt shingles in the single-family case. In the multifamily models, the roof is a built-up gabled with a slope of 4/12 and has asphalt shingles and ½ inch oriented strand board Exterior walls are wood-framed (2 × 4 16” o.c. or 2 × 6 24” o.c.) and composed of 1” stucco + building paper felt + insulating sheathing + 5/8” oriented strand board + wall insulation/framing + 1/2” drywall. Windows are modeled with properties equivalent to triple glazed or a better window type.
- Window shading: Windows in the advanced cases were modeled with blinds and overhangs when needed to meet the PHIUS criteria.
- Envelope air leakage: Air tightness in the advanced cases were assumed to meet a target air leakage rate of 0.06 cfm/sf of the building envelope at a pressure differential of 50 pascals.

- Lighting: 100% of all light sources were assumed to be of high efficiency (equal to or greater than 50 lumens/W) in the advanced case. This was achieved by modeling high-efficiency lights for hard-wired, plug-in, and garage lights in the prototypes.
- Plug loads: The advanced cases were modeled with energy-efficient dryers, dishwashers, fridges, cooking stoves, and clothes washers. Appliances in a typical single-family prototype were assumed to have the following appliances, as shown in Table C.5.
- Cooling Efficiency: Cooling equipment in the advanced cases were modeled with a seasonal energy efficiency ratio per PHIUS specifications.
- Heating Equipment Efficiency: Prototypes with a gas furnace were modeled in the advanced case with an average fuel utilization efficiency of 90%, and prototypes with a heat pump for heating were modeled with a heat seasonal performance factor per PHIUS specifications.

Table C.5. Appliances for Typical Single-Family Residences

Major Appliances	Appliance Type	Energy Rating	Predicted (kWh/yr)
Refrigerator	Electric	360 kWh/yr	360
Clothes Washer	Electric	116 kWh/yr	57
Clothes Dryer	Condensation Dryer	3.93 CEF	397
Dishwasher	Electric	260 kWh/yr	129
Cooking	Electric	0.2 kWh/use	400

While the PHIUS WUFI design solutions included energy recovery ventilation (ERV), it was not included in the PNNL analysis. The IECC code equivalent prototypes do not include an ERV. It was added to the EnergyPlus prototype models, but its impact was not consistent and could not be calibrated to the WUFI model results.

Appendix D – Commercial Building Beyond-Code Measure Analysis

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) 1651 research project (RP-1651) evaluated the impact of advanced technologies to estimate the current lowest technically achievable energy efficiency level in commercial buildings (Glazer 2016). The expected performance of these technologies was established using a whole-building simulation approach and applying the EnergyPlus software, where 30 of the 220 measures considered were simulated in all U.S climate zones using the model code commercial prototype building models, which were based on ASHRAE Standard 90.1-2013.

This study leverages the effort carried out in RP-1651 to implement 17 advanced energy efficiency measures in prototype building models. Most of the measures were modeled identically to RP-1651, with some exceptions (refer to Table D.1 for more details). While similar measures were included in RP-1651 and this study, the general modeling approach is different. In RP-1651, measures were modeled on top of code-compliant building models. In this study, measures were integrated into the building energy code prototype models.

The main difference between these two approaches is that if measures are modeled as code requirements, they are likely to affect other requirements that in turn are likely to change the prototype building models to be simulated. For example, a load-reducing measure such as a very high-efficiency lighting system will affect the size of the heating, ventilation, and air conditioning (HVAC) equipment, which triggers a different set of minimum efficiency requirements or removes the need to comply with other code requirements, such as those for fan controls.

For our study, 17 of the 30 measures analyzed in RP-1651 were evaluated. This subset was selected using engineering judgment based on the perceived higher current market share, as well as the fact that the ASHRAE study results indicate that this subset comprises approximately 90% of the identified energy-saving technical potential. Table D.1 describes the 17 measures and provides the corresponding name utilized in the RP-1651 study. The measures were applied to each prototype building and climate zone if applicable. For example, the chiller, direct expansion cooling system, or heat pump measures were only applied in buildings that had the same mechanical system in the current code prototype building. In addition, substituting the base mechanical system with the variable refrigerant flow (VRF) system made some of the measures irrelevant to the VRF package of measures. The measures comprising the VRF package are indicated in Table D.1. In the analysis, the VRF package of measures was applied when it resulted in an overall reduction in annual energy costs compared to the base system package of measures. More information about the measures and their application is provided below.

Table D.1. Beyond-Code Commercial Building Efficiency Measures

Measure	Corresponding Name in RP-1651	Included in VRF Bundle?	Description
Optimal Choice of Vertical Fenestration	EF01_Fene	Yes	Replace the fenestration assemblies in each prototype for each orientation with one specified in a set of preselected high-performance fenestration products that reduces building loads the most
Optimal Roof Insulation	EO04_RfInsul	Yes	Increase the roof insulation R-value by a 2 to 5 multiplication factor based on the climate zone and building type
Highest-Efficiency Office Equipment	IE03_OffcEqp	Yes	Reduce equipment power densities in office areas assuming that the most efficient office equipment available are used
High-Performance Lighting	IL06_IntLtg	Yes	Reduce lighting power densities (LPDs), assuming that the prototypes include high-performance lighting systems[(a)]
Shift from General to Task Illumination	IL05_TskIllm	Yes	Reduce ambient lighting by 50% and add task lighting at an LPD of 0.0362 W/ft^2 in all office spaces
Daylighting Control by Fixture	DA05_DyLtFix	Yes	A lighting profile schedule was developed using intermediate simulations that include illuminance maps in each space with windows. The lighting schedules include an hourly multiplier that represents the potential benefits from daylighting control by fixture
LED Exterior Lighting	XL01_ExtLtg	Yes	Reduce the exterior lighting power, assuming a high-efficacy lighting system[(a)]
High-Efficiency/Variable-Speed Packaged Direct Expansion (DX) Cooling	HCE16_DXcool	No	DX equipment was modeled with the highest efficiency available reported for each size category. Single-speed DX cooling coils were swapped for two-speed coils
High-Efficiency Heat Pumps	HHE06_HtPump	No	Prototypes served by single-zone systems were modeled with high-efficiency heat pumps. This corresponds to a system replacement for some and system efficiency upgrade for others
Optimal Water/Air Cooling Coils	HDE12_WtrAir	No	For prototypes served by chilled water, a set of optimized supply air temperature and chilled water delta-T was used for each combination of prototype and climate zone
High-Performance Fans	HDE01_Fans	Yes	Fan efficiency was upgraded from the code-compliant values to high-efficiency fans and motors
High-Performance Ducts to Reduce Static Pressure	HDP05_DuctPrs	No	Fan static pressure was reduced, assuming that systems are designed to reduce static pressure
High-Efficiency and Variable-Speed Chillers	HCE15_Chlr	No	Full and part-load efficiency of chillers was updated to match the performance of the high-efficiency chillers
Demand Controlled Ventilation/CO_2 Controls	VENT_HV17_DCVIAQ	No	Demand controlled ventilation control was implemented. The setpoint for CO_2 concentration is either 0 (not installed), 1000, or 2000 ppm above

Measure	Corresponding Name in RP-1651	Included in VRF Bundle?	Description
			outdoor ambient values. The specific value is determined for each building type - climate zone based on the highest reduction in energy use.
Indirect Evaporative Cooling	HS39_EvapCl	No	Use an indirect evaporating cooling system to precondition the ventilation air
VRF Air Conditioning	HS57_VRF	Yes	Prototype HVAC systems were replaced by air-source VRF systems with a dedicated outside air system

a. Adjustments in the RP-1651 were based on baseline lighting levels defined in ASHRAE Standard 90.1-2013. While the models used as the basis for this study include more aggressive lighting levels, actions were taken to make sure that the same lighting levels as in RP-1651 were modeled in this study.

PNNL's commercial prototype building models, which are used for the ongoing Progress Indicator and representing ASHRAE Standard 90.1-2019, were used as the base model for the analysis. While these prototypes share the same origin with the RP-1651 90.1-2013 prototypes, there are significant differences. These include additional code requirements and were developed for a newer version of the EnergyPlus simulation software.

The commercial code prototype models include all code requirements that affect energy use. The models are generated using a template-based simulation framework, which has been developed specifically to handle large-scale prototypical analysis to inform the development of building energy codes. While the framework is designed around a PNNL-developed program called GPARM written in the PERL programming language, the framework is programming-language agnostic. This means that scripts written using different programming languages can easily be included as part of the workflow and be used to generate the EnergyPlus input files and/or process simulation output files. The framework conducts several simulation sizing runs to capture information necessary to inform decisions to apply certain code requirements. These decisions are made during specific steps in the process. For instance, equipment efficiency and the presence or absence of economizers and energy recovery is determined based on the simulation sizing run occurring before the final annual simulation because at that point, building loads and HVAC equipment size have been determined.
Measures in RP-1651 were modeled using scripts written in the Python programming language. The scripts created for RP-1651 are publicly available and can be downloaded for free for all ASHRAE members. The scripts use a Python package called Eppy, which turns Python into a scripting language for EnergyPlus. It allows energy modelers to programmatically edit EnergyPlus input files while incurring all the additional advantageous features of the Python programming language. This makes for much easier repetitive tasks and cumbersome input file modifications when using a template-based approach (such as removing all HVAC-related objects from an input file and adding a totally new HVAC system). Computer code related to the measures shown in

Table D.2 was extracted from the RP-1651 scripts. The code was updated to work with version 9.0 of EnergyPlus and modified so it could be integrated in the simulation workflow previously described. Additional modifications to the code were made to make sure that measures were modeled as intended. As with some of the sizing scripts, some of the measures must be applied during certain steps of the simulation process, and the simulation framework was also modified to accommodate this requirement.

Because of differences in the prototype mechanical systems, space activities, and occupancies, not all of the beyond-code measures were applicable to all commercial building types and climate zones applied in the analysis. The building types and the corresponding number of climate zones that they were applied to in the individual measure performance analysis (see Table 5 and Table 7) are presented in

Table D.2. This table also indicates the corresponding total new construction floor area fraction represented by the building type/climate zone combinations analyzed for each measure. Also as previously mentioned, two packages of measures were considered—the base package of measures and the VRF package of measures. The latter was only applied in instances where it resulted in lower annual energy costs.

Table D.2 reflects the measures included in either the base or VRF package that was applied for each building type/climate zone combination.

For quality control (QC) and quality assurance (QA) purposes, measures were simulated individually and incrementally for the two packages of measures considered. This drove the total number of simulations needed for completing the analysis to just over 15,000. Because of the large number of simulations required, they were carried out on Constance, PNNL's Research Computing cluster, where all individual simulations could be run in parallel.

The QA and QC processes included a thorough review of the simulation results to make sure that the changes in building site energy use intensity (EUI) were consistent with the measure definitions. Unmet load hours were carefully examined to make sure that an increase in unmet load hours was not correlated to a decrease in building site EUI and that the overall amount of unmet load hours was reasonable for each incremental iteration.

Table D.2 Climate Zones and Floor Area Considered in the Individual Measure Analyses

	Apartment High-Rise	Apartment Mid-Rise	Hospital	Hotel Large	Hotel Small	Office Large	Office Medium	Office Small	Out-Patient Health Care	Restaurant Quick Service	Restaurant Full Service	Retail Stand-alone	Retail Strip Mall	School Primary	School Secondary	Warehouse	Total	Total Floor Area Fraction
Optimal Choice of Vertical Fenestration	15	14	15	14	15	16	16	16	14	16	16	15	15	16	16	15	244	0.95
Optimal Roof Insulation	15	16	14	8	15	15	15	16	16	16	16	16	15	16	15	16	240	0.97
Highest-Efficiency Office Equipment	16	16	16	16	16	15	16	16	16	16	16	16	16	16	16	15	254	0.96
Optimal Choice of Vertical Fenestration	15	14	15	14	15	16	16	16	14	16	16	15	15	16	16	15	244	0.95
High-Performance Lighting	16	16	16	16	16	14	16	16	16	16	16	16	16	16	16	16	254	0.99
Shift from General to Task Illumination	16	16	15	0	16	14	16	16	16	0	0	0	0	15	16	15	171	0.77
Daylighting Control by Fixture	16	16	0	16	14	15	16	16	16	15	16	16	16	16	13	16	233	0.94
LED Exterior Lighting	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	256	1.00
High-Efficiency/Variable-Speed Packaged DX Cooling	0	16	0	0	16	0	16	16	16	16	16	16	16	16	16	16	192	0.78
High-Efficiency Heat Pumps	16	16	0	0	16	16	0	16	0	16	16	16	16	16	16	16	192	0.83
Optimal Water/Air Cooling Coils	0	0	15	0	0	16	0	0	0	0	0	0	0	0	2	0	33	0.12
High-Performance Fans	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	256	1.00
High-Performance Ducts	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	256	1.00
High-Efficiency and Variable-Speed Chillers	0	0	16	16	0	16	0	0	0	0	0	0	0	0	16	0	64	0.23
Demand Controlled Ventilation/CO_2 Controls	10	13	16	16	15	16	16	12	16	2	1	16	15	16	16	16	212	0.91
Indirect Evaporative Cooling	2	2	15	16	15	16	16	5	16	16	16	16	16	16	16	16	215	0.76
VRF Air Conditioning	15	16	16	16	10	16	6	14	16	15	15	16	16	13	9	9	218	0.83

Table D.3 Climate Zones and Floor Area Considered in the Bundled Measure Analysis

	Apartment High-Rise	Apartment Mid-Rise	Hospital	Hotel Large	Hotel Small	Office Large	Office Medium	Office Small	Out-Patient Health Care	Restaurant Quick Service	Restaurant Full Service	Retail Stand-alone	Retail Strip Mall	School Primary	School Secondary	Warehouse	Total	Total Floor Area Fraction
Optimal Choice of Vertical Fenestration	15	14	15	14	15	16	16	16	14	16	16	15	15	16	16	15	244	0.95
Optimal Roof Insulation	15	16	14	8	15	15	15	16	16	16	16	16	15	16	15	16	240	0.97
Highest-Efficiency Office Equipment	16	16	16	16	16	15	16	16	16	16	16	16	16	16	16	15	254	0.96
Optimal Choice of Vertical Fenestration	15	14	15	14	15	16	16	16	14	16	16	15	15	16	16	15	244	0.95
High-Performance Lighting	16	16	16	16	16	14	16	16	16	16	16	16	16	16	16	16	254	0.99
Shift from General to Task Illumination	16	16	15	0	16	14	16	16	16	0	0	0	0	15	16	15	171	0.77
Daylighting Control by Fixture	16	16	0	16	14	15	16	16	16	15	16	16	16	16	13	16	233	0.94
LED Exterior Lighting	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	256	1.00
High-Efficiency/Variable-Speed Packaged DX Cooling	0	0	0	0	15	0	16	16	10	13	13	16	16	16	16	13	160	0.60
High-Efficiency Heat Pumps	14	0	0	0	15	15	0	16	0	13	13	16	16	16	16	13	163	0.63
Optimal Water/Air Cooling Coils	0	0	0	0	0	15	0	0	0	0	0	0	0	0	2	0	17	0.08
High-Performance Fans	14	0	0	14	15	15	16	16	10	13	13	16	16	16	16	13	203	0.74
High-Performance Ducts	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	256	1.00
High-Efficiency and Variable-Speed Chillers	0	0	0	14	0	15	0	0	0	0	0	0	0	0	16	0	45	0.18
Demand Controlled Ventilation/CO_2 Controls	10	0	0	14	14	15	16	12	10	2	1	16	15	16	16	13	170	0.71
Indirect Evaporative Cooling	2	0	0	14	14	15	16	5	10	13	13	16	16	16	16	13	179	0.64
VRF Air Conditioning	14	0	0	14	15	15	16	16	10	13	13	16	16	16	16	13	203	0.26

Appendix E – Rooftop Photovoltaic Generation Potential Analysis

This study evaluated two methods for developing national on-site rooftop photovoltaic (PV) generation potential for both residential and commercial buildings. The first method utilized the building code prototype models' geometries, the climate zone locations' solar resources, and national new construction weighting factors. For this approach, the annual renewable energy generation was calculated using PVWatts Version 6.[1]

In the second method, we evaluated the solar generation potential per unit floor area based on a published study that examined rooftop PV technical potential for U.S. buildings using optical imaging of existing building rooftops in cities in the United States. Our assessment was augmented by statistical building data used to allocate and associate the rooftop PV generation technical potential with the building types and their associated floor areas addressed by residential or commercial energy codes.

Both methods drew upon data and assumptions from recent work on rooftop PV potential published by the National Renewable Energy Laboratory (NREL). The report estimates the overall national generation potential of photovoltaic (PV) systems on existing U.S. buildings (Gagnon et al. 2016). This study utilized detailed light detection and ranging (lidar) data taken over 128 cities and surrounding areas, representing approximately 23% of U.S. buildings, to provide a direct assessment of rooftop shading, roof tilt, and area of roof faces by azimuth angle suitable for PV installation. Statistical models were created to assess the suitable rooftop area, allocated into small, medium, and large building footprint categories defined as ≤ 5,000 ft^2, > 5,000 ft^2 but ≤ 25,000 ft^2, and > 25,000 ft^2, respectively. These data were combined with models of PV system installation size and annual energy production that were applied to the identified suitable rooftop area. The results were aggregated to a national potential using national building stock counts.

A discussion of both analysis methods follows, along with a comparison of their estimates for the PV energy generation potential associated with buildings addressed by (1) residential model codes and (2) commercial model codes.

E.1 Photovoltaic Potential Based on Prototype Buildings Analysis

PV potential analysis was used to estimate rooftop PV production offsets based on the residential and commercial building prototypes, their associated geometries, and the code climate zone locations. The process was broken down into the following steps:

1. Determine maximum suitable PV rooftop area for each prototype.
2. Determine PV DC system size (kW_p) for each prototype under two installation scenarios, (a) all roof orientations and (b) all non-north roof orientations.
3. Determine normalized annual PV production energy production (kWh/kW) per unit of PV DC size by prototype, climate zone, and installation scenario assuming typical installation assumptions.
4. Apply the normalized PV production values of Step 3 to the maximum potential PV capacity determined in Step 2 to get annual kWh by prototype, climate zone, and installation

[1] https://pvwatts.nrel.gov/

scenario. Normalize these annual kWh values by building floorspace for each prototype, climate, and installation scenario and convert to a site kBtu/ft^2 of building floor area reflecting a potential PV production offset for each separate prototype and climate in each installation scenario.

5. Aggregate to national PV potential offset in kBtu/ft^2 using construction weighting factors separately for the residential and commercial building code regimes.

Details and assumptions used for each of the steps above are discussed in more detail in the subsections below.

E.1.1 Maximum Suitable Photovoltaic Rooftop Area for Each Prototype

For each prototype, two installation scenarios were considered: one in which the entire rooftop was examined for suitable area (Scenario 1) and one in which the north-facing fraction of sloped roofs was not considered (Scenario 2). There is no difference between assumptions for flat roofs for the two scenarios. The east-, west-, and south-facing planes of sloped roofs are also treated identically in the two scenarios. Analyzing the two scenarios is intended to address potential concerns regarding the economic viability of PV panels installed on north-facing sloped roofs. Due to these concerns, the efficiency gap analysis utilizes Scenario 2. In addition, the suitable roof area determined for Scenario 2, following the methods outlined below, results in the percent of total building roof area (including the north area) deemed suitable for PV development to be about 40% for residential code prototype buildings and 55% for commercial code prototype buildings based on the prototypes' geometries. These values are consistent with those determined for existing buildings by Gagnon et al. 2018.

Roof area adjustment factors were applied to the building prototypes for the two installation scenarios to calculate the maximum rooftop area suitable for PV installation. The prototypes have either flat, gable, or hip-roof designs. For all prototypes, it was assumed that 20% of each sloped-roof face area and 20% of flat roof area would be unsuitable for PV panel installation due to obstructions and roof shading. These values are used for both low-rise residential buildings as well as commercial buildings (including residential buildings greater than three stories) and under both installation scenarios.[1]

Once the maximum suitable PV roof area for each prototype was calculated, the maximum installed PV capacity (in terms of rated PV direct current [DC] panel capacity) was estimated for the suitable rooftop area. An estimate of the panel or "collector" area was first made. The ratio of collector area to suitable roof area was based on that reported by NREL (Gagnon et al. 2016). For flat roofs, the ratio of collector to suitable roof area was assumed to be 0.7.[2] For tilted roofs (hip or gable construction), it was assumed that panels would be installed in the plane of each rooftop face, and the collector to suitable roof area ratio was 0.98. The combination of roof area adjustment factors resulted in 78% of east-, west-, and south-facing roof areas and 56% of

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[1] The 80% usable roof area assumption was checked against usable roof area findings determined for existing buildings determined in the NREL study (Gagnon et al. 2016)

[2] For flat roofs, the ratio of module area to roof area was assumed to be 0.7 in the NREL study (Gagnon et al. 2016) to account for the row spacing necessary to limit self-shading losses to 2.5% for south-facing modules at 15-degree tilt. A 3% shading loss is assumed in the PVWatts default loss factors. A more detailed analysis of self-shading for a PV array was not considered in the current report. However, a review of the assumptions suggests that slightly higher self-shading losses may occur at this module-to-roof area ratio for flat roofs, given other factors included in the analysis (PV panel tilt and latitude of installations).

flat roof areas being identified as suitable area for PV installation. Note that for buildings with sloped-roof construction, the actual areas of the rooftop PV change between Scenario 1 to Scenario 2 as the north-facing sloped roof is not utilized in Scenario 2.

Multiplying the collector area of each prototype by the corresponding rated PV panel output yields the potential PV DC system output capacity (kW_p).[1] This is calculated for each prototype, and the products are shown in Table E.1. PV panels were assumed to have a rated PV DC output equal to 0.16 kW/m^2 (16% efficiency). The rating method is the PV Standard Test Condition rating[2] consistent with the use of the PVWatts calculation tool. This is a rated installed capacity value and does not vary by climate but will vary with each installation scenario.

Because the same roof area adjustment factors are used for the two scenarios, the PV system sizes for flat roofs are the same in both scenarios. Under Scenario 1, the PV system size is 8.32 W/ft^2 of roof area for the flat roof commercial buildings and 11.65 W/ft^2 of roof area for the hip-roof commercial building, the gable roof single family, and the multifamily residential prototypes. For gable roofs used in the two residential prototypes, the Scenario 2 system size is one-half that of Scenario 1. For the two smaller hip-roof commercial prototypes (Office Small, Restaurant Quick Service), the Scenario 2 PV system size was 60% of Scenario 1. For Restaurant Full Service, the Scenario 2 system size was 89% of Scenario 1. This is because a small fraction of the roof area faces north in the Restaurant Full Service.

Table E.1. PV DC System Size by Prototype and Installation Scenario

Building Prototype	Roof Type	Roof Area ft^2	PV System Size (kW_p) Scenario 1	PV System Size (kW_p) Scenario 2
Single Family	Gable	1,253	14.6	7.3
Low-Rise Multifamily	Gable	8,451	98.5	49.3
Apartment High-Rise	Flat	8,435	70.2	70.2
Apartment Mid-Rise	Flat	8,435	70.2	70.2
Hospital	Flat	48,300	402.2	402.2
Hotel Large	Flat	20,353	169.5	169.5
Hotel Small	Flat	10,801	89.9	89.9
Office Large	Flat	41,549	346.0	346.0
Office Medium	Flat	17,876	148.9	148.9
Office Small	Hip	5,348	62.4	37.6
Out-Patient Health Care	Flat	13,649	113.7	113.7
Restaurant Quick Service	Hip	2,786	32.5	19.7

[1] kW_p in different studies can refer to the nominal DC installed PV system size, the AC installed system peak output at the panel rated conditions, or the anticipated AC installed peak output at other-than-rated conditions. For this work, we have used kW_p to refer to the nominal DC installed PV system size based on Standard Test Condition rating.

[2] The Standard Test Condition rating corresponds to DC watts from a panel with solar irradiance at 1,000 W/m^2, ambient temperature at 25 °C, and an air mass index of 1.5.

Building Prototype	Roof Type	Roof Area ft^2	PV System Size (kW_p)	
			Scenario 1	Scenario 2
Restaurant Full Service	Hip	6,130	71.5	63.9
Retail Stand Alone	Flat	24,692	205.6	205.6
Retail Strip Mall	Flat	22,500	187.4	187.4
School Primary	Flat	73,959	615.9	615.9
School Secondary	Flat	105,444	878.0	878.0
Warehouse	Flat	52,045	433.4	433.4

E.1.2 Normalized PV Production Calculations

Roof-mounted *normalized* PV annual production in terms of annual kWh energy production per unit of installed PV DC capacity (kW_p) was separately developed using PVWatts simulations for each prototype in each climate zone. For the purpose of the PVWatts simulations, buildings were assigned 1 W/ft^2 of capacity peak production per square foot of building floor area for determining a PV system size. The representative city locations were used as the geographical location for the simulation of PV energy production in each climate zone. Assumptions for PV panel tilt for flat roofs were based on a 20° tilt from horizontal in all climates with panels oriented due south. For the two residential prototypes and for the small office buildings, all with sloped roofs, the long axis of the building is assumed to be oriented east-west. For the quick-service restaurant and full-service restaurant prototypes, the buildings have a hip-roof and a square footprint. These buildings were oriented with the kitchen area placed on the north side of the building and the dining area to the south. The PV panels on each roof face lie in the same plane as the roof face, and thus are tilted from horizontal at the same angle of the roof face with a panel orientation (azimuth) identical to each roof face.[1]

Each roof face and orientation were first considered separately in terms of developing normalized PV production. Other key PV system production assumptions were consistent across prototypes and orientation and based on PVWatts defaults. These key assumptions are shown in Table E.2.

[1] For the single-family prototype, the north and south facing roof slopes are inclined 18.4° from horizontal. For the low-rise multifamily prototype, the north and south facing roof slopes are inclined 22.6° from horizontal. For the small office, roof slope is inclined 18.4° in each orientation. For the quick-service restaurant, it is 18.4° in the north and south orientation and 45° in the east and west orientation. For full-service restaurant, it is 45° in the north and south orientation and 18.4° in the east and west orientation.

Table E.2 PVWatts Simulation Assumptions

Assumption Type	Value
DC-to-AC Ratio	1.2
Inverter Efficiency	96%
System Losses	14.08%

The DC-to-AC size ratio is the ratio of the array's DC-rated size to the inverter's AC-rated size. When the DC output multiplied by the inverter efficiency exceeds the AC output of the inverter, the inverter operates electrically to limit the DC production so that the AC output matches the maximum rating of the inverter, "clipping" the power production. The selection of DC-to-AC ratio is an economic decision for each installation, but for most installations over the course of the day the PV array panel output is seldom capable of generation at the rated value due to the variation of operating conditions from the rated conditions. Therefore, a DC-to-AC ratio of greater than 1.0 is not uncommon.[1] Note that with the DC-to-AC ratio of 1.2, 0.5 W/ft^2 of AC system peak size is equivalent to 0.6 W/ft^2 DC peak size.

The inverter efficiency is the nominal ratio of the AC output kW to the DC input kW of the inverter. For this analysis, a constant inverter efficiency is assumed.

System loss assumptions in PVWatts take into account a real system performance loss that is not explicitly calculated by the PVWatts model equations. The loss includes various factors such as dirt/soiling, minor shading, wiring and wiring connections, light-induced degradation and deviation from rating. A 14.08% value is applied as the default in PVWatts to account for these system losses, which is assumed for all hours of production.

For each prototype and climate, the annual PV production was calculated for each roof face for sloped roofs, or for the flat roof. The annual electric energy production was then divided by the installed DC capacity to provide normalized PV production metric (kWh/kW$_p$) for each roof face. For buildings with sloped roofs, the normalized PV production in each face was then multiplied by the estimated maximum potential PV system size on each of the roof faces, as developed under Scenario 1 and Scenario 2. The results are next divided by the corresponding total PV system size on all faces utilized to provide overall normalized PV production values for each prototype and installation scenario. The results for commercial and residential prototypes are shown in Table E.3 and Table E.4. The normalized PV production is higher in Scenario 2 than in Scenario 1 for sloped roofs because the north orientation, which is less well suited to PV production, is not considered. However, as noted previously, a smaller roof area and total PV system size is associated with Scenario 2 for sloped-roof buildings.

[1] Over the course of the year, solar irradiation on the PV array is often lower than 1,000 W/m^2 due to weather and solar angle considerations relative to the geometric normal of the installed array. In addition, a solar radiation incident on the array surface raises the temperature of the PV array often above the 25 °C rating condition. Typical crystalline silicon PV panel designs will lose approximately 0.4–0.5% output for each 1 °C of panel temperature. These effects in combination will reduce the actual DC output during most of the year to less than the DC-rated output of the PV array.

Table E.3. Annual Normalized Rooftop PV Generation by Prototype, Climate Zone, and Installation Scenario – Commercial

		Annual PV Production (kWh/kWp)						
		Scenario 1				Scenario 2		
Climate Zone	Location	Flat Roof Prototypes	Small Office	Restaurant Quick Service	Restaurant Full Service	Small Office	Restaurant Quick Service	Restaurant Full Service
1A	Honolulu HI	1609	1355	1345	1334	1413	1415	1380
2A	Tampa FL	1540	1238	1231	1224	1321	1335	1278
2B	Tucson AZ	1729	1349	1342	1336	1462	1485	1406
3A	Atlanta GA	1405	1111	1106	1103	1195	1214	1154
3B	El Paso TX	1765	1383	1376	1370	1496	1519	1440
3C	San Diego CA	1556	1232	1225	1221	1325	1342	1279
4A	New York NY	1297	996	994	994	1087	1114	1044
4B	Albuquerque NM	1727	1330	1324	1322	1451	1480	1393
4C	Seattle WA	1079	832	832	829	905	928	870
5A	Buffalo NY	1209	947	945	942	1023	1044	987
5B	Denver CO	1580	1191	1171	1171	1313	1320	1224
5C	Port Angeles WA	1134	873	940	934	951	1087	970
6A	Rochester MN	1182	995	1018	1013	1094	1164	1048
6B	Great Falls MT	1303	979	981	979	1079	1114	1033
7	International Falls MN	1212	907	911	909	1002	1038	959
8	Fairbanks AK	917	673	682	679	748	787	714

Table E.4. Annual Normalized Rooftop PV Generation by Prototype, Climate Zone, and Installation Scenario – Residential

Climate Zone	Weather Location	Annual PV Production (kWh/kWp)			
		Scenario 1		Scenario 2	
		Single-Family	Multifamily	Single-Family	Multifamily
1A	Miami FL	1423	1364	1589	1563
1-T	Honolulu HI	1524	1462	1651	1614
2A	Houston TX	1282	1229	1446	1423
2B	Phoenix AZ	1472	1408	1714	1696
3A	Memphis TN	1245	1194	1438	1421
3B	El Paso TX	1554	1488	1803	1784
3C	San Francisco CA	1332	1278	1557	1542
4A	Baltimore MD	1169	1123	1378	1370
4B	Albuquerque NM	1493	1432	1762	1749
4C	Salem OR	1009	970	1170	1159
5A	Chicago IL	1130	1085	1322	1311
5B	Boise ID	1230	1182	1454	1445
6A	Burlington VT	1039	1000	1232	1225
6B	Helena MT	1103	1063	1324	1321
7	Duluth MN	1072	1033	1289	1286
8	Fairbanks AK	759	737	930	937

E.1.3 Photovoltaic Production by Prototype and Weighted to National Offset

The normalized PV production values from Section E.1.2 were multiplied by the estimated PV system size for each prototype building in each installation scenario in Section E.1.1 to provide annualized PV production values (kWh) by prototype, climate zone, and installation scenario. These results by prototype were then converted to a PV site electrical energy offset value in kBtu/ft^2 consistent with the savings calculated from other energy-efficiency measures.

The PV energy offset values by prototype and climate zone for each installation scenario were multiplied by the weighting factors for each prototype in the residential and commercial sectors, as shown in Appendix B. This results in a single national PV offset factor for residential and separately for commercial buildings for each installation scenario. These final PV offsets are shown in Table E.5.

Table E.5. Calculated Potential PV Offset

Building Code Regime	PV Offset (kBtu/ft^2)	
	Scenario 1 (all roof orientations)	Scenario 2 (all but north orientations)
Residential	23.5	13.7
Commercial	23.6	22.9

E.2 Potential Photovoltaic Offset Based on Building Stock Analysis

A separate estimate was made of the potential for PV to reduce household and commercial building energy consumption based on previous work and national datasets describing the existing building stock. The estimate was normalized to a per square foot of building floor area basis for comparison with the PV offset estimates for new construction based on the prototypes, as shown in Section 0.

This second PV analysis utilized existing building PV generation technical potential values (Gagnon et al. 2016) developed for the U.S. residential and commercial building stock. This work was distinctive in that it was based on lidar data taken over 128 cities and surrounding areas, representing approximately 23% of U.S. buildings, to provide a direct assessment of rooftop shading, roof tilt, and azimuth of solar normal on roof faces to estimate how much roof area would be suitable for PV installation. Statistical models were then created to assess the suitable rooftop area for buildings falling separately into small, medium, and large building footprint categories, defined by ≤ 5,000 ft^2, > 5,000 ft^2 but ≤ 25,000 ft^2, and > 25,000 ft^2, respectively. These data were combined with models of PV system installation size and annual energy production that could be applied to the suitable rooftop area by location, and the results were then aggregated to a national potential using national building stock counts. A summary of the results of the NREL work is shown in Table E.6.

Table E.6. Summary of National PV Generation Potential (NREL 2016)

Footprint Category	Total Suitable Area Roof Area (billion m^2)	Installed Cap (GW)[a]	Annual Generation Potential (TWh/yr)	Annual Generation Potential % Nat Sales	Fraction of Roof Area PV Suitable
Small ≤ 5000 ft^2	4.92	731	926	25.0%	26%
Medium > 5000, ≤ 25,000 ft^2	1.22	154	201	5.4%	49%
Large > 25,000 ft^2	1.99	232	305	8.2%	66%
Total	8.13	1118	1432	38.6%	32%

a. Installed capacity in this context is the solar PV DC capacity of panels and not AC capacity.

The above data were utilized to make a second estimate of the PV potential in terms of annual kBtu/ft^2 of electric energy production potential for PV systems, which could be applied separately to the low-rise residential, commercial, and high-rise residential building stock in the United States, corresponding to the allocation of buildings between the two model building codes. This potential can then be compared to that calculated based on the prototype building analysis shown in Section 0.

The floor area allocation analysis included the following assumptions:

- The NREL estimates reflect building data for residential and commercial building stock. The summary aggregate data exclude buildings primarily used for manufacturing and agriculture[1] but include manufactured housing.
- The installed capacity estimate is accurate for the represented building potential based on the PV suitable rooftop area and PV system assumptions of module efficiency, DC-AC ratio, and final PV energy potential.
- The location and solar availability of the building stock are nationally representative and can serve as reasonable proxy for new construction when normalized per unit of footprint area.
- All of the building data used are recent enough that minor differences in survey years for the data sources would not substantially affect the result.
- The footprint-to-floor area of the new building construction is similar to that of the building stock such that estimates of PV production using building stock data will provide results reasonably reflective of new construction when normalized to floor area of new construction.

The steps taken to estimate the potential solar offset for residential low-rise buildings and separately for the commercial building stock are as follows:

1. Ascertain the total footprint of buildings in the residential sector and commercial sectors for small, medium, and large footprint buildings.
2. Allocate these to the building code regimes appropriately to provide a comparative estimate for building codes.
3. Normalize the annual PV production potential by footprint area from the NREL study for small, medium, and large buildings.
4. Allocate this normalized potential to the building stock by code regime.
5. Normalize the results by floor area for buildings in each code regime.

[1] Note that the NREL work focused on identification of building rooftop planes from lidar data and forming a statistical sample of these planes to generate suitable rooftop area statistics for small, medium, and large buildings as independent categories based on footprint. These data were then used to represent characteristics of available building area that could be assigned to numbered building counts using EIA CBECS for large and small buildings and from the Census American Community Survey data for small buildings. Thus, while manufacturing buildings may have been captured in the lidar statistical description of the potential PV roof area, the actual building counts to which these are subscribed did not include buildings in the manufacturing sector. CBECS excludes such manufacturing and agricultural buildings unless over 50% of the building falls into one of the primary commercial use categories (e.g., office or retail). Because the building counts did not include industrial buildings, it is assumed that the overall medium and large building installed capacity estimate could be most generally ascribed to the commercial sector entirely. In addition, the NREL study did not indicate whether the building count from the American Community Survey data included mobile homes, although it is presumed that these would have been captured in the lidar data. Thus, the residential building stock floorspace in mobile homes/manufactured housing identified in RECS has been included in this analysis for the purpose of normalizing the NREL PV potential to the building stock floorspace.

E.2.1 Calculation of Total Building Footprint for Residential and Commercial Floor Space

E.2.1.1 Residential Buildings

The total residential floorspace in specific residential building categories as tabulated by the 2015 Residential Energy Consumption Survey (RECS) (DOE/EIA 2018) was a starting point for determining the residential building footprint area in the analysis of potential solar offset. The RECS data contain statistics for single-family homes, mobile homes, and residential multifamily units in low-rise buildings (three stories or less) and in medium- to high-rise buildings (collectively four stories or greater). This distinction is important for this analysis because low-rise residential buildings generally fall under residential building construction codes, and medium- and high-rise buildings fall under the commercial construction code regime. Multifamily medium and high-rise buildings (grouped later in this appendix as “high-rise” for brevity) have a smaller ratio of building footprint-to-floor area than low-rise multifamily buildings, which affects their PV potential when normalized to building area. However, the 2015 RECS data generally provide limited information regarding the building construction for multifamily buildings, rather than focusing on the characteristics of the housing units. To disaggregate the RECS residential space into low-rise and high-rise commercial space, data from the 2017 American Housing Survey (AHS) (U.S. Census 2018) were used to augment the RECS data.

The RECS data used were based on overall national square footage reported (including unconditioned space) by four building categories as shown in Table E.7.

Table E.7. Residential Building Floor Area from 2015 RECS

Building Type	Billion ft^2
Residential single family (attached or detached)	201.0
Residential MF, 2–4 units	9.6
Residential MF, 5+ units	18.7
Mobile homes	8.1
Total	237.4

The AHS data are also on a per-housing-unit basis, with statistical weights per housing sample corresponding to the number of similar units in the U.S. housing population. AHS has categorical variables to allow the survey data to be grouped in the same fashion as RECS data shown in Table E.8. It also contains details on the floor space per housing unit and the number of floors in the building, categorically identifying buildings by number of floors 1–6 and lumping all building with seven or more floors into the same category. Housing unit size, in square feet, is also a categorical variable, with per-unit floorspace binned into nine categories (e.g., 2,000 to 2,499 ft^2). For this work, the middle value in each housing unit size bin was used for bins between 500 and 4,000 ft^2. For units between 0 and 500 ft^2 in size, 500 ft^2 were used. For buildings categorized as greater than 4,000 ft^2, 5,000 ft^2 were used based on heated floorspace reported in a similar population bin from the 2015 Residential Energy Consumption Survey (RECS).[1] Note that buildings with seven or more floors were considered as having seven floors.

[1] Note: This threshold puts all single-family residential floorspace into the small building category, which is consistent with the NREL analysis. Analysis of RECS 2015 data suggested that approximately 2% of single-family floorspace may be in the low-rise medium category, although near the small end of that building footprint range.

Using these data, an estimate was made of the floor space per building and the footprint per building as follows.

In single-family buildings and multifamily buildings with up to four housing units, the per-unit area was that reported based on the AHS survey categorization.

In multifamily buildings with more than four units, it was assumed that the building floor area was 120% of the product of the number of units per building and the sampled floor space per unit. The 120% factor was used to represent both the area per housing unit and a 20% floorspace adder to account for common space in multifamily buildings not captured in the per-unit floor space data.

The building footprint for each building was estimated as the total floor space divided by the number of floors in the building and presumes an equal floor area per floor of the building.

For each AHS sample, a building weighting factor was calculated based on the per-housing-unit weights divided by the number of units recorded per sample. Aggregations of building-level data using these building weighting factors allowed for a national estimate of building floorspace and building footprint to be developed.

The resulting AHS sample was then disaggregated by buildings fitting into the RECS categories shown in Table E.8 using the “Units in Structure” variable (“BLD”). The AHS data in each RECS summary category data were further broken down into buildings less than or equal to three stories and buildings four stories or greater using the AHS variable “Stories in Structure” (“Stories”). Within these categories, the data were further disaggregated into small, medium, or large footprint categories as defined by NREL.

Note that roof eaves and overhangs are not included in this estimate of building footprint. Associated building area are not considered part of the building area captured in the AHS survey (e.g., unconditioned garages) and are not assigned floorspace or footprint area. In addition, buildings where the number of floors may vary across the building’s plan projection are assigned the number of stories provided in the AHS data, expected to be the maximum number of floors in the building. These factors may result in some understatement of total available building footprint and footprint-to-floorspace ratio (and total roof area), particularly for single-family low-rise buildings. For high-rise buildings, the assumption that buildings with seven or more stories have exactly seven floors that will likely overstate the footprint area in taller multifamily structures. These assumptions should be considered areas for future exploration.

The total floor area and calculated total footprint area for the AHS data building population in each subgroup were calculated using the building weighting factor, building floorspace, and building footprint for each housing sample. The ratio of the total building footprint to the total building floorspace in each category was then computed, with results shown in Table E.9. Statistics showing the fraction of residential floorspace in each category from the AHS survey are shown in Table E.8. Statistics showing the calculated footprint-to-floor area ratio in each category are shown in Table E.9.

Table E.8. AHS Floor Area Fractions within Residential Building Types

Building Type	Low Rise 1–3 Stories			High Rise 4+ Stories		
	Small	Medium	Large	Small	Medium	Large
Residential floor area (attached or detached) RECS 2015	1.000	0.000	0.000	0.000	0.000	0.000
Residential MF, 2–4 units	0.910	0.033	0.000	0.057	0.000	0.000
Residential MF, 5+ units	0.164	0.482	0.063	0.050	0.230	0.012
Mobile homes	1.000	0.000	0.000	0.000	0.000	0.000

Table E.9. AHS Footprint-to-Floor Area Ratio within Residential Building Types

Building Type	Low Rise 1–3 Stories			High Rise 4+ Stories		
	Small	Medium	Large	Small	Medium	Large
Residential SF (attached or detached) RECS 2015	0.621	NA	NA	NA	NA	NA
Residential MF, 2–4 units	0.564	0.801	NA	0.229	NA	NA
Residential MF, 5+ units	0.430	0.464	0.626	0.204	0.184	0.177
Mobile Homes	1.000	NA	NA	NA	NA	NA

E.2.1.2 Commercial Buildings

Commercial floor space in the DOE/Energy Information Agency (EIA) 2012 CBECS (DOE/EIA 2012) survey was similarly disaggregated into the categories of small, medium, and large footprint buildings. For each CBECS sample in the CBECS Microdata, the building footprint was calculated by dividing the building floor area by the number of stories reported for that observation. The total commercial floorspace and footprint area for small, medium, and large footprint categories were then aggregated using the samples and CBECS weights. In addition, an aggregate footprint-to-floorspace ratio was calculated as shown in Table E.10. For the same reasons discussed under residential data, the use of the reported number of stories and lack of inclusion of overhangs may underestimate the building footprint and corresponding building roof area for certain building types.

Table E.10. CBECS Floor Area Fractions and Aggregate Footprint-to-Floor Area Ratio by Building Footprint Category

	Footprint Category		
	Small	Medium	Large
CBECS Total Floor Area (Billion ft^2)	11.86	32.38	42.85
Total CBECS Floor Area Fraction	0.14	0.37	0.49
Aggregate Footprint-to-Floor Area Ratio	0.73	0.63	0.63

E.2.2 Combined Building Data by Code Regime

All of the commercial building data from CBECS are considered to fall under the commercial code regime. In addition, the multifamily high-rise data from RECS will also fall into the commercial code regime. The total floorspace and footprint area within the residential and commercial code regimes were calculated using the total building floorspace from RECS by residential building type and the floorspace and footprint breakouts from Table E.8 and Table E.9, combined with the footprint breakouts from CBECS.

Table E.11 and Table E.12 show corresponding floor area and footprint area for small, medium, and large building aggregated to corresponding residential code (low-rise residential) and commercial code (commercial buildings and multifamily residential four stories and greater) regimes.

Table E.11. Building Floorspace By Code Regime, Building Footprint Category and Type Classification (billion ft^2)

Building Type	Residential Codes by Footprint			Commercial Code by Footprint		
	Small	Medium	Large	Small	Medium	Large
Residential SF (attached or detached) RECS 2015	201.00	NA	NA	NA	NA	NA
Residential MF, 2–4 units	8.74	0.32	NA	0.55	NA	NA
Residential MF, 5+ units	3.06	9.01	1.19	0.93	4.29	0.22
Mobile Homes	8.10	NA	NA	NA	NA	NA
Commercial	NA	NA	NA	11.86	32.38	42.85
Total	220.90	9.32	1.19	13.34	36.68	43.07

Table E.12. Building Footprint by Code Regime, Building Size and Type Classification (billion ft^2)

Building Type	Residential Codes by Footprint			Commercial Code by Footprint		
	Small	Medium	Large	Small	Medium	Large
Residential SF (attached or detached) RECS 2015	124.84	NA	NA	NA	NA	NA
Residential MF, 2–4 units	4.93	0.25	NA	0.13	NA	NA
Residential MF, 5+ units	1.32	4.17	0.74	0.19	0.79	0.04
Mobile Homes	8.10	NA	NA	NA	NA	NA
Commercial	NA	NA	NA	8.63	20.33	26.80
Total	139.18	4.43	0.74	8.94	21.12	26.84

In terms of footprint area, the data in Table E.12 show approximately 94% of the small footprint category falls under the residential code regime. Approximately 83% of the medium footprint area, and 97% of the large footprint area fall under the commercial code regime with the remainder of the building footprint in the medium and large footprint categories being attributed to medium- and high-rise multifamily buildings.

E.2.3 Allocation of Photovoltaic Production to Building Stock by Code Regime

The PV potential in terms of national kWh/yr in each building footprint category as determined by NREL (Gagnon et al. 2016) was divided by the total footprint in each footprint category from Table E.12 regardless of code regime. This results in 6.25 kWh/yr-ft^2, 7.87 kWh/yr-ft^2, and 11.06 kWh/yr-ft^2 of footprint area for the small, medium, and large footprint buildings, respectively.

These normalized solar potential values were applied to the corresponding footprint areas in Table E.12 for residential code and commercial code regimes, and the total solar potential in each code regime was calculated by summing over small, medium, and large footprint buildings, as shown in Table E.13. This was then normalized by the total building floorspace in each code regime to provide an estimate of the PV potential offset both in kWh/ft^2 and site kBtu/ft^2 based on the building stock.

Table E.13. PV Generation Potential (TWh/yr)

Code Regime	PV Generation Potential				Normalized by Floorspace	
	Total Building Stock (TWH/yr)				kWh/ft^2	kBtu/ft^2
	Small	Medium	Large	Total	All	All
Residential	870.1	34.9	8.2	913.2	3.95	13.5
Commercial	55.9	166.2	296.8	518.8	5.57	19.0
Overall					4.41	15.1

E.2.4 Comparison of Potential Photovoltaic Offsets and Calculation Assumptions

The normalized to floorspace values for the residential and commercial code regimes are compared to that calculated for the prototype buildings directly in Table E.14. Note that in the NREL study (Gagnon et al. 2016), all roof planes facing northwest through northeast (with normal orientation 67.5° east or west from true north) were considered unsuitable for PV and excluded from the assessment of PV potential. For this reason, building stock-based offsets are most directly comparable to Scenario 2 from the prototype analysis and were relatively close in value for both the residential and commercial code regimes.

Table E.14. Comparison of PV Offsets Calculated from Prototype and Building Stock Analysis

PV Potential Offset	Prototype Developed		Building Stock Developed
Code Regime	Scenario 1	Scenario 2	
Residential (kBtu/ft^2)	23.5	13.7	13.5
Commercial (kBtu/ft^2)	23.6	22.9	19.0

There are obviously a number of areas where the prototype-based PV offset and the building-stock-based PV offset differ, even where some of the underlying PVWatts assumptions were held the same in both studies. Therefore, we caution the reader from making too much of the degree of agreement between the PV offsets calculated in these two approaches. Some key fundamental differences are shown in Table E.15. A more detailed investigation of the NREL (2016) data and modeling approach may shed light on the factors that affect the PV offset calculations the most. A key finding of the prototype-based analysis is that the comparison of the Scenario 1 and Scenario 2 offsets, in the prototype-based analysis, suggests that there is significant additional potential in the residential sector for considering PV on north-facing roofs, at least for the purposes of assessing PV potential on the path to ZE. With the gable roof design and orientation assumptions of the prototype analysis, 40% (50% × 0.8) of the available roof in the predominant building prototype (single family) was considered suitable for PV in Scenario 1. That analysis did not separately consider more random building orientations or the impact of flat or hip-roof designs with a lower fraction of north-facing roof area, which might have increased the residential PV offset in Scenario 2. However, it is noted that NREL (Gagnon et al. 2016) reported an even lower figure (26%) for available roof area for small footprint buildings as a group.

Table E.15. Comparison of Key Assumptions in Prototype-Based and Building-Stock-Based PV Analysis

Analytical Assumptions	Prototype Based	Building Stock Based
Building Geometry and Orientation	Roof slope and orientations limited to building prototypes and fixed orientation assumptions	Range of roof slope and building orientations considered for sloped roof based on Lidar data. Similar assumptions for flat roofs
Suitable Roof Area Fraction	80% used for all buildings for roof area considered in each installation scenario. Total small footprint building suitable roof area fraction	Varies based on lidar analysis, but was characterized by building type
Roof-to-Floor Area Ratio	Based on specific prototypes	Original analysis did not consider floor area. Building stock floor area developed independently from National Survey Data (CBECS/RECS/AHS)
Climate and Solar Availability	Based on new construction estimates by climate zones	Based on geographic prevalence in building stock. Detail down to the zip code level
Elimination of North-Facing Roof Slopes for PV	Only in Scenario 2	All buildings in analysis
Use of Building Stock Data	Uses CBECS, RECS, and AHS data to determine building floor area and building floor-to-roof area ratios. Specific assumptions in utilizing these data may affect estimates of available roof area. Manufacturing and agricultural buildings not considered except where may be incidentally captured in CBECS data.	Uses statistical approach to get suitable roof area distributions for small, medium, and large footprint buildings. Uses national survey data to determine number of buildings in footprint categories in building stock. Small buildings represented by residential stock counts. Medium and large represented by commercial building counts. Manufacturing and agricultural buildings may be captured in lidar representations of suitable roof area but are not considered in building counts.

Appendix F – Residential Beyond-Code Efficiency Improvements by Climate Zone

Table F.1 through Table F.8 summarize the residential Passive House Institute U.S. (PHIUS) measure values and compare these to the current code baseline values for the eight climate zone groups. The energy cost savings and justified first costs are associated with these improvements.

Table F.1. Residential Efficiency Values for Climate Zone 1

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 1	Floor		U-value	0.06	0.06
	Foundation	Slab	U-value	0	1.667
		Crawl Space	U-value	0.477	0.340
	Envelope	Walls	U-value	0.082	0.082
		Ceiling	U-value	0.035	0.033
		Windows	U-value	No Requirement	0.37
			SHGC	0.25	0.30
	Air Leakage		ACH50	5.0	0.5
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Table F.2. Residential Efficiency Values for Climate Zone 2

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 2	Floor		U-value	0.06	0.06
	Foundation	Slab	U-value	0	0.179
		Crawl Space	U-value	0.477	0.060
	Envelope	Walls	U-value	0.082	0.042
		Ceiling	U-value	0.03	0.02
		Windows	U-value	0.40	0.29
			SHGC	0.25	0.31
	Air Leakage		ACH50	5.0	0.5
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Table F.3. Residential Efficiency Values for Climate Zone 3

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 3	Floor		U-value	0.06	0.06
	Foundation	Slab	U-value	0	0.094
		Crawl Space	U-value	0.136	0.050
	Envelope	Walls	U-value	0.06	0.042
		Ceiling	U-value	0.03	0.016
		Windows	U-value	0.32	0.26
			SHGC	0.25	0.31
	Air Leakage		ACH50	3.0	0.33
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	17.2

Table F.4. Residential Efficiency Values for Climate Zone 4

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 4	Floor		U-value	0.05	0.05
	Foundation	Slab	U-value	0.1	0.048
		Crawl Space	U-value	0.065	0.050
	Envelope	Walls	U-value	0.06	0.034
		Ceiling	U-value	0.026	0.016
		Windows	U-value	0.32	0.26
			SHGC	0.4	0.31
	Air Leakage		ACH50	3.0	0.33
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Table F.5. Residential Efficiency Values for Climate Zone 5

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 5	Floor		U-value	0.03	0.03
	Foundation	Slab	U-value	0.1	0.048
		Crawl space	U-value	0.055	0.040
	Envelope	Walls	U-value	0.045	0.024
		Ceiling	U-value	0.026	0.011
		Windows	U-value	0.30	0.19
			SHGC	No Requirement	0.27
	Air Leakage		ACH50	3.0	0.33
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Table F.6. Residential Efficiency Values for Climate Zone 6

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 6	Floor		U-value	0.03	0.03
	Foundation	Slab	U-value	0.1	0.048
		Crawl space	U-value	0.055	0.040
	Envelope	Walls	U-value	0.045	0.024
		Ceiling	U-value	0.026	0.011
		Windows	U-value	0.30	0.19
			SHGC	No Requirement	0.27
	Air Leakage		ACH50	3.0	0.33
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Table F.7. Residential Efficiency Values for Climate Zone 7

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 7	Floor		U-value	0.03	0.03
	Foundation	Slab	U-value	0.1	0.033
		Crawl Space	U-value	0.1	0.030
	Envelope	Walls	U-value	0.045	0.027
		Ceiling	U-value	0.026	0.012
		Windows	U-value	0.30	0.17
			SHGC	No Requirement	0.27
	Air Leakage		ACH50	3.0	0.33
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Table F.8. Residential Efficiency Values for Climate Zone 8

Group	Measure		Efficiency Units	IECC 2018	FS Beyond Code
CZ 8	Floor		U-value	0.03	0.03
	Foundation	Slab	U-value	0.1	0.025
		Crawl Space	U-value	0.055	0.020
	Envelope	Walls	U-value	0.045	0.017
		Ceiling	U-value	0.026	0.01
		Windows	U-value	0.30	0.17
			SHGC	No Requirement	0.27
	Air Leakage		ACH50	3.0	0.33
	Lighting		Relative Efficacy (%)	90	100
	Heating	Gas Furnace	AFUE	79.8	90.0
		Heat Pump	HSPF	8.2	8.2
	Cooling		SEER	13.4	21.9

Appendix G – Commercial Beyond-Code Efficiency Improvements by Climate Zone

Table G.1 through Table G.15 summarize the commercial beyond-code efficiency values and compare these to the current code baseline values for the 15 U.S. locations associated with the ASHRAE climate zones. The energy cost savings and justified first costs are associated with these improvements.

Table G.1. Commercial Efficiency Values for Climate Zone 1A

CZ	FS Advanced Measures		Efficiency Units	90.1-2019	FS
1A	Envelope	Roof, above deck	Roof U-Value	0.049	0.010
1A		Windows	Window U-Value	0.52	0.09
1A	Lighting	Exterior lighting	Exterior Lighting W	6,748	2,081
1A		Interior lighting	Interior Lighting LPD	0.55	0.25
1A		Task Lighting	Interior Lighting LPD (inc. task)	0.55	0.49
1A		Daylighting	Lighting kWh/year	108,736	99,069
1A	Plug Loads	Office equipment	Equipment Power EPD	1.58	1.47
1A	HVAC	Fans	Fan Power W/CFM	0.58	0.42
1A		Ducts	Fan Power W/CFM	0.58	0.44
1A		Chillers	Chiller COP	3.86	4.73
1A		Chillers	DT, SAT (varies), $/ft2	1.23	1.23
1A		HE Packaged DX	Cooling DX Equipment COP	3.93	4.54
1A		HE Heat pump	Cooling DX Equipment COP	3.93	5.36
1A			Heating DX Equipment COP	4.23	6.60
1A			Gas Equipment Eff.	0.81	0.81
1A		VRF system	Cooling COP	-	4.82
1A			Heating COP	-	4.80
1A		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
1A		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.2. Commercial Efficiency Values for Climate Zone 2A

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
2A	Envelope	Roof, above deck	Roof U-Value	0.046	0.010
2A		Windows	Window U-Value	0.46	0.10
2A	Lighting	Exterior lighting	Exterior Lighting W	5,955	1,815
2A		Interior lighting	Interior Lighting LPD	0.61	0.26
2A		Task Lighting	Interior Lighting LPD (inc. task)	0.61	0.52
2A		Daylighting	Lighting kWh/year	134,366	123,927
2A	Plug Loads	Office equipment	Equipment Power EPD	2.00	1.88
2A	HVAC	Fans	Fan Power W/CFM	0.62	0.46
2A		Ducts	Fan Power W/CFM	0.62	0.46
2A		Chillers	Chiller COP	3.89	4.81
2A		Chillers	DT, SAT (varies), $/ft2	1.23	1.23
2A		HE Packaged DX	Cooling DX Equipment COP	3.78	4.72
2A		HE Heat pump	Cooling DX Equipment COP	3.78	4.82
2A			Heating DX Equipment COP	3.98	5.89
2A			Gas Equipment Eff.	0.81	0.81
2A		VRF system	Cooling COP	-	4.82
2A			Heating COP	-	4.80
2A		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
2A		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.3. Commercial Efficiency Values for Climate Zone 2B

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
2B	Envelope	Roof, above deck	Roof U-Value	0.048	0.010
2B		Windows	Window U-Value	0.46	0.10
2B	Lighting	Exterior lighting	Exterior Lighting W	5,653	1,713
2B		Interior lighting	Interior Lighting LPD	0.62	0.26
2B		Task Lighting	Interior Lighting LPD (inc. task)	0.62	0.51
2B		Daylighting	Lighting kWh/year	125,992	115,981
2B	Plug Loads	Office equipment	Equipment Power EPD	1.84	1.71
2B	HVAC	Fans	Fan Power W/CFM	0.63	0.47
2B		Ducts	Fan Power W/CFM	0.63	0.46
2B		Chillers	Chiller COP	3.97	4.95

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
2B		Chillers	DT, SAT (varies), $/ft2	1.14	1.14
2B		HE Packaged DX	Cooling DX Equipment COP	3.73	4.74
2B		HE Heat pump	Cooling DX Equipment COP	3.73	4.69
2B			Heating DX Equipment COP	3.80	5.77
2B			Gas Equipment Eff.	0.81	0.81
2B		VRF system	Cooling COP	-	4.82
2B			Heating COP	-	4.80
2B		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
2B		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.4. Commercial Efficiency Values for Climate Zone 3A

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
3A	Envelope	Roof, above deck	Roof U-Value	0.045	0.009
3A		Windows	Window U-Value	0.43	0.10
3A	Lighting	Exterior lighting	Exterior Lighting W	6,020	1,838
3A		Interior lighting	Interior Lighting LPD	0.63	0.27
3A		Task Lighting	Interior Lighting LPD (inc. task)	0.63	0.54
3A		Daylighting	Lighting kWh/year	142,770	131,978
3A	Plug Loads	Office equipment	Equipment Power EPD	2.14	2.00
3A	HVAC	Fans	Fan Power W/CFM	0.62	0.46
3A		Ducts	Fan Power W/CFM	0.62	0.46
3A		Chillers	Chiller COP	3.81	4.68
3A		Chillers	DT, SAT (varies), $/ft2	1.16	1.16
3A		HE Packaged DX	Cooling DX Equipment COP	3.74	4.71
3A		HE Heat pump	Cooling DX Equipment COP	3.74	4.73
3A			Heating DX Equipment COP	3.89	5.80
3A			Gas Equipment Eff.	0.80	0.81
3A		VRF system	Cooling COP	-	4.82
3A			Heating COP	-	4.80
3A		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
3A		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.5. Commercial Efficiency Values for Climate Zone 3B

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
3B	Envelope	Roof, above deck	Roof U-Value	0.049	0.010
3B		Windows	Window U-Value	0.43	0.09
3B	Lighting	Exterior lighting	Exterior Lighting W	6,064	1,835
3B		Interior lighting	Interior Lighting LPD	0.59	0.26
3B		Task Lighting	Interior Lighting LPD (inc. task)	0.59	0.51
3B		Daylighting	Lighting kWh/year	125,078	114,669
3B	Plug Loads	Office equipment	Equipment Power EPD	1.76	1.65
3B	HVAC	Fans	Fan Power W/CFM	0.59	0.44
3B		Ducts	Fan Power W/CFM	0.59	0.44
3B		Chillers	Chiller COP	3.81	4.69
3B		Chillers	DT, SAT (varies), $/ft2	1.04	1.04
3B		HE Packaged DX	Cooling DX Equipment COP	3.80	4.73
3B		HE Heat pump	Cooling DX Equipment COP	3.80	4.84
3B			Heating DX Equipment COP	4.05	5.89
3B			Gas Equipment Eff.	0.80	0.81
3B		VRF system	Cooling COP	-	4.82
3B			Heating COP	-	4.80
3B		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
3B		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.6. Commercial Efficiency Values for Climate Zone 3C

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
3C	Envelope	Roof, above deck	Roof U-Value	0.042	0.009
3C		Windows	Window U-Value	0.43	0.09
3C	Lighting	Exterior lighting	Exterior Lighting W	8,807	2,734
3C		Interior lighting	Interior Lighting LPD	0.58	0.25
3C		Task Lighting	Interior Lighting LPD (inc. task)	0.58	0.46
3C		Daylighting	Lighting kWh/year	180,834	165,686
3C	Plug Loads	Office equipment	Equipment Power EPD	1.63	1.47
3C	HVAC	Fans	Fan Power W/CFM	0.65	0.48
3C		Ducts	Fan Power W/CFM	0.65	0.48
3C		Chillers	Chiller COP	4.36	5.79

CZ	FS Advanced Measure		Efficiency Units	90.1-2019	FS
3C		Chillers	DT, SAT (varies), $/ft2	1.07	1.07
3C		HE Packaged DX	Cooling DX Equipment COP	3.91	4.65
3C		HE Heat pump	Cooling DX Equipment COP	3.91	5.13
3C			Heating DX Equipment COP	4.18	6.51
3C			Gas Equipment Eff.	0.81	0.81
3C		VRF system	Cooling COP	-	4.82
3C			Heating COP	-	4.80
3C		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
3C		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.7. Commercial Efficiency Values for Climate Zone 4A

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
4A	Envelope	Roof, above deck	Roof U-Value	0.038	0.008
4A		Windows	Window U-Value	0.37	0.09
4A	Lighting	Exterior lighting	Exterior Lighting W	6,981	2,144
4A		Interior lighting	Interior Lighting LPD	0.59	0.26
4A		Task Lighting	Interior Lighting LPD (inc. task)	0.59	0.51
4A		Daylighting	Lighting kWh/year	146,158	133,779
4A	Plug Loads	Office equipment	Equipment Power EPD	1.78	1.65
4A	HVAC	Fans	Fan Power W/CFM	0.59	0.44
4A		Ducts	Fan Power W/CFM	0.59	0.44
4A		Chillers	Chiller COP	4.18	5.15
4A		Chillers	DT, SAT (varies), $/ft2	1.13	1.12
4A		HE Packaged DX	Cooling DX Equipment COP	3.84	4.65
4A		HE Heat pump	Cooling DX Equipment COP	3.84	5.02
4A			Heating DX Equipment COP	4.16	6.20
4A			Gas Equipment Eff.	0.81	0.81
4A		VRF system	Cooling COP	-	4.82
4A			Heating COP	-	4.80
4A		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
4A		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.8. Commercial Efficiency Values for Climate Zone 4B

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
4B	Envelope	Roof, above deck	Roof U-Value	0.035	0.009
4B		Windows	Window U-Value	0.36	0.10
4B	Lighting	Exterior lighting	Exterior Lighting W	4,766	1,454
4B		Interior lighting	Interior Lighting LPD	0.68	0.28
4B		Task Lighting	Interior Lighting LPD (inc. task)	0.68	0.58
4B		Daylighting	Lighting kWh/year	139,430	127,860
4B	Plug Loads	Office equipment	Equipment Power EPD	2.51	2.36
4B	HVAC	Fans	Fan Power W/CFM	0.67	0.50
4B		Ducts	Fan Power W/CFM	0.67	0.49
4B		Chillers	Chiller COP	3.48	4.36
4B		Chillers	DT, SAT (varies), $/ft2	1.21	1.21
4B		HE Packaged DX	Cooling DX Equipment COP	3.68	4.73
4B		HE Heat pump	Cooling DX Equipment COP	3.68	4.55
4B			Heating DX Equipment COP	3.38	5.61
4B			Gas Equipment Eff.	0.80	0.81
4B		VRF system	Cooling COP	-	4.82
4B			Heating COP	-	4.80
4B		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
4B		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.9. Commercial Efficiency Values for Climate Zone 4C

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
4C	Envelope	Roof, above deck	Roof U-Value	0.037	0.008
4C		Windows	Window U-Value	0.37	0.09
4C	Lighting	Exterior lighting	Exterior Lighting W	7,356	2,267
4C		Interior lighting	Interior Lighting LPD	0.58	0.25
4C		Task Lighting	Interior Lighting LPD (inc. task)	0.58	0.49
4C		Daylighting	Lighting kWh/year	148,483	136,710
4C	Plug Loads	Office equipment	Equipment Power EPD	1.62	1.49
4C	HVAC	Fans	Fan Power W/CFM	0.61	0.45
4C		Ducts	Fan Power W/CFM	0.61	0.46
4C		Chillers	Chiller COP	4.09	5.35

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
4C		Chillers	DT, SAT (varies), $/ft2	1.01	1.01
4C		HE Packaged DX	Cooling DX Equipment COP	3.90	4.69
4C		HE Heat pump	Cooling DX Equipment COP	3.90	5.09
4C			Heating DX Equipment COP	4.16	6.31
4C			Gas Equipment Eff.	0.81	0.81
4C		VRF system	Cooling COP	-	4.82
4C			Heating COP	-	4.80
4C		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
4C		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.10. Commercial Efficiency Values for Climate Zone 5A

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
5A	Envelope	Roof, above deck	Roof U-Value	0.038	0.008
5A		Windows	Window U-Value	0.37	0.10
5A	Lighting	Exterior lighting	Exterior Lighting W	5,876	1,797
5A		Interior lighting	Interior Lighting LPD	0.63	0.27
5A		Task Lighting	Interior Lighting LPD (inc. task)	0.63	0.54
5A		Daylighting	Lighting kWh/year	142,919	132,129
5A	Plug Loads	Office equipment	Equipment Power EPD	2.01	1.89
5A	HVAC	Fans	Fan Power W/CFM	0.61	0.46
5A		Ducts	Fan Power W/CFM	0.61	0.46
5A		Chillers	Chiller COP	3.86	4.81
5A		Chillers	DT, SAT (varies), $/ft2	1.19	1.19
5A		HE Packaged DX	Cooling DX Equipment COP	3.78	4.71
5A		HE Heat pump	Cooling DX Equipment COP	3.78	4.78
5A			Heating DX Equipment COP	4.02	5.93
5A			Gas Equipment Eff.	0.80	0.81
5A		VRF system	Cooling COP	-	4.82
5A			Heating COP	-	4.80
5A		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
5A		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.11. Commercial Efficiency Values for Climate Zone 5B

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
5B	Envelope	Roof, above deck	Roof U-Value	0.038	0.008
5B		Windows	Window U-Value	0.37	0.10
5B	Lighting	Exterior lighting	Exterior Lighting W	5,809	1,780
5B		Interior lighting	Interior Lighting LPD	0.62	0.27
5B		Task Lighting	Interior Lighting LPD (inc. task)	0.62	0.52
5B		Daylighting	Lighting kWh/year	139,945	127,857
5B	Plug Loads	Office equipment	Equipment Power EPD	2.00	1.86
5B	HVAC	Fans	Fan Power W/CFM	0.63	0.47
5B		Ducts	Fan Power W/CFM	0.63	0.47
5B		Chillers	Chiller COP	3.81	4.89
5B		Chillers	DT, SAT (varies), $/ft2	1.15	1.14
5B		HE Packaged DX	Cooling DX Equipment COP	3.80	4.76
5B		HE Heat pump	Cooling DX Equipment COP	3.80	4.72
5B			Heating DX Equipment COP	3.86	5.86
5B			Gas Equipment Eff.	0.81	0.81
5B		VRF system	Cooling COP	-	4.82
5B			Heating COP	-	4.80
5B		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
5B		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.12. Commercial Efficiency Values for Climate Zone 6A

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
6A	Envelope	Roof, above deck	Roof U-Value	0.034	0.007
6A		Windows	Window U-Value	0.35	0.10
6A	Lighting	Exterior lighting	Exterior Lighting W	5,650	1,740
6A		Interior lighting	Interior Lighting LPD	0.64	0.27
6A		Task Lighting	Interior Lighting LPD (inc. task)	0.64	0.56
6A		Daylighting	Lighting kWh/year	152,905	142,415
6A	Plug Loads	Office equipment	Equipment Power EPD	2.07	1.94
6A	HVAC	Fans	Fan Power W/CFM	0.64	0.48
6A		Ducts	Fan Power W/CFM	0.64	0.48
6A		Chillers	Chiller COP	3.92	4.91

CZ	FS Advanced Measure		Efficiency Unit	90.1-2019	FS
6A		Chillers	DT, SAT (varies), $/ft2	1.36	1.36
6A		HE Packaged DX	Cooling DX Equipment COP	3.76	4.72
6A		HE Heat pump	Cooling DX Equipment COP	3.76	4.64
6A			Heating DX Equipment COP	3.90	5.83
6A			Gas Equipment Eff.	0.81	0.81
6A		VRF system	Cooling COP	-	4.82
6A			Heating COP	-	4.80
6A		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
6A		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.13. Commercial Efficiency Values for Climate Zone 6B

CZ	FS Advanced Measures		Efficiency Unit	90.1-2019	FS
6B	Envelope	Roof, above deck	Roof U-Value	0.033	0.007
6B		Windows	Window U-Value	0.35	0.09
6B	Lighting	Exterior lighting	Exterior Lighting W	5,346	1,647
6B		Interior lighting	Interior Lighting LPD	0.66	0.27
6B		Task Lighting	Interior Lighting LPD (inc. task)	0.66	0.58
6B		Daylighting	Lighting kWh/year	161,070	149,791
6B	Plug Loads	Office equipment	Equipment Power EPD	2.63	2.48
6B	HVAC	Fans	Fan Power W/CFM	0.70	0.52
6B		Ducts	Fan Power W/CFM	0.70	0.51
6B		Chillers	Chiller COP	3.45	4.32
6B		Chillers	DT, SAT (varies), $/ft2	1.30	1.30
6B		HE Packaged DX	Cooling DX Equipment COP	3.71	4.74
6B		HE Heat pump	Cooling DX Equipment COP	3.71	4.55
6B			Heating DX Equipment COP	3.68	5.69
6B			Gas Equipment Eff.	0.80	0.81
6B		VRF system	Cooling COP	-	4.82
6B			Heating COP	-	4.80
6B		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
6B		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.14. Commercial Efficiency Values for Climate Zone 7

CZ	FS Advanced Measures		Efficiency Unit	90.1-2019	FS
7	Envelope	Roof, above deck	Roof U-Value	0.028	0.006
7		Windows	Window U-Value	0.30	0.09
7	Lighting	Exterior lighting	Exterior Lighting W	5,879	1,809
7		Interior lighting	Interior Lighting LPD	0.67	0.28
7		Task Lighting	Interior Lighting LPD (inc. task)	0.67	0.58
7		Daylighting	Lighting kWh/year	181,138	170,285
7	Plug Loads	Office equipment	Equipment Power EPD	2.34	2.20
7	HVAC	Fans	Fan Power W/CFM	0.69	0.51
7		Ducts	Fan Power W/CFM	0.69	0.51
7		Chillers	Chiller COP	3.80	4.78
7		Chillers	DT, SAT (varies), $/ft2	1.46	1.46
7		HE Packaged DX	Cooling DX Equipment COP	3.69	4.70
7		HE Heat pump	Cooling DX Equipment COP	3.69	4.52
7			Heating DX Equipment COP	3.75	5.73
7			Gas Equipment Eff.	0.80	0.81
7		VRF system	Cooling COP	-	4.82
7			Heating COP	-	4.80
7		Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
7		Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Table G.15. Commercial Efficiency Values for Climate Zone 8

CZ	FS Advanced Measures		Efficiency Unit	90.1-2019	FS
8	Envelope	Roof, above deck	Roof U-Value	0.028	0.006
8		Windows	Window U-Value	0.26	0.09
8	Lighting	Exterior lighting	Exterior Lighting W	5,152	1,588
8		Interior lighting	Interior Lighting LPD	0.74	0.30
8		Task Lighting	Interior Lighting LPD (inc. task)	0.74	0.64
8		Daylighting	Lighting kWh/year	186,506	177,043
8	Plug Loads	Office equipment	Equipment Power EPD	2.86	2.71
8	HVAC	Fans	Fan Power W/CFM	0.72	0.54
8		Ducts	Fan Power W/CFM	0.72	0.52
8		Chillers	Chiller COP	3.54	4.46

CZ	FS Advanced Measures	Efficiency Unit	90.1-2019	FS
8	Chillers	DT, SAT (varies), $/ft2	1.62	1.62
8	HE Packaged DX	Cooling DX Equipment COP	3.66	4.76
8	HE Heat pump	Cooling DX Equipment COP	3.66	4.52
8		Heating DX Equipment COP	3.36	5.61
8		Gas Equipment Eff.	0.80	0.81
8	VRF system	Cooling COP	-	4.82
8		Heating COP	-	4.80
8	Demand Control Ventilation	Carbon Dioxide Setpoint (ppm)	-	2000
8	Indirect evaporative pre-cooling	Cooler Wetbulb Design Effectiveness	-	0.85

Appendix H – Justified First Cost Analysis

Table H.1 and Table H.2 summarize economic parameters and their values used in the justified first cost (JFC) analysis, which is applied to the savings determined for each beyond-code measure and package of measures. Figure H.1 and Figure H.2 present the normalized JFC (per $1 of measure annual energy cost savings) as a function of measure life. The curves reflect the assumed residential and commercial economic parameter values. The equations, included in the figures, describe the curves and were used to evaluate the normalized JFC values based on the measure life. The JFC was determined for each measure by multiplying the normalized JFC value by the measure annual savings value

Table H.1. Residential Economic Analysis Parameter Values

Parameter	Value
Mortgage Interest Rate	5%
Loan Term	30 years
Down-Payment Rate	10% of home price
Points and Loan Fees	0.7% (non-deductible)
Analysis Period	30 years
Property Tax Rate	1.5% of home price/value
Income Tax Rate	12% federal
Inflation Rate	2.52% annual
Home Price Escalation Rate	Equal to inflation rate

Table H.2. Commercial Economic Analysis Parameter Values

Parameter	Value
Study Period – Years	30
Nominal Discount Rate	6.00%
Real Discount Rate	4.05%
Electricity and Natural Gas Price Escalation	Uniform PV factors: Electric 14.12, Gas 17.28
Loan Interest Rate	6.00%
Federal Corporate Tax Rate	21.00%
State Corporate Tax Rate	6.50%

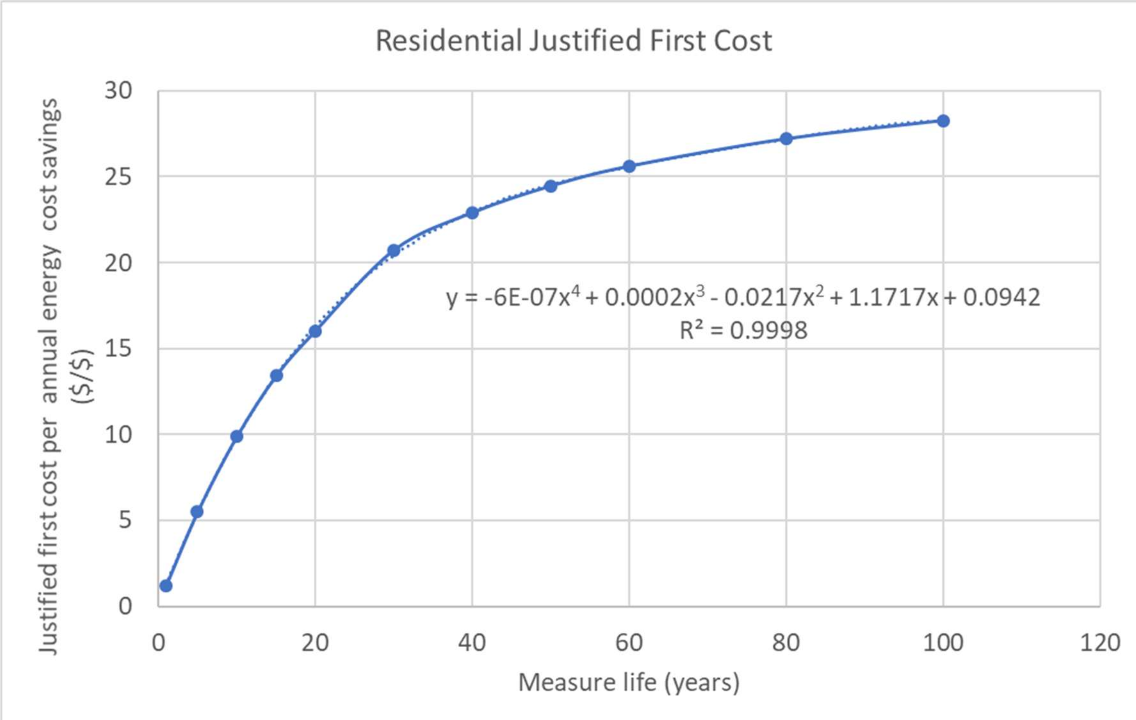

Figure H.1. Justified First Cost Curve for Residential Energy Efficiency Measures

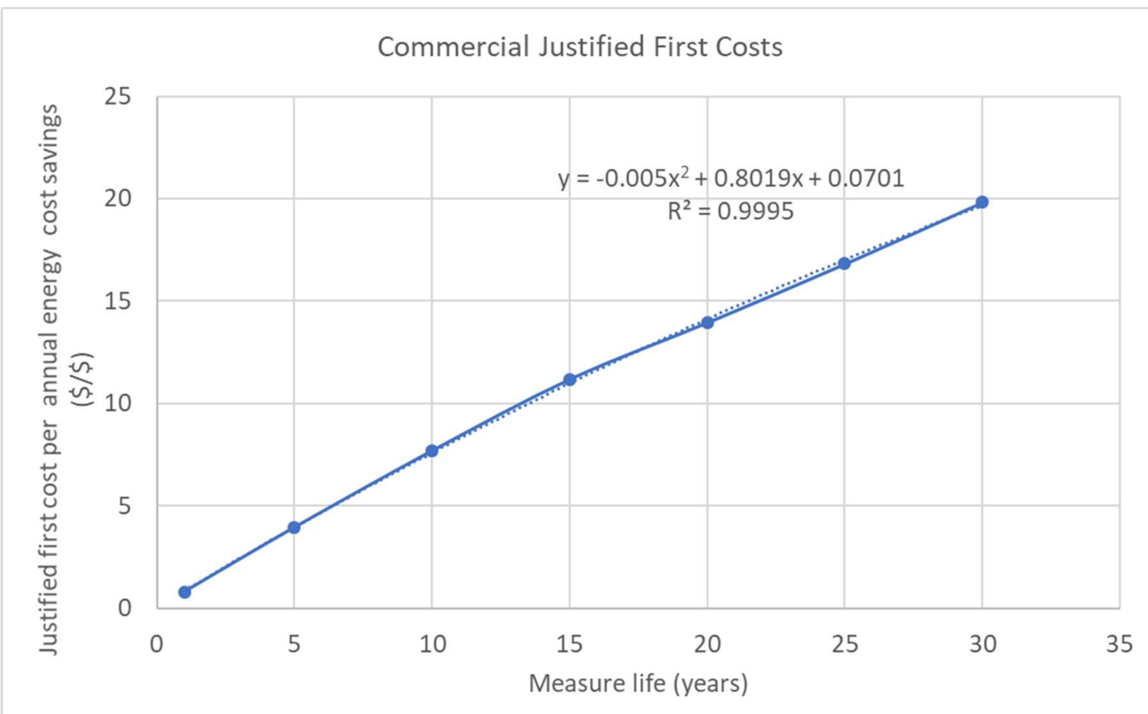

Figure H.2. Justified First Cost for Commercial Efficiency Measures (privately owned with loans and taxes)

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