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IEA HPT Annex 49

Design and Integration of Heat pumps for nearly Zero Energy Buildings

Country Report US Task 1

State-of-the-Art Analysis of Nearly Zero Energy Buildings

Country report IEA HPT Annex 49 Task 1 USA

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Abstract

The IEA HPT Annex 49 "Design and integration of heat pumps for Nearly Zero Energy Buildings" deals with the design and integration of heat pumps as core component of the HVAC system for Nearly or Net Zero energy buildings (NZEB).
The IEA HPT Annex 49 has been structured into four tasks which comprise the following investigations:

Task 1: State-of-the-art analysis
The Task 1 is to give an overview on NZEB on the national level of the participating countries. In more detail, the political framework in terms of NZEB (e.g. building codes, legislation, definition(s) of NZEB), the state of market introduction and applied technologies both on the building envelope and the building HVAC system shall be characterised. The compiled technical concepts shall be analysed regarding the heat pump application. Moreover, technologies can be classified in a technology matrix and evaluated regarding specific advantages of single technologies for dedicated applications like new buildings, retrofit, office, residential etc. Technologies shall also be considered regarding different aspects of the definitions, e.g. characteristics regarding load match and grid interaction, the necessity of a grid connection or the capability to integrate local storage. This information can be updated from IEA HPT Annex 40. Moreover, information shall be extended regarding the technologies for group of buildings and neighbourhoods and as well as for current market conditions for renewables energy.

Task 2: Integration options of system technology
Task 2 is dedicated to identifying promising integration options to increase the performance. This can be done for single buildings, i.e. simultaneous operation modes or storage integration, but the investigations shall also be extended to group of buildings or neighbourhoods, which may offer collective heat source/heat sink and a load balancing in case of different buildings uses. Concepts and technologies can be analysed by simulations regarding the benefits in performance or cost of the system integration options, but also regarding further aspects like self-consumption of energy, load match and grid interaction. Evaluation can also be linked to Task 4 regarding the design and control of system configurations.

Task 3: Technology development and field monitoring
Task 3 is dedicated to technology developments on the component and system level as well to gather field experiences of system solutions in field monitoring projects. Marketable and prototype technologies could be lab-tested or investigated in field monitoring. Task 3 is accomplished in parallel to Task 2.

Task 4: Design and control of nZEB technical building systems
Task 4 is also to be accomplished in parallel and deals with the design and control of building systems in nZEB. On the one hand this is related to the integration option investigate in Task 2 and include the design for groups of buildings and neighbourhood. Besides the function of the components control also address strategies for demand response to enhance the flexibility of the building technology, either for higher self-consumption or for a grid-supportive operation, e.g. based on price signals. Thus, a holistic evaluation of the design and control of the building technology based on the criteria performance, cost and flexibility shall be derived.

This report gives the results with the state-of-the-art analysis of Task 1.

Contents

1 POLICY FRAMEWORK AND DEFINITION

1.1 Political Framework

1.1.1 Overview of U.S. Energy Consumption

The building sector is the largest sectoral energy consumer in the United States. Residential and commercial buildings combined account for 39% of total U. S. energy consumption. As shown in Figure 1-1, residential buildings consume over half the energy in the sector. Heating and cooling expenditures account for 40% of residential energy consumption [1]. Buildings and the space conditioning systems within them have large energy savings opportunities that can be exploited by using both existing and emerging technologies.

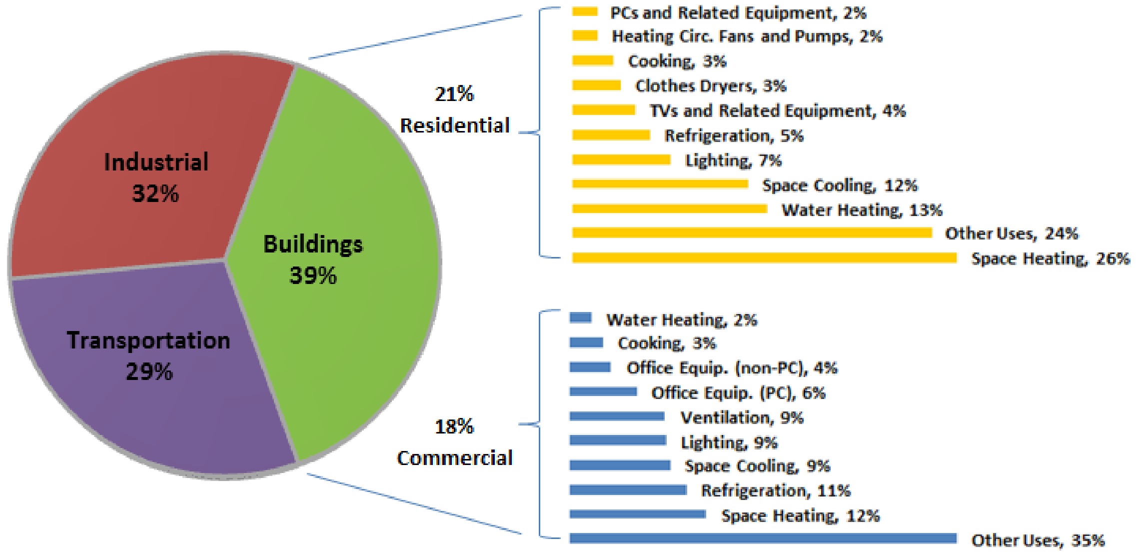


Figure 1-1: Energy Consumption in the United States, 2016 [1]

As can be seen in Figure 1-2, the United States has a very large variation in climate, causing a corresponding wide variation in residential energy usage depending upon location, particularly regarding heating and cooling expenditures. Descriptions of the Building America Program (BAP) climate zones are provided in Table 1-1. Also, a large variation exists in size of U.S. homes. Data indicate that over 118 million homes existed in the United States as of 2015, and the average home size ranged from 156 to 217 m^2 (1,685 to 2,337 ft^2). Single-family homes were the predominant type in the country comprising about 68% of the total, with the remainder split between homes in multi-family buildings (~26%) and mobile or manufactured homes (~6%) [2].

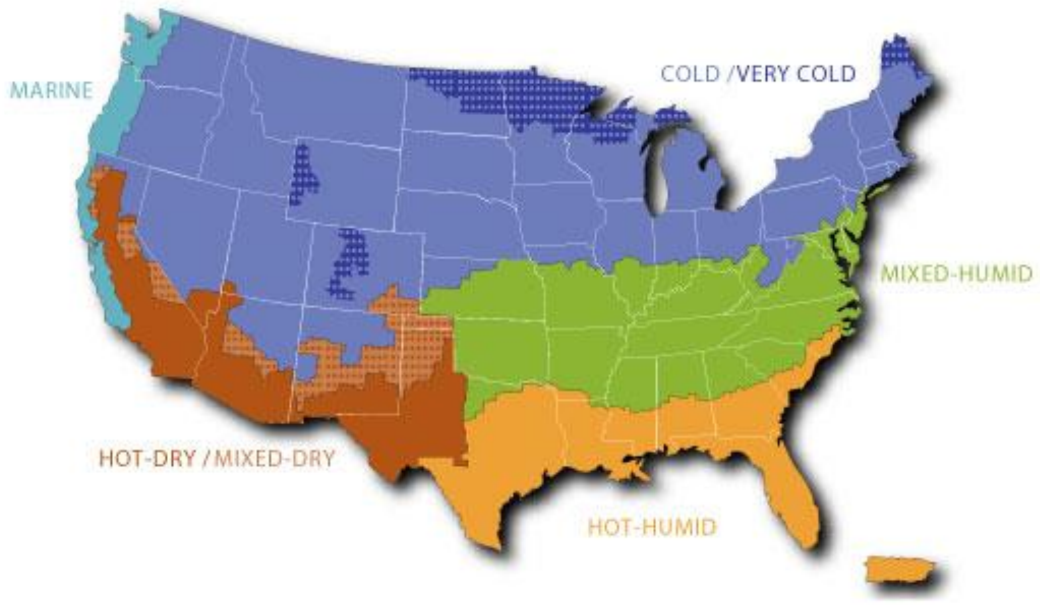


Figure 1-2: Seven of the eight climate zones recognized by BAP occur in the continental United States. The only subarctic regions in the country are found in Alaska (not shown on the map) [3]

Table 1-1: Description of BAP Climate Zones [3]

BAP Climate Zones	Description
Marine	Region that meets all of the following criteria: • A coldest month mean temperature between -3°C (27°F) and 18°C (65°F) • A warmest month mean of less than 22°C (72°F) • At least 4 months with mean temperatures higher than 10°C (50°F) • A dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere
Hot-Dry	Region that receives less than 50 cm (20 inches) of annual precipitation and where the monthly average outdoor temperature remains above 7°C (45°F) throughout the year
Hot-Humid	Region that receives more than 50 cm (20 inches) of annual precipitation and where one or both of the following occur: • A 19.5°C (67°F) or higher wet bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or • A 23°C (73°F) or higher wet bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year
Mixed-Dry	Region that receives less than 50 cm (20 inches) of annual precipitation, has approximately 3,000°C heating degree days - 18°C basis (5,400 °F heating degree days - 65°F basis) or less, and where the average monthly outdoor temperature drops below 7°C (45°F) during the winter months
Mixed-Humid	Region that receives more than 50 cm (20 inches) of annual precipitation, has approximately 3,000°C heating degree days - 18°C basis (5,400 °F heating degree days - 65°F basis) or less, and where the average monthly outdoor temperature drops below 7°C (45°F) during the winter months
Cold	Region with between 3,000 and 5,000 heating degree days - 18°C basis (5,400 and 9,000 heating degree days - 65°F basis).
Very Cold	Region with between 5,000 and 7,000 heating degree days - 18°C basis (9,000 and 12,600 heating degree days - 65°F basis).
Subarctic	Region with 7,000 heating degree days - 18°C basis (12,600 heating degree days - 65° basis) or more. The only subarctic regions in the United States are in found Alaska.

About half of U.S. residences use some type of fuel-fired furnace system for heating, predominantly natural gas (48% of all homes). About 37% of U.S. homes use electricity for heating, and about 12 million of those (~1/4) use heat pumps [2]. It is worthy to note that the use of heat pump heating systems has gained market share in U.S. new single-family homes in recent years, rising from 23% in 2001 to 38% in 2010. Of the 20.8 million homes constructed between 2000 and 2015, 3 million use heat pumps. Nearly 2.4 million heat pumps (air-source) were shipped by all U.S. manufacturers in 2016, up 7% compared to the previous year [4] As of 2015, air conditioning (AC) was used in 87% of all U.S. homes, mostly of the central air distribution type (~75% of homes that use AC) with the rest by window or wall units [2]. Except for a very few gas ACs, almost all ACs in U.S. residences use electricity.

The average size of U.S. homes increased steadily up through about 2010 in all regions, as shown in Figure 1-3. Average home size decreased slightly in all regions but the South. To sufficiently heat and cool these larger spaces, logic implies that a greater burden would be placed on heating and cooling equipment, light fixtures, appliances, etc. Furthermore, the upsurge in central AC units has significantly increased the amount of residential space that is cooled. Therefore, one would expect higher energy consumption per house. On the contrary, survey results show that average energy consumption per home has stayed fairly constant over the past decade (see Figure 1-4), in part due to larger homes having key energy efficient features, better insulation, and more efficient windows. These improvements are further enhanced by more stringent equipment, appliance, and construction standards in the last 15 years [5].

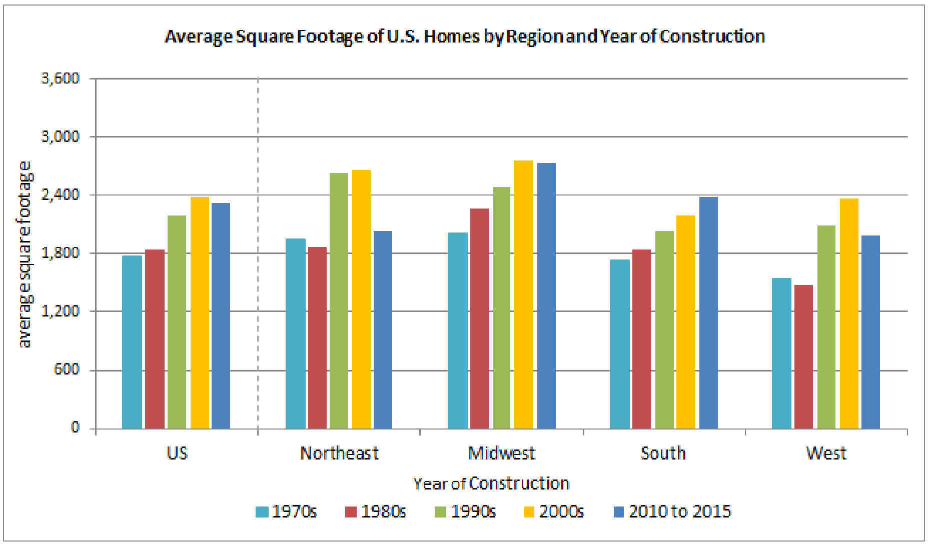


Figure 1-3: Demonstration of How Average Home Size (Square Footage) has Increased over Time [2]

Year of construction	Average size
1970 to 1979	1,772 ft^2 (165 m^2)
1980 to 1989	1,827 ft^2 (170 m^2)
1990 to 1999	2,198 ft^2 (204 m^2)
2000 to 2009	2,381 ft^2 (221 m^2)
2010 to 2015	2,320 ft^2 (216 m^2)

Table 1-2: National Average U.S. Home Size [2]

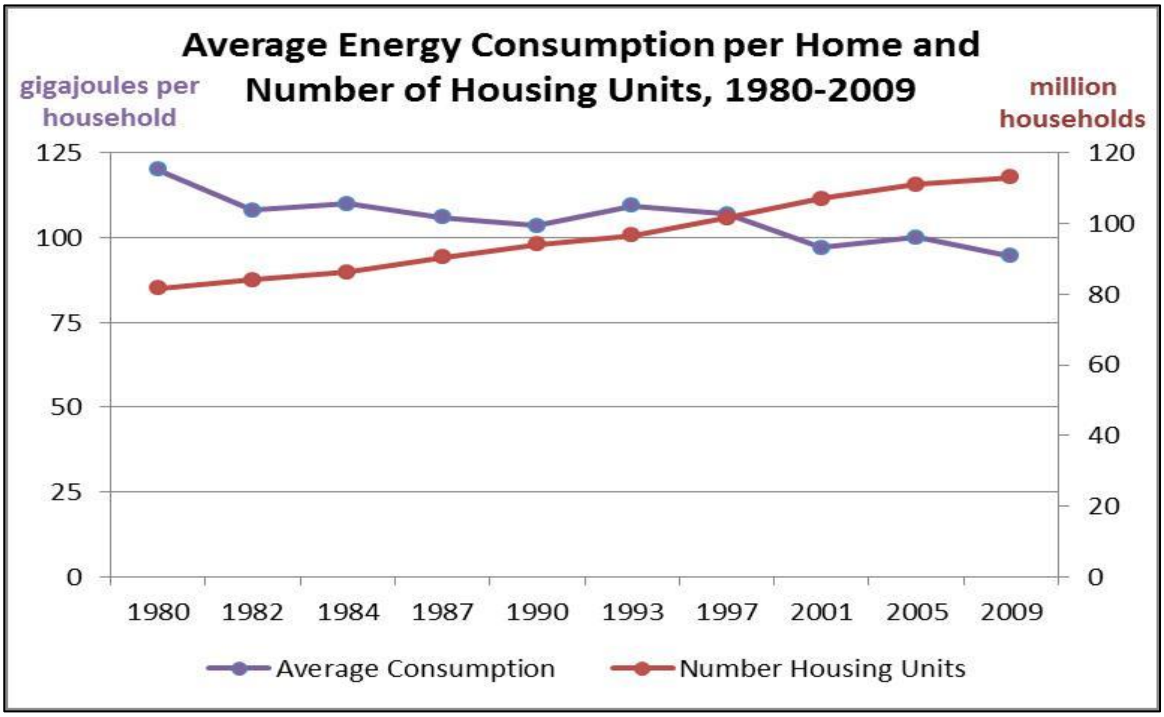


Figure 1-4: Average Energy Consumption per Home and Number of Housing Units, 1980-2009 [5]

Furthermore, building energy consumption is projected to remain relatively flat or, in some cases, decline between 2016 and 2040 because of efficiency standards and improved equipment, particularly in space heating and water heating. Energy demand for space cooling, however, is anticipated to decline by 20% between 2016 and 2040 as energy efficiency improvements more than offset the increased demand for space cooling [6].

1.1.2 Political Drivers to Reduce Consumption

Executive measures have been taken by federal agencies to increase energy efficiency and reduce greenhouse gas emissions, including President Obama's Executive Order (EO) 13693, "Planning for Federal Sustainability in the Next Decade." The EO outlines forward-looking goals for federal agencies in the area of energy, climate change, water use, vehicle fleets, construction and acquisition. Specifically the EO directs Federal Agencies to, where life-cycle cost-effective, beginning in fiscal year 2016, unless otherwise specified, promote building energy conservation, efficiency, and management by reducing agency building energy intensity measured in British thermal units per gross square foot by 2.5 percent annually through the end of fiscal year 2025, relative to the baseline of the agency's building energy use in fiscal year 2015 and taking into account agency progress to date [7].

Prior to EO 13693, the Energy Independence and Security Act of 2007 (EISA) established a goal of net-zero energy use for: (1) all commercial buildings newly constructed in the United States by 2030, (2) 50% of commercial building stock of the United States by 2040, and (3) 100% of commercial building stock by 2050 [8].

1.1.3 DOE Goals for Building Energy Consumption

Research and development (R&D) of highly efficient buildings in the United States is primarily supported by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). BTO's Residential Building Integration (RBI), including BAP, and Commercial Building Integration (CBI) offices focus on residential and commercial building R&D, respectively. BAP is a cost-shared industry partnership research program working with national laboratories and building science research teams to accelerate the development and adoption of advanced building energy technologies and practices in new and existing homes. BTO's Emerging Technologies (ET) offices supports the RBI and CBI programs with an R&D portfolio designed to develop advanced technologies to enable maximizing residential and commercial building efficiency. ET's focus includes heating, ventilating, and air-conditioning (HVAC), refrigeration (R), and water heating (WH); lighting; and thermal envelope equipment and systems.

Many of BTO's research projects that help to dramatically improve energy efficiency in American homes are managed by DOE national laboratories, including:

- National Renewable Energy Laboratory (NREL),
- Oak Ridge National Laboratory (ORNL),
- Lawrence Berkeley National Laboratory (LBNL), and
- Pacific Northwest National Laboratory (PNNL).

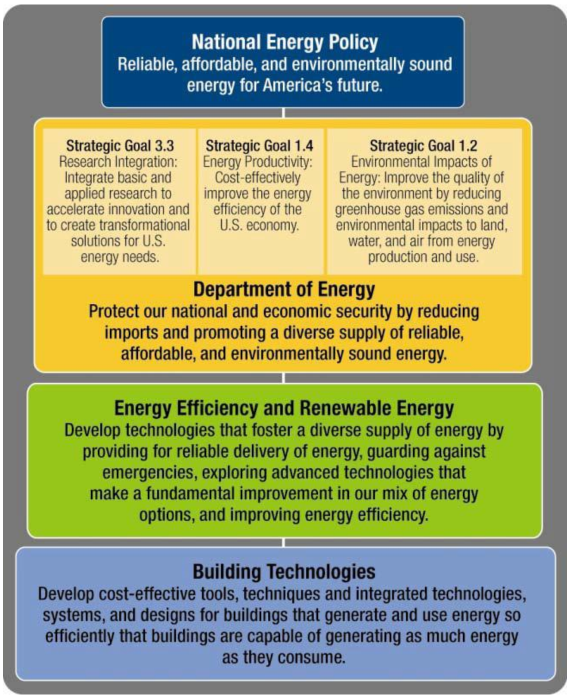


Figure 1-5: Goals of BTO align with National Energy Policy

The ultimate goal of BTO is to reduce the average building energy use intensity (EUI, kWh/m^2 or Btu/hft^2) by 50% compared to a 2010 baseline [9]. Sub goals for the HVAC, water heating (WH), and Appliances R&D activities are to develop technologies by 2020 with potential EUI reductions of 60%, 25%, and 15%, respectively, vs. a 2010 baseline. This goal is aggressive but resulting outcomes would make a lasting impact on both homeowners and the nation. For example, calculations show that if one of every 10 U.S. homes cut their energy expenditures by 25%, Americans would see a reduction of $5 billion per year on collective energy bills and a drop in greenhouse gas emissions equivalent to removing 225 million automobiles from the road.

1.1.4 DOE Initiatives to Accelerate Market

DOE BTO has kicked off several initiatives in recent years to accelerate the deployment and adoption of advanced building energy technologies and practices in new and existing homes. One example is the DOE Zero Energy Ready Home program (successor to the Builders Challenge program and formerly known as the Challenge Home program). This initiative represents a whole new level of home performance, with rigorous requirements that ensure outstanding levels of energy savings, comfort, health, and durability. As a result, hundreds of leading builders have been recognized for their leadership in increasing energy efficiency, improving indoor air quality, and making homes zero net-energy ready [10].

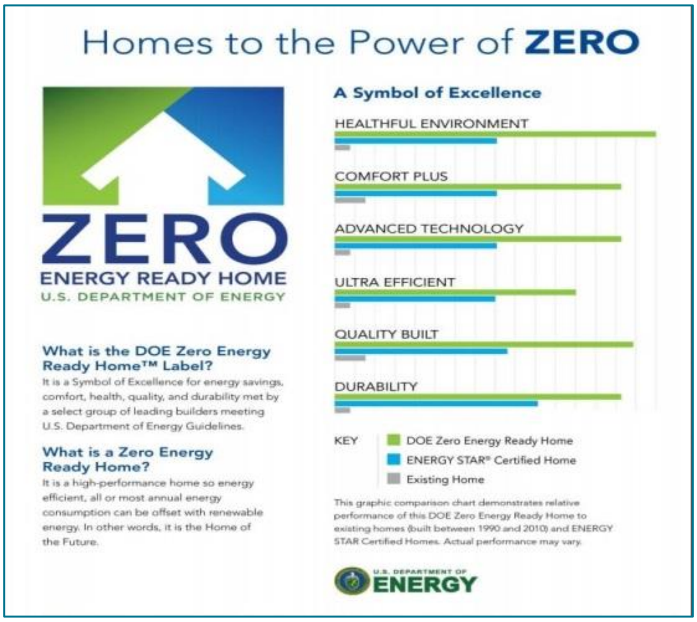


Figure 1-6: DOE Zero Energy Ready Home Sample Label [10]

For homeowners and contractors that choose to retrofit their existing buildings, DOE and the U.S. Environmental Protection Agency (EPA) established the Home Performance with ENERGY STAR (HPwES) Program to help homeowners perform green remodelling in their homes, with a focus on whole-house solutions that emphasize home comfort, indoor air quality, and safety. Since 2002, over 600,000 homeowners, 42 local sponsors, and more than 1,500 participating contractors have committed to use less energy through this program [11].

Other DOE initiatives that facilitate the market introduction of highly efficient residential buildings include the biennial Solar Decathlon, the Home Energy Score, and the Better Buildings Neighborhood Program.

In the commercial building area BTO's Better Buildings Challenge (part of its Better Buildings Initiative) aims to make U.S. commercial and industrial buildings at least 20% more efficient during the next decade (by 2020). To achieve this aggressive target, DOE is working with public and private sector partners that commit to being leaders in energy efficiency. These partners will implement energy savings practices that improve energy efficiency and save money and will showcase effective strategies and the results of their efforts. The Better Buildings Challenge initiative supports commercial and industrial building owners by providing technical assistance and proven energy efficiency solutions. This initiative also connects Partners with Allies, such as financial institutions and utilities, to encourage collaboration and problem solving in energy efficiency [12].

One specific HVAC/R equipment example within the BTO/CBI program is the Rooftop Challenge. Current rooftop unit (RTU) AC equipment for commercial buildings are required to have a minimum-rated coefficient of performance (COP) of 3.2 W/W (energy efficiency ratio (EER) of 11 Btu/Wh) at 35°C (95°F) outdoor temperature and an integrated COP (ICOP) of 3.3 (integrated EER (IEER) of 11.2 Btu/Wh) – ICOP/IEER are approximate measures of seasonal efficiency for RTUs. The program provides incentives to manufacturers to develop RTU equipment with an ICOP of 5.3 W/W (IEER of 18 Btu/WH) [13]. A companion R&D effort, Next Generation Rooftop Unit, under the ET program sought to develop technology for even more efficient RTU equipment with an original goal to demonstrate a prototype RTU with an ICOP of 5.9 W/W (IEER of 20.2 Btu/WH). This effort has estimated a predicted annual energy savings for cooling of small office buildings at 16 U.S. locations ranging from 44% to 48% compared with a baseline 11.0 IEER system. A 14-ton prototype RTU met the project goal in laboratory tests in 2015, i.e. reaching 21.6 IEER [14].

1.1.5 Impacts of DOE Initiatives

The federal and state initiatives above have shown to impact both building owners and the entire nation through reduced energy bills and more comfortable living spaces. They have also helped to increase the market share of low energy buildings, as demonstrated below:

- Since 2008, over 14,000 homes across the United States have achieved the energy efficiency criteria of DOE's Zero Energy Ready Home program. These homes are approximately 30% more energy efficient than a typical new home built to code [10].
- Over 600,000 homes have been retrofitted under the HPwES since its inception, with 1,500 participating contractors, and estimated savings ranging from 15% to 30% for homeowners. [11]
- The Solar Decathlon has become the national showcase for the future of housing. Its success has spread to Europe, Africa, China, Latin America and the Middle East, all of which have hosted or will host events [15].
- The Home Energy Score, which allows homeowners to compare the energy performance of their homes to other homes nationwide, has grown to 29 partner locations and has accounted for over 75,000 energy audits completed to date [16].
- The Better Buildings Neighborhood Program is testing new business models for community-scale energy efficiency upgrades with more than 40 competitively-selected state and local governments. To date, 119,000 buildings have been retrofitted and 250,000 audits have been conducted [17].
- Better Buildings Challenge partners represent more than 400 million square meters of building space, more than 1,000 industrial facilities, and $7 billion in committed financing. Through 2016, 200 partners shared energy performance results for nearly 38,000 properties. On average, partners in the Better Buildings Challenge are now saving more than 2% per year and are on track to meet their energy savings goals of 20% over the next 10 years [18].
- At least four manufacturers, three under the Rooftop Challenge program and one in partnership with ET on the Next Generation RTU project, have collaborated with DOE to make advanced commercial building rooftop HVAC equipment options available to building owners [13] [14].

1.1.6 Incentives for Energy Efficiency Upgrades or Renewable Energy Installations

Federal financial incentives, such as investment tax credits, are (or were until recently, in some instances) available for renewables and efficiency measures taken in new or existing houses, such as heating, cooling, and insulating system improvements. Table 1-2 provides examples of such federal tax credits. Incentives for geothermal or ground-source heat pumps which expired at the end of 2016 may be reinstated if potential new legislation becomes law [19]:

Table 1-3: Existing incentives for renewable and efficiency measures [19]

Federal Incentive	Eligible Efficiency Technologies	Expiration Date	Maximum Incentive
Business Energy Investment Tax Credit (ITC)	Solar Water Heat, Solar Space Heat, Geothermal Electric, Solar Thermal Electric, Solar Thermal Process Heat, Solar Photovoltaics, Wind (All), Geothermal Heat Pumps, Municipal Solid Waste, Combined Heat & Power, Fuel Cells using Non-Renewable Fuels, Tidal, Wind (Small), Geothermal Direct-Use, Fuel Cells using Renewable Fuels, Microturbines	December 31, 2022. With a gradual step down of the credits between 2019 and 2022.	Fuel cells: $1,500 per 0.5 kW, Microturbines: $200 per kW, Small wind turbines placed in service after 12/31/08: no limit, All other eligible technologies: no limit
Renewable Electricity Production Tax Credit (PTC)	Geothermal Electric, Solar Thermal Electric, Solar Photovoltaics, Wind (All), Biomass, Hydroelectric, Municipal Solid Waste, Landfill Gas, Tidal, Wave, Ocean Thermal, Wind (Small), Hydroelectric (Small)	Wind facilities: 12/31/2019; Other technologies: 12/31/2016	Wind: $0.019/kWh for first 10 years of operation
Residential Renewable Energy Tax Credit	Solar Water Heat, Photovoltaics, Other Solar-Electric Technologies (Wind, Fuel Cells, Geothermal Heat Pumps, and Fuel Cells using Renewable fuels were incentivized until December 31, 2016.	12/31/21 for solar; 12/31/16 for all other technologies	30%; no maximum (fuel cells were eligible for $500 per 0.5 kW until December 31, 2016.)

According to the Annual Energy Outlook 2017 published by the U.S. Energy Information Administration (EIA), the number of ground-source heat pumps and solar water heaters is expected to grow to a combined 2.4 million units in 2021 (from a combined 1.3 million units in 2011), largely due to the Residential Renewable Energy Tax Credit [1].

Property Assessed Clean Energy (PACE) financing also presents a low-cost, long-term financing opportunity for both commercial and residential building owners and developers to obtain a loan for energy upgrades. Such loans help to eliminate the high upfront costs associated with some green technologies and to benefit from lower energy costs while paying off the loan. Additionally, PACE enables homeowners to roll the loan into a home's mortgage. The loan is repaid over time as an annual assessment on property tax for up to 20 years. PACE is enabled in 31 states and the District of Columbia [20].

1.2 Definition(s) of nZEB

While both the EU Directive on Energy Performance of Buildings recast (EPBD) and the US Department of Energy's Building Technologies Program have mandated goals related to the adoption of nZEB-like structures, until recently standardized definitions of the latter have not been extant, and the potential for incomplete or biased commercial definitions lead Sartori et al to propose a consistent definition framework for nZEBs in 2012 [21]. That proposed framework is detailed in section 1.2.1. DOE has relatively recently developed its own nZEB definition discussed in section 1.2.2.

1.2.1: Sartori

Igor Sartori (SINTEF) and his colleagues [21] suggests that the term Net Zero Energy Building indicates an energy-efficient building connected to the energy grid, capable of generating renewable energy on-site and exporting that energy to the grid. There should be a balance between energy taken from and supplied back to the grid over a period of time (nominally a year), and nZEBs should be designed to work in synergy with the electrical grid and not put additional burden on its function. Tailoring of an nZEB definition to particular national needs is recognized, with countries encouraged to uniquely define, for example, the primary energy or carbon emission conversion factors for various energy carriers, establishing requirements on energy efficiency or prioritizing certain supply technologies.

This definition framework is organized into the following criteria:

1. <u>Definition of the building system boundary</u>, including the physical and balance boundaries and boundary conditions. Regarding the former, on-site generation systems and available two-way grids should be identified. Definitions of the balance boundary should specify which energy uses are considered for the nZEB balance; operational energy uses typically include heating, cooling, ventilation, domestic hot water, fixed lighting and plug loads.

   Boundary conditions including functionality (what types of uses is the building designed for?), space effectiveness (people/m^2 or, consequently, energy use per person), climate (reference climate used in building design) and comfort (comfort standards) should be defined; doing so permits similar buildings in similar climates to be compared, in addition to assessing differences between expected and monitored performance of the building.

2. <u>Definition of the weighting system</u>, which converts the physical units of different energy carriers into uniform metrics, allowing the evaluation of the entire supply chain vis-à-vis energy balance calculations. There are no correct conversion factors in absolute terms; rather, different factors are possible depending on the scope and assumptions of the analysis and any political or strategic priorities.

   Each two-way energy carrier (e.g. electricity) can be weighted symmetrically, using the same weighting factors for both delivered and exported quantities, or asymmetrically, using different factors.

   Regarding time-dependent accounting, it is preferable to calculate nZEB balance with static or quasi-static values and then use, in addition, dynamic values to address the temporal energy match characteristics (see criterion 4 below).

3. <u>Definition of nZEB balance,</u> including the balancing period, the type of balance to be measured, and energy efficiency & supply requirements. It is recommended that the energy balance of weighted demand and weighted supply be calculated over a one-year period, and that one of three methods be used to determine the balance: an import/export balance, a load/generation balance or a hybrid of the two.

   An nZEB definition may set mandatory energy efficiency requirements, but whether or not these are codified it has been demonstrated that the path to success prioritizes energy efficiency (rather than generation). Requirements addressing energy supply are also permissible; for example, by setting a threshold for the minimum share of renewable energy which must be used for covering the buildings energy demand. If using a hierarchy of options, a clear and unambiguous definition of what is on-site and off-site must be stated in criterion 1.

4. Temporal energy match characteristics: Beyond merely achieving an annual energy balance, nZEB buildings are characterized by their ability to match the load and to work beneficially with respect to the needs of the local grid infrastructure. Suitable indicators can be used to express these characteristics of an nZEB, such as the temporal match between a building's load and its energy generation (load matching) and the temporal match of import/export energy with respect to the grid. Any such indicators are intended as assessment tools only: there is no inherent positive or negative value associated with them, e.g. increasing the load match may or may not be appropriate depending on circumstances on the grid side. Load matching and grid interaction calculations must be performed for each energy carrier separately.

5. Measurement and verification: To check that a building is in compliance with the nZEB definition applied, a proper measurement and verification (M&V) process is required. Such a process is strictly dependent on the options selected for each criteria of the definition and on the features of the building to be assessed. At a minimum, an M&V protocol should enable the assessment of the import/export balance, as this is the core of the nZEB concept.

   As comfort is a mandatory requirement in buildings, an M&V protocol should also check the indoor environmental quality (IEQ); to warranty indoor comfort is always the first priority in building design and the risk of designing nZEBs with poor IEQ shall be avoided.

   Furthermore, in order to implement a measured rating for nZEBs is necessary to specify the required validity over time and over variable boundary conditions, including (1) the time span over which the measured rating shall satisfy the nZEB balance; (2) tolerances on the balance and required comfort conditions; and (3) parametric analysis approaches to show the relationship between the balance and influencing variables, such as comfort, climate, building use, occupancy, and user behavior.

1.2.2 DOE Definition

In its 2015 report, "A Common Definition for Zero Energy Buildings," the United States Department of Energy (DOE) sought to establish a commonly agreed upon definition of Zero Energy Buildings (ZEBs; alternatively known as Net Zero Energy Buildings and Zero Net Energy Buildings), including supporting nomenclature and measurement guidelines [22].

Broadly, the document defines ZEB as "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." Extending the concept of ZEB, the document includes definitions for "Zero Energy Campuses," "Zero Energy Communities" and "Zero Energy Portfolios", each with the same criteria as ZEBs but applied to campuses, communities and portfolios, respectively.

The project group declared that a comprehensive ZEB definition should:

- Create a standardized basis for identification of ZEBs for use by industry.
- Be capable of being measured and verified and should be rigorous and transparent.

- Influence the design and operation of buildings to substantially reduce building operational energy consumption.
- Be clear and easy to understand by industry and policy makers.
- Set a long-term goal and be durable for some time into the future.

Addressing with more specificity the measurement and implementation of ZEBs, guidelines were provided which identified the methodology for establishing boundary conditions, conducting energy measurements and achieving energy balances that support applying the Zero Energy Building, Zero Energy Campus, Zero Energy Portfolio and Zero Energy Community definitions. The guidelines address:

- Measurement and boundaries for all definitions
- Energy accounting and measurements
- Source energy calculations
- Using the “Zero Energy Building” designation
- Using Renewable Energy Certificates

Boundaries

The site boundary represents a meaningful boundary that is functionally part of the building(s). For a single building on a single property, the site boundary is typically the property boundary. The site boundary should include the point of utility interface. Figure 1-7 [22] shows the site boundary for ZEB energy accounting based on building energy use, on-site renewable energy production, delivered energy and exported energy.

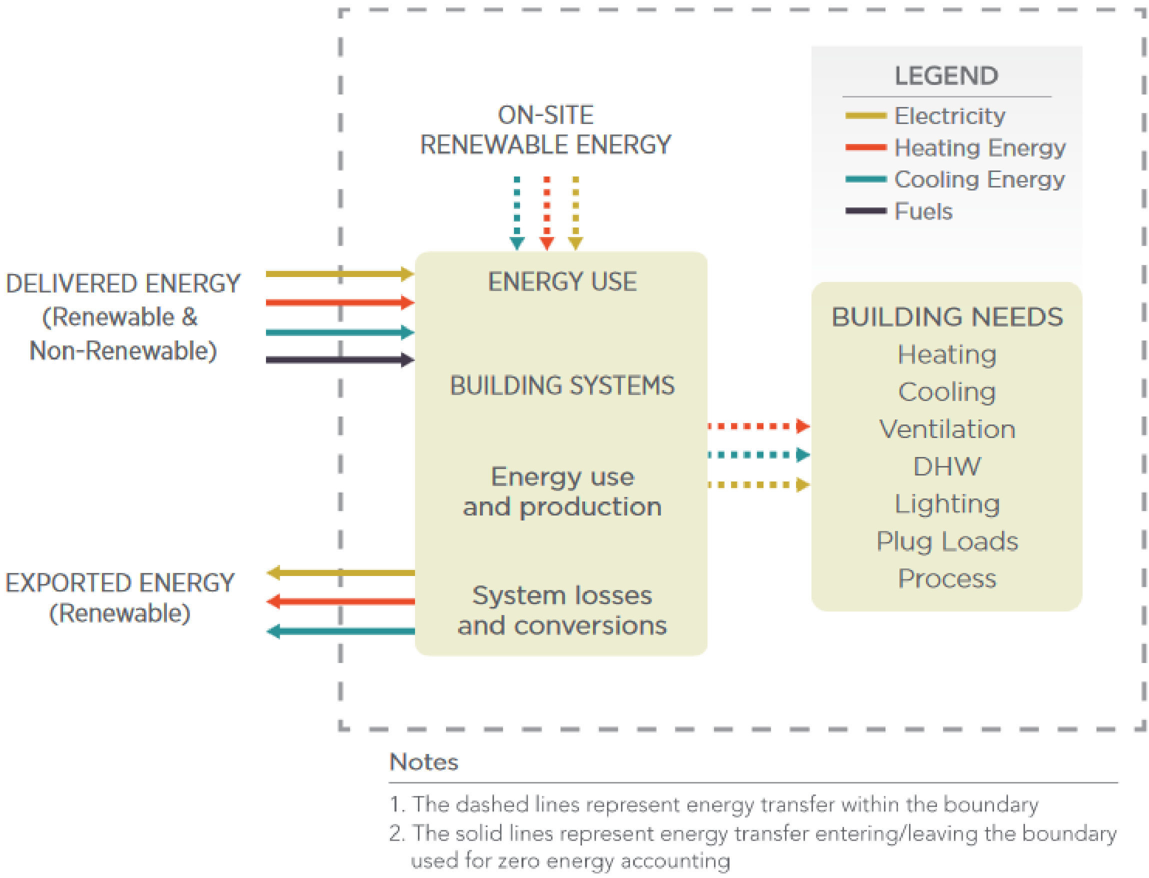


Figure 1-7: Site Boundary of Energy Transfer for Zero Energy Accounting [22]

The site boundary for a ZEB could be around the building footprint if the on-site renewable energy is located within the building footprint, or around the building site if some of the on-site renewable energy is on-site but not within the building footprint. Delivered energy and exported energy are measured at the site boundary.

<u>Energy Accounting and Measurements</u>

A ZEB is typically a grid-connected building that is very energy efficient. The premise is that ZEBs use the electric grid or other energy networks to transfer any surplus on-site renewable energy to other users.

ZEB energy accounting would include energy used for heating, cooling, ventilation, domestic hot water (DHW), indoor and outdoor lighting, plug loads, process energy and transportation within the building. Vehicle charging energy for transportation inside the building would be included in the energy accounting. On-site renewable energy may be exported through transmission means other than the electricity grid such as charging of electric vehicles used outside the building.

Delivered energy to the building includes grid electricity, district heat and cooling, renewable and non-renewable fuels. A ZEB balances its energy use so that the exported energy to the grid or other energy network (i.e., campus or facility) is equal to or greater than the delivered energy to the building on an annual basis.

A ZEB may only use on-site renewable energy in offsetting the delivered energy. On-site renewable energy is energy produced from renewable energy sources within the site boundary. Renewable fuels delivered to the site boundary are not included in this term, because they are treated as delivered energy to the building, i.e. off-site renewables. For example, the wood chips or biofuel harvested on-site would be considered on-site renewable energy. The ZEB energy accounting does not allow non-renewable energy that is exported from the site boundary to offset delivered energy.

On site renewable energy production systems may supply building energy, thus reducing the need for delivered energy to the building, and/or may be directly exported to energy networks. This is considered in the net delivered energy balance. Zero Energy Campuses, Portfolios and Communities can combine the on-site renewable energy among different sites under an aggregated site boundary to balance the delivered energy.

<u>Source Energy Calculations</u>

Most building managers are familiar with site energy, the amount of energy consumed by a building as measured by utility meters. Site energy consumption can be useful for understanding the performance of the building and the building systems, but it does not tell the whole story of impacts from resource consumption and emissions associated with the energy use. In addition, site energy is not a good comparison metric for buildings that have different mixes of energy types, buildings with on-site energy generation, such as photovoltaics, or buildings with cogeneration units. Therefore, to assess the relative efficiencies of buildings with varying fuel types, it is necessary to convert these types of energy into equivalent units of raw fuel consumed in generating one unit of energy consumed on-site. To achieve this equivalency, the convention of source energy is utilized.

When energy is consumed on-site, the conversion to source energy must account for the energy consumed in the extraction, processing and transport of primary fuels such as coal, oil, and natural gas; energy losses in thermal combustion in power generation plants; and energy losses in transmission and distribution to the building site. The ZEB definition uses national average ratios to accomplish the conversion to source energy because the use of national average source-site ratios ensures that no specific building will be credited (or penalized) for the relative efficiency of its energy provider(s).

Source energy is calculated from delivered energy and exported energy for each energy type using source energy conversion factors. Source energy conversion factors are applied to convert energy delivered and exported on-site into the total equivalent source energy. The source energy conversion factors utilized are from ASHRAE Standard 105. While on-site renewable energy is a carbon-free, zero-energy-loss resource, when it is exported to the grid as electricity, it displaces electricity that would have been required from the grid. In ZEB accounting, the exported energy is given the same source energy conversion factor as the delivered energy to appropriately credit its displacement of delivered electricity.

Source energy would be calculated using the following formula (see Figure 1-8 for example calculation from [22]):

$E_{source} = \Sigma_i(E_{del,i} r_{del,i}) - \Sigma_i(E_{exp,i} r_{exp,i})$

Where

$E_{del,i}$ is the delivered energy for energy type *i*;

$E_{exp,i}$ is the exported on-site renewable energy for energy type *i*;

$r_{del,i}$ is the source energy conversion factor for the delivered energy type *i*;

$r_{exp,i}$ is the source energy conversion factor for the exported energy type *i*;

Example Calculation for ZEB with Multiple Delivered Energy Types

A *building* has the following actual *annual delivered energy* types: 200,000 kBtu electricity, 60,000 kBtu natural gas and 100,000 kBtu chilled water. The on-site renewable *exported energy* is 260,000 kBtu electricity from photovoltaics.

Using the formula above, the *annual source energy* balance would be:

$$E_{source} = [(200{,}000kBtu \times 3.15) + (60{,}000kBtu \times 1.09) + (100{,}000kBtu \times 1.04)] - (260{,}000kBtu \times 3.15)$$

$$= 799{,}400\ kBtu - 819{,}000kBtu$$

$$= -19{,}600kBtu$$

Since $E_{source} \leq 0$, the building would be a *Zero Energy Building*.

Figure 1-8: Example Calculation for ZEB with Multiple Delivered Energy Types [22]

1.2.3 EPBD Definitions & Progress

Internationally, the European Union Member States have been pursuing the process of defining nZEBs as mandated by Directive 2010/31/EU (also known as the EPBD). Article 9(1) of the EPBD requires member states to “ensure that: (a) by 31 December 2020, all new buildings are nearly zero-energy buildings; and (2) after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings.” Further, Article 9(2) states that “The national plans shall include, inter alia, the following elements: (a) the

Member State's detailed application in practice of the definition of nearly zero-energy buildings, reflecting their national, regional or local conditions, and including a numerical indicator of primary energy use expressed in kWh/m2 per year… (b) intermediate targets for improving the energy performance of new buildings, by 2015…; (c) information on the policies and financial or other measures (…) including details of energy from renewable sources in new buildings and existing buildings undergoing major renovation in the context of Article 13(4) of Directive 2009/28/EC and Articles 6 and 7 of this Directive." [23]

According to Article 2(2) of the EPBD a NZEB "means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;" [23]

So, while the EPBD sets the framework definition of NZEBs, Member States have the responsibility to report on the detailed application in practice of that definition (i.e. reflecting their national, regional or local conditions). [23]

In 2015, the Buildings Performance Institute Europe (BPIE) published a fact sheet assessing national definitions of nZEB buildings across Europe. In contrast with the DOE and Sartori definitions, which generally align on the general points of their respective frameworks, the approaches taken by the European Member States (and Norway) exhibit much greater diversity [24].

This assessment of the report's findings concluded the following [24]:

- To date, a definition is available in 15 countries (plus Brussels Capital Region and Flanders).
- In a further 3 countries, the nZEB requirements have been defined and are expected to be implemented in the national legislation.
- In the remaining 9 member states (plus Norway and the Belgian Region of Wallonia), the definition is still under discussion and has not been finalized.
- Values defined for maximum primary energy consumptions vary by a factor of 4-5, making comparisons across member states difficult.
- Only 8 countries have formally established nZEB requirements for existing buildings.
- Five jurisdictions have set the same requirements for new and existing buildings.
- In three cases (Austria, France and Brussels Capital Region) the requirements for major renovations of existing buildings are less strict than those set for new buildings.

<u>What are the main approaches?</u>

- In most countries, the nZEB definitions refer to maximum primary energy as one of the main indicators.
- In a few cases, the primary energy use of the building is assessed through a non-dimensional coefficient, comparing the buildings' primary energy use with a "reference" building with similar characteristics (e.g. building geometry).
- In several countries, carbon emissions are used as the main indicator.
- For residential buildings, most jurisdictions aim to have a primary energy use not higher than 50 kWh/m2/y.

- Often, different requirements are established for single family houses as well as apartment buildings and higher values are established for regions with a colder climate.
- For non-residential buildings, some jurisdictions set a single target only for offices and schools.
- Others also include requirements for hospitals.

Overall, due to the different calculation methodology, climate conditions and building typology, the maximal primary energy level for non-residential buildings in Europe ranges from 0 to 270 kWh/m2/y.

What about the means for calculating energy performance of buildings?

The EPBD (Annex I) lists the main end-uses that should be included such as heating, domestic hot water, cooling, ventilation and (mainly in non-residential sector) lighting. How have countries responded?

- In most jurisdictions, energy needs for cooling and ventilation are considered for residential buildings but only a few consider household appliances or the energy consumption of elevators and escalators.
- Apart from the requirement for primary energy consumption, most countries also set separate requirements on final energy use, as suggested by the European Committee for Standardisation, in most cases referring to the final energy required for space heating or to the mean transmittance coefficient of the building.
- In some cases, the evaluation of the building airtightness is also included.
- In a few cases, additional requirements are established for the performance of the technical systems and to additionally reduce the building overheating risk.

What about the use of renewable energy?

- 11 Member States plus Brussels Capital Region and Flanders set a definition that comprises both a numerical target for primary energy use (or final energy) and assess the share of renewables in a quantitative or qualitative way.
- In 8 of these states, the share of primary energy consumption which has to be covered by renewable energy sources is explicitly stated.
- In other jurisdictions, renewable sources are considered indirectly.
- In Denmark, while a minimum share of renewable sources has not been established, a gradual evolution of primary energy factors has been planned and an increase in the share of renewable energy above 50% is expected in 2020.

2 MARKET STATE OF NEARLY/NET ZERO ENERGY OR HIGHLY-EFFICIENT BUILDINGS

2.1 Loads and Boundary Conditions for Buildings

Primary energy Primary energy consumption in the residential sector totalled 21.1 exajoules (20 quads) in 2016, equal to ~53% of consumption in the buildings sector and 21% of total primary energy consumption in the U.S. Nearly half (49%) of this primary energy was lost during transmission and distribution (T&D). Space heating and cooling – which combined account for 54% of site energy consumption and 43% of primary energy consumption – drive residential energy demand. Space heating demanded the greatest share of on-site energy consumption at 5.23 quads, or 45%. Forty-three percent of site energy was consumed as natural gas. All the energy used for space cooling, lighting, electronics, and refrigeration was consumed as electricity. Electricity accounted for 70% of total primary energy consumption, but only 4.95 quads of electricity were actually delivered to U.S. households due to T&D losses. [6]

Figure 2-1 below illustrates U.S. energy consumption by sector and source during 2016:

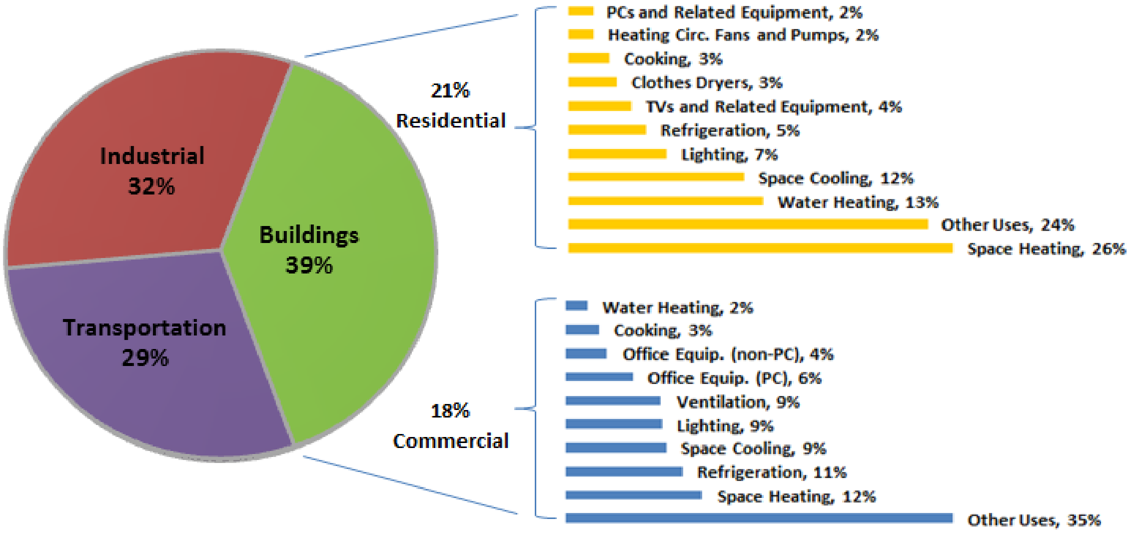


Figure 2-1: Energy Consumption by Sector and Source, 2016 [6]

2.2 Market State of Nearly or Net Zero Energy Buildings

Green building practices that would be implemented into NZEBs (e.g., high-efficiency HVAC systems, solar photovoltaic systems, glazing systems) have become more prevalent in new building construction in recent years, largely due to consumer incentive programs and the introduction of stricter government regulations. The states of California, Massachusetts, and Oregon are among the most proactive regarding strategic plans and policies for NZEB developments. Although the market is growing, NZEBs currently comprise only a small fraction of the overall building construction industry in the United States. However, they are no longer constrained to just "demonstration" buildings.

2.2.1 Commercial Market

As part of a 2016 research report published by New Buildings Institute, the number and location of existing zero-energy commercial buildings were examined. Out of a total of 395 buildings identified in the United States, 53 were "zero energy buildings" (ZEB) (see Figure 2-2), 279 were ZEBs under construction or had limited data to verify zero energy performance, and 62 were classified as "ultra-low energy verified buildings", meaning they could be zero energy if final steps were taken to implement on-site renewable generation. The assessment also concluded that the location of commercial ZEBs was quite diversified across climate zones [25].

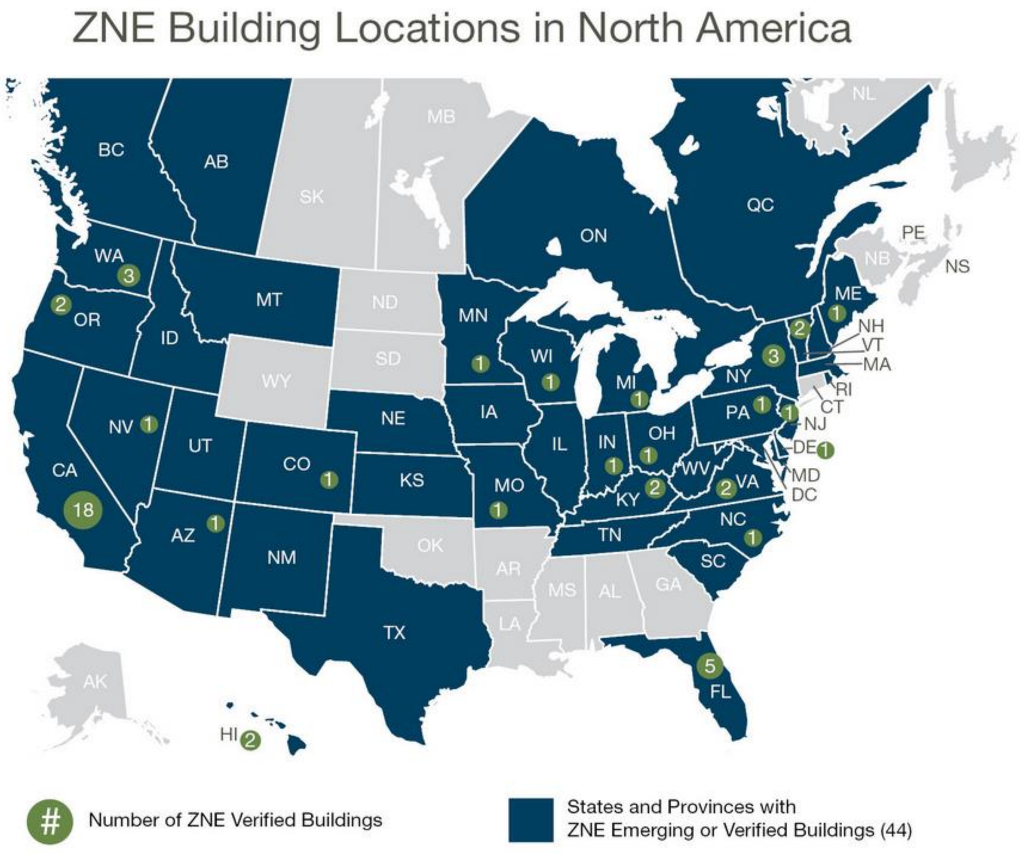
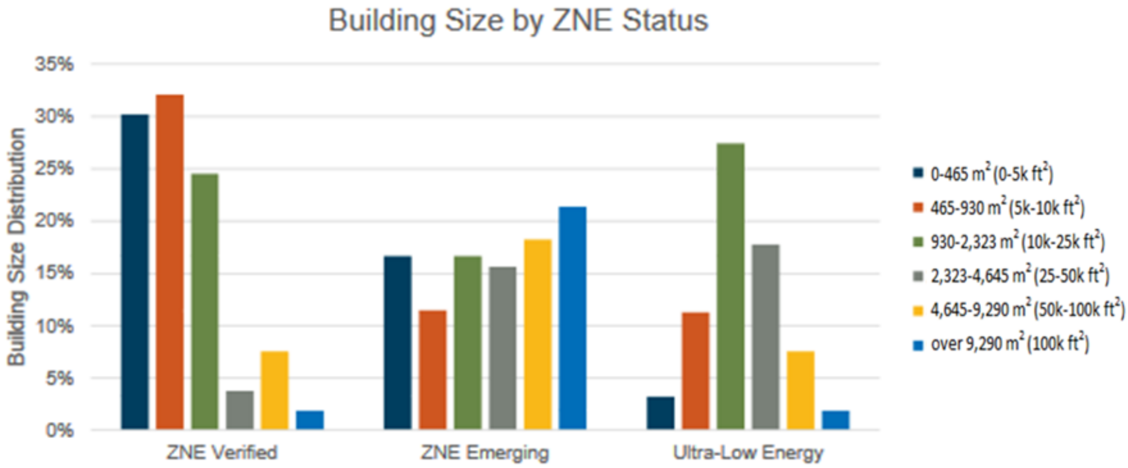


Figure 2-2: Geographic Distribution of ZNE Building Locations as Tracked by New Buildings Institute [25]

While most existing commercial ZEBs are relatively small >930 m^2 (10,000 ft^2), projects are expanding in size and building type, including office buildings and K-12 schools. This conclusion is supported by combining the New Buildings Institute study's ZEBs with the verified and emerging ZNEs for a total of 332 projects and observing the breakdown of building types shown in Figure 2-3 [25].

Figure 2-3: Breakdown of Building Types in New Buildings Institute Study [25]



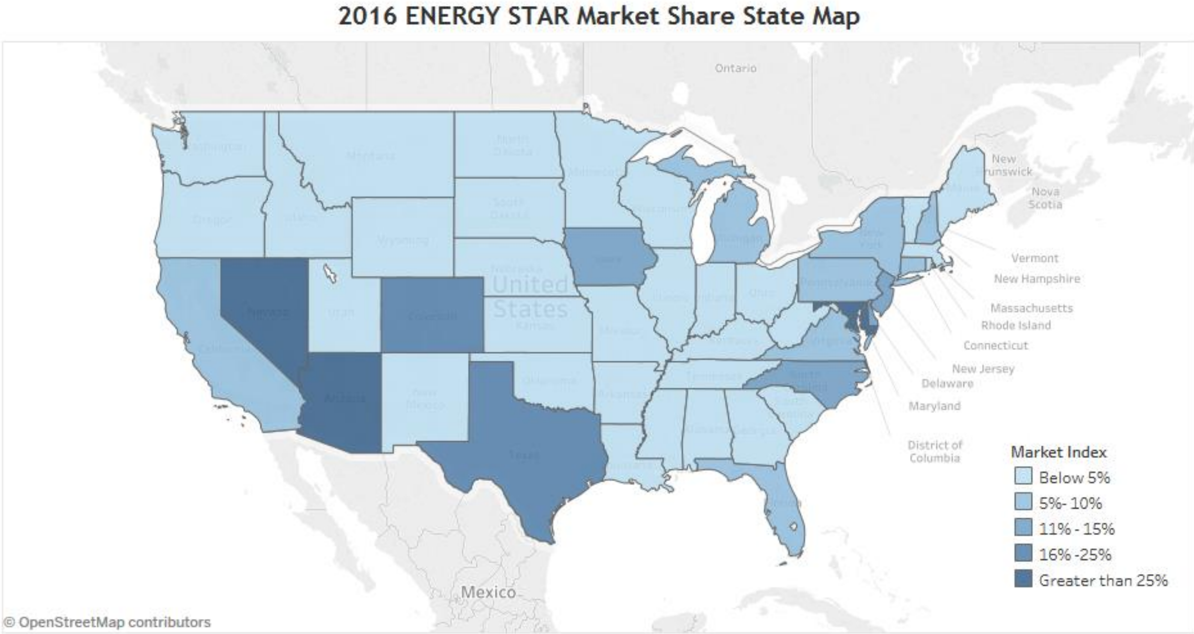
2.2.2 Residential Market

In the U.S. the most recognizable high-efficiency home market indicator is the ENERGY STAR program (http://www.energystar.gov/) for new homes [11]. Section 2.2.6.1 of this report provides a listing of criteria that must be satisfied for a home to be ENERGY STAR certified. As noted earlier, maximizing the energy efficiency of a home (or any building) is important to facilitate reaching the NZEB performance level. Recent estimates of cost and energy savings for the Version 3 ENERGY STAR home criteria indicate that monthly energy cost savings can exceed investment costs by 5-65% depending on U.S. location [26]. To date, over 1,700,000 ENERGY STAR-certified homes have been built, with estimates for 2016 ranging from about 72,000 to more than 92,000 [27][28]. According to ENERGY STAR, savings from the construction of these homes is the equivalent of [28]:

- Eliminating the emissions from over 22,000 passenger vehicles,
- The carbon sequestered by nearly 3,000,000 tree seedlings over ten years.
- Saving the environment 105,000 metric tons of CO_2.

The national market share in the new homes sector of ENERGY STAR-certified homes reached 10% in 2016. This figure was exceeded in 9 states during the same year, with Arizona topping the list at 53% of new homes being certified. Figure 2-4 displays ENERGY STAR market share for all states within the Continental United States [28]:

Figure 2-4: 2016 ENERGY STAR Market Share State Map [28]



2.2.3 Market Potential and Planned Developments: State-specific

Individual states have developed specific goals and accompanying plans to achieve certain levels of nearly/net zero energy. For example, the California Public Utilities Commission (CPUC) has adopted the Big Bold Energy Efficiency Strategies, or BBEES, that identifies near-term, mid-term, and long-term milestones to move the state towards:

- All new residential construction in California will be zero net energy by 2020,
- All new commercial construction in California will be zero net energy by 2030,
- HVAC will be transformed to ensure that its energy performance is optimal for California‘s climate, and
- All eligible low-income customers will be given the opportunity to participate in the low-income energy efficiency program by 2020 [29].

The CPUC has chosen to use the following market diffusion theory in Figure 2-5 as part of their strategy to implement the goals of improving market penetration of low-energy/net-zero energy buildings through 2030.

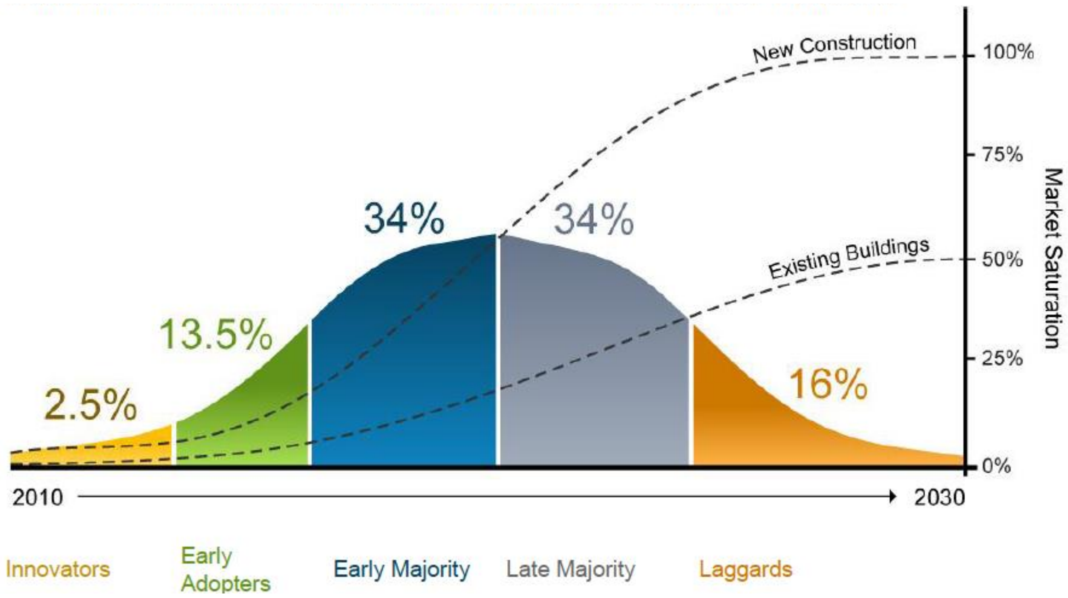


Figure 2-5: Conceptual Market Diffusion for Net Zero Energy Targets [29]

2.2.4 Key Market Players/Stakeholders

As previously mentioned the U.S. government and supporting DOE national laboratories are highly involved in the R&D supporting NZEBs. BAP, for example, currently has thirteen research teams comprised of industry consortia that design, test, upgrade, and build high-performance homes designed to cut energy use [30]:

- Building Envelope Materials
- Building Science Corporation
- Center for Energy and Environment
- Fraunhofer Center for Sustainable Energy Systems
- Gas Technology Institute
- Home Innovation Research Labs
- The Levy Partnership, Inc.
- Newport Partners, Inc.
- Northern STAR Building America Partnership
- Rocky Mountain Institute
- Southface Energy Institute
- Steven Winter Associates
- University of Central Florida

More than 345 organizations have taken the Better Buildings Challenge. Many are Commercial and Industrial Partners (including real estate, healthcare food service, retail, educational, and industrial organizations) that represent more than 409 million m^2 (4.4 billion ft^2) of real estate across diverse public and private sectors. Local city and county governments are also represented. In addition, a network of financial and utility allies assist Partners in overcoming financial and data access barriers – over $8 billion in financial assistance extended to date [18].

In addition to the government programs, there are several other market players and stakeholders invested in the NZEB sector. Private entities involved in the NZEB sector mostly include building developers and contractors, as well as energy-efficient building equipment and materials manufacturers. Perhaps the best-known NZEB homebuilder in the United States is Meritage Homes, recipient of EPA's ENERGY STAR Partner of the Year – Sustained Excellence Award each year from 2013 to 2017. Meritage was also the first 100% ENERGY STAR production builder and the first Net Zero Energy production builder in the United States. Another builder worthy of mention is Shea Homes, the first major production home builder in the United States to build zero-energy homes as a standard home in a subdivision.

Non-profit and environmental organizations play an important role in promoting and educating consumers on the benefits of NZEB market growth. Notable organizations include the Alliance to Save Energy (administers the Zero Energy Commercial Buildings Consortium), the Energy Trust of Oregon, U.S. Green Building Council (USGBC), Architecture 2030, Rocky Mountain Institute (RMI), the National Trust for Historic Preservation, Habitat for Humanity, and the American Council for an Energy Efficient Economy (ACEEE).

Finally, professional membership associations provide a wealth of information and resources on NZEBs, energy-efficient technologies, and renewable energy systems. Such associations include the American Institute of Architects (AIA); American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); Building Owners and Managers Association International (BOMA), and the National Association of Home Builders (NAHB).

2.2.5 Market Barriers

Major strides have been made in the United States regarding increases in high-performance, low-energy buildings. Obtaining a United States Green Building Council Leadership in Energy and Environmental Design (LEED) rating in new commercial buildings that provides occupants with a low-consumption and healthy environment has to some extent become expected. In residential markets, the use of highly efficient appliances and systems are on the rise, especially in new construction.

However, several barriers must be addressed before nearly or net-zero energy buildings obtain a sizeable portion of the market. Market barriers include:

- Cost premiums and payback period. High price premiums often accompany NZEB technologies, and investors need assurance that a small payback period can be expected before making the initial investment. Financial incentives, like existing tax credits, will benefit market adoption. Also, warranty policies for NZEBs and technologies that guarantee a certain level of electric or gas payments over a specified time period should continue to be considered by companies.

- Grid integration. Active utility participation is critical to successful NZEB market penetration. Without utility participation, technical difficulties with system integration and net-metering regulations may stifle NZEB implementation. Utility acceptance also enables optimal economics of solar energy and other renewables since they are most favorable when excess energy can be sold back to the utility grid.

- Builder Hesitation. Although it is improving, the perception of NZEBs by many builders is that building owners' willingness to pay for advanced energy efficiency and **renewable** energy systems is low and therefore they are reluctant to build NZEBs. There is also an increase in transaction cost (selling and scheduling) associated with

NZEBs. In addition, until NZEBs and associated technologies become more mainstream, building owners may be concerned with aesthetics and structural soundness of roof-mounted solar thermal and electric systems. Findings from of the PassReg project in Europe and interviews with North American practitioners and policy makers indicated that barriers to nZEB adoption include regulation and political agenda, the business case and financing, capacity, knowledge, scarcity of competitively-priced applied products, lack of public and builder awareness of passive design and benefits, and quality assurance issues were ongoing challenges [31].

2.2.6 Building Standards, Labels and Certifications: Buildings

2.2.6.1 ENERGY STAR

Several standards and certifications for low-energy buildings have been established by DOE and other organizations. One of the most recognizable energy-efficient home programs in the United States is the ENERGY STAR Certified Homes Program. To earn an ENERGY STAR label, homes must meet the guidelines for energy efficiency set by the EPA [32]. ENERGY STAR certified homes deliver approximately 20% savings on annual utility bills, and they are equipped with a comprehensive package of building science measures including:

- A **complete thermal enclosure system**, with comprehensive air sealing, properly installed insulation, and high performance windows that work together to enhance comfort, improve durability, reduce maintenance costs, and lower monthly utility bills;
- A **complete heating and cooling system**, with high-efficiency systems engineered and installed to deliver more comfort, better moisture control, improved indoor air quality, and quieter operation;
- A **complete water management system**, with a comprehensive package of best building practices and materials that protects roofs, walls and foundations from water damage, provides added protection, and reduces the risk of indoor air quality problems; and
- **Energy-efficient lighting and appliances**, such as ENERGY STAR certified lighting, appliances, and fans that help reduce monthly utility bills, while providing high-quality performance.

The requirements for the ENERGY STAR Certified Homes Program have changed over time as mandated code requirements have become more rigorous and builder standard practices have become more efficient. A timeline of how the has evolved since its inception in 1995 is shown in Figure 2-6 [33]:

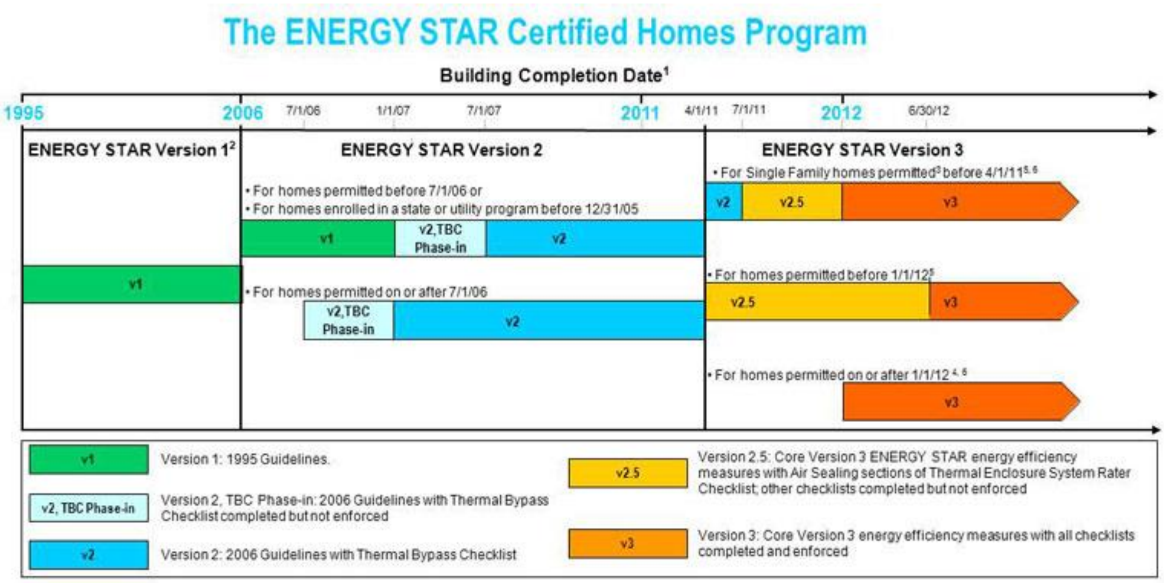


Figure 2-6: History of ENERGY STAR Guidelines for New Homes [33]

Commercial buildings may also earn ENERGY STAR certification; to be eligible, a building must earn an ENERGY STAR score of 75 or higher, indicating that it performs better than at least 75% of similar buildings nationwide. Through the Portfolio Manager tool, EPA delivers 1-100 ENERGY STAR scores for many types of buildings. The ENERGY STAR score accounts for differences in operating conditions, regional weather data, and other important considerations. Certification is given on an annual basis, and information submitted as part of the application must be verified by a licensed Professional Engineer or Registered Architect. As of 2015, more than 25,000 properties have been ENERGY STAR-certified in the United States [34].

2.2.6.2 Leadership in Energy and Environmental Design (LEED®)

In addition to the ENERGY STAR Certified Homes Program, the USGBC established a Leadership in Energy and Environmental Design (LEED®) certification in 2000. LEED has evolved over time to offer a suite of Green Building rating systems that are each designed to address unique needs of a project or building type, such as healthcare facilities, schools, homes, and entire neighborhoods. The five main categories where a project can earn points toward LEED certification are sustainable site credits, water efficiency credits, energy & atmosphere credits, materials & resources credits, and indoor environmental quality credits. [35]

The USGBC announced that the last day projects can submit for v3 certification (the LEED 2009 rating system) is June 30, 2021. After that date, new registrations must meet the criteria set out in LEED v4. High-level changes in v4 include adaptations for global growth, market sector improvements, improved environmental outcomes and a more user-friendly interface. Additionally, a new credit category of “location and transportation” has been added to the existing five categories; this new credit category rewards projects for using a variety of transportation options and addresses sustainable communities [36].

As of October 2017, there were:

- 150,000 LEED-certified residential units
- More than 92,000 total commercial projects
- 2,000 K-12 projects certified
- 2,900 local government projects and 961 state government projects certified [37]

LEED rating systems have been developed for both new construction and existing buildings. The “LEED for New Construction & Major Renovations” rating system takes an integrated approach to creating buildings that are highly efficient and have a lower environmental impact. The “LEED for Existing Buildings” rating system is designed to help owners and residents to implement sustainable practices with low environmental impacts into a building’s operations. All whole buildings (i.e. not individual tenant spaces) can apply to be either certified, silver status, gold status, or platinum status [35].

2.2.6.3 International Living Future Institute

The International Living Future Institute developed the Net Zero Energy Building Certification. This certification is designed as part of the Living Building Challenge to enhance integrity and transparency when building a NZEB. The Institute has certified 21 NZEB buildings to date [38].

2.2.6.4 Environments for Living®

Another efficient home program in the United States is the *Environments for Living®* program, launched in 2001 by TopBuild Home Services. This program assists builders in constructing energy-efficient homes that will ultimately lead to more comfortable and durable living spaces for homeowners, compared to houses built using more conventional methods. The organization’s *Certified Green* program, introduced in 2007, sets requirements for indoor environmental quality, interior water conservation, and appliance efficiency. Criteria for this program meet those of the ENERGY STAR program [39].

2.2.7 Building Standards, Labels and Certifications: Appliances

2.2.7.1 ENERGY STAR

The ENERGY STAR program establishes criteria for over 60 different categories of energy efficient products including HVAC and water heating (HVAC/WH) equipment, and more than 5 billion ENERGY STAR-qualified products have been purchased by consumers over the past twenty years [40]. These products are designed to save energy without sacrificing features or functionality. To earn the ENERGY STAR label, products must undergo certification by a third-party testing in an EPA-recognized laboratory. Beyond initial testing, certain ENERGY STAR products are subject to “off-the-shelf” testing to verify the product’s qualifications that may have been modified due to changes or variations in the manufacturing process. A complete list of ENERGY STAR products can be found at http://www.energystar.gov.

2.2.7.2 Air-Conditioning, Heating, and Refrigeration Institute

In addition to ENERGY STAR-efficient appliances, the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) has an established certification program that tests and certifies the performance of HVAC, refrigeration, and water heating equipment. This program, entitled the AHRI Product Performance Certification Program, consists of voluntarily testing products to ensure that they perform according to the manufacturers' published claims. The Institute publishes a directory of all HVAC and refrigeration equipment and components that have been AHRI-tested and certified. Recently, AHRI was named a recognized Certification Body for ENERGY STAR, meaning that products certified by AHRI do not have to undergo any additional testing to obtain an ENERGY STAR label [41].

2.2.7.3 ASHRAE

ASHRAE develops method of test standards for HVAC and refrigeration equipment and systems to establish a consensus for performance criteria and testing methods. These are referenced by AHRI in its rating standards and certification program noted above. The Society also produces several building performance related standards including minimum requirements for energy-efficient building design (the 90 series), requirements for design of high efficiency "green" buildings (the 189 series) and building ventilation requirements (the 62 series) [42]. Versions of these standards covering both single-family/small multi-family residential and commercial/high-rise multi-story residential buildings are available.

2.2.7.4 DOE Appliance and Equipment Standards Program

Finally, the DOE Appliance and Equipment Standards Program has developed test procedures and set federal minimum energy conservation standards that manufacturers must meet for residential products and commercial and industrial equipment sold and imported into the United States. Each standard set by this program aims to reduce energy demand, lower harmful emissions, and save consumers money. Currently, over 60 different categories exist for equipment and appliances used in homes, businesses, and other applications. A sample list of products covered by these standards includes furnaces and boilers, central ACs and heat pumps, dehumidifiers and water heaters. Specific standards and test procedures for appliances and equipment are accessible on the program's web site: https://energy.gov/eere/buildings/standards-and-test-procedures [43].

ASHPs and central ACs manufactured after January 1, 2015 must meet newer, more stringent minimum performance ratings as shown in Table 2-1 [44]:

Table 2-1[1]: Minimum seasonal performance ratings for residential central ACs and ASHPs after January 1, 2015 [44]

Product class	Seasonal energy efficiency ratio (SEER)	Heating seasonal performance factor (HSPF)
(i) Split-system air conditioners	13	
(ii) Split-system heat pumps	14	8.2
(iii) Single-package air conditioners	14	
(iv) Single-package heat pumps	14	8.0
(v) Small-duct, high-velocity systems	12	7.2
(vi)(A) Space-constrained products—air conditioners	12	
(B) Space-constrained products—heat pumps	12	7.4

The rating metrics in Table 2-1 are the official U.S. DOE rating metrics SEER (for cooling) and HSPF (for heating), and both are in units of Btu/Wh. Equivalent SI metrics ($SCOP_c$ and $SCOP_h$, respectively) are obtained by dividing these values by 3.412 Btu/Wh – e.g., a SEER of 13 is equivalent to a cooling seasonal COP ($SCOP_c$) of ~3.8.

WSHPs and GSHPs currently have no consensus seasonal performance test standards and, thus, no minimum seasonal performance ratings. These are rated in accordance with the rating conditions and test procedures specified by ASHRAE/ANSI/AHRI/ISO Standard 13256 1&2.

The official DOE efficiency metric for WHs today is the Uniform Energy Factor (UEF). Minimum performance ratings for residential WHs are listed below [45]:

[1] Conversion of SEER and HSPF to SI equivalents ($SCOP_c$ or $SCOP_h$, respectively) may be done by dividing either value by 3.412

Table 2-2: Minimum Uniform Energy Factor of Water Heaters (Title 10, Chapter II, Subchapter D, Part 430, Subpart C, §430.32 of the Electronic Code of Federal Regulations) [45]

Product class	Rated storage volume and input rating (if applicable)	Draw pattern	Uniform energy factor
Gas-fired Storage Water Heater	≥75.7 L (20 gal) and ≤208.2 L (55 gal)	Very Small	0.3456 – (0.0020 × Vr)
		Low	0.5982 – (0.0019 × Vr)
		Medium	0.6483 – (0.0017 × Vr)
		High	0.6920 – (0.0013 × Vr)
	>208.2 L (55 gal) and ≤378.5 L (100 gal)	Very Small	0.6470 – (0.0006 × Vr)
		Low	0.7689 – (0.0005 × Vr)
		Medium	0.7897 – (0.0004 × Vr)
		High	0.8072 – (0.0003 × Vr)
Oil-fired Storage Water Heater	≤189.3 L (50 gal)	Very Small	0.2509 – (0.0012 × Vr)
		Low	0.5330 – (0.0016 × Vr)
		Medium	0.6078 – (0.0016 × Vr)
		High	0.6815 – (0.0014 × Vr)
Electric Storage Water Heaters	≥75.7 L (20 gal) and ≤208.2 L (55 gal)	Very Small	0.8808 – (0.0008 × Vr)
		Low	0.9254 – (0.0003 × Vr)
		Medium	0.9307 – (0.0002 × Vr)
		High	0.9349 – (0.0001 × Vr)
	>208.2 L (55 gal) and ≤454.2 L (120 gal)	Very Small	1.9236 – (0.0011 × Vr)
		Low	2.0440 – (0.0011 × Vr)
		Medium	2.1171 – (0.0011 × Vr)
		High	2.2418 – (0.0011 × Vr)
Tabletop Water Heater	≥75.7 L (20 gal) and ≤454.2L (120 gal)	Very Small	0.6323 – (0.0058 × Vr)
		Low	0.9188 – (0.0031 × Vr)
		Medium	0.9577 – (0.0023 × Vr)
		High	0.9884 – (0.0016 × Vr)
Instantaneous Gas-fired Water Heater	<7.6 L (2 gal) and >52.75 MJ/h (50,000 Btu/h)	Very Small	0.8
		Low	0.81
		Medium	0.81
		High	0.81
Instantaneous Electric Water Heater	<7.6 L (2 gal)	Very Small	0.91
		Low	0.91
		Medium	0.91
		High	0.92
Grid-Enabled Water Heater	>284 L (75 gal)	Very Small	1.0136 – (0.0028 × Vr)
		Low	0.9984 – (0.0014 × Vr)
		Medium	0.9853 – (0.0010 × Vr)
		High	0.9720 – (0.0007 × Vr)

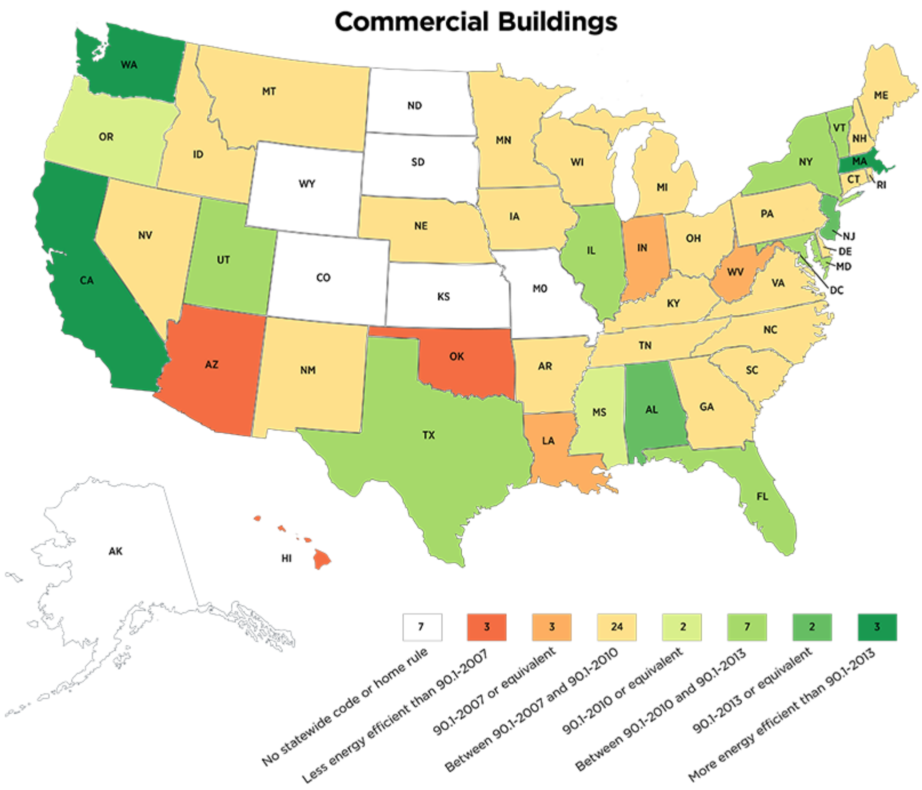
Table 2-3: Draw Pattern Definitions for Table 2-2 (* Denotes draw in first cluster) [46]

Draw Pattern	Liters/day (gal/day)
Very Small	38 (10)
Low	144 (38)
Medium	208 (55)
High	318 (84)

2.3 Building envelope (passive) technologies

DOE BTO established the Buildings Energy Codes Program to define the energy efficiency requirements for new federal commercial and residential buildings as well as energy efficiency standards for manufactured homes. Such standards apply to building thermal envelopes, mechanical system performance and building lighting and power system performance. For mechanical systems (e.g., HVAC, refrigeration, and water heating equipment and systems) these generally refer to the AHRI rating standards (section 2.2.7.2, above) and DOE minimum efficiency standards (2.2.7.4 above).

The Building Codes Assistance Project supports states adoption of building energy codes. Figures 2-7 and 2-8 illustrate current residential and commercial building energy codes and standards adoption status by U.S. states and territories, respectively. As of December 2017, all but 8 states have a state-wide code for both residential and commercial sectors [47]. As noted in the figures below, various versions of the International Energy Conservation Code (IECC), published by the International Code Council (http://shop.iccsafe.org/codes/2012-international-codes/2012-international-energy-conservation-code.html) are used for single-family and low-rise multi-family (3 stories or less) residential buildings while both ASHRAE 90.1 and IECC are used for commercial buildings. ASHRAE 90.1 is also used for multi-family buildings over three stories.



[

Figure 2-7: Commercial Building Energy Code Adoption Status [47]

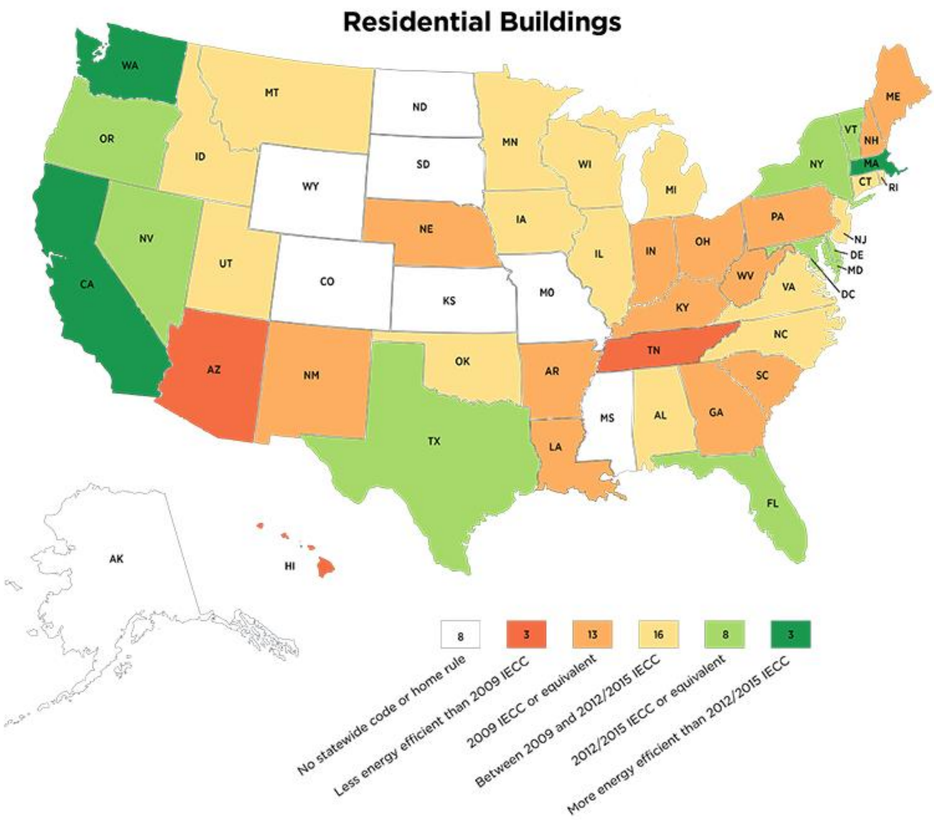


Figure 2-8: Residential Building Energy Code Adoption Status [47]

There are no DOE-mandated building envelop minimum insulation level requirements in the US. The most recent versions of the International Code Council's 2015 IECC (2015 International Energy Conservation Code) [48] and ASHRAE Standard 90.1-2016 (Energy Standard for Buildings Except Low-Rise Residential Buildings) [49] (Energy Standard for Buildings Except Low-Rise Residential Buildings) include the latest insulation requirements for residential and commercial buildings.

U-value requirements for single-family and small multi-family residential buildings from IECC 2015 are listed below (range for coldest to warmest climate zones):

- Uroof - 0,15 to 0,20 W/m²K
- Uwall - 0,25 to 0,48 W/m²K
- Uwindow - 1,82 to 2,84 W/m²K
- Ufloor - 0,16 to 0,36 W/m²K

Requirements for commercial buildings and large (over three stories) multi-family buildings from 90.1-2016 are listed below (range for coldest to warmest climate zones):

- Uroof - 0,10 to 0,15 W/m²K for wood frame (higher values allowed for metal frame buildings)
- Uwall - 0,18 to 0,50 W/m²K for wood frame (higher values allowed for metal frame buildings)
- Uwindow - 1,40 to 1,80 W/m²K for nonmetal frame (higher values for metal frame windows or if shaded)
- Ufloor - 0,15 to 1,60 W/m²K for wood frame (higher values allowed for metal frame buildings)

3 HVAC TECHNOLOGIES APPLIED IN NZEB

3.1 HVAC system (active) technologies

Residential (from DOE Tour of Zero homes)

Section 4.1 details findings on the residential homes and their relevant features as featured on the U.S. Department of Energy's Tour of Zero page.

Commercial

In an analysis of the design strategies used in 60 zero-energy and zero-energy-capable buildings, the New Buildings Institute found that high-efficiency HVAC systems with heat recovery were implemented in one-third of buildings; a similar ratio (30%) made use of radiant heating/cooling systems, and about that many again rely on ground-source heat pumps. Displacement ventilation appeared in 15% of projects [50].

Figure 3-1 below describes the penetration of 11 HVAC technologies into the buildings investigated by NBI:

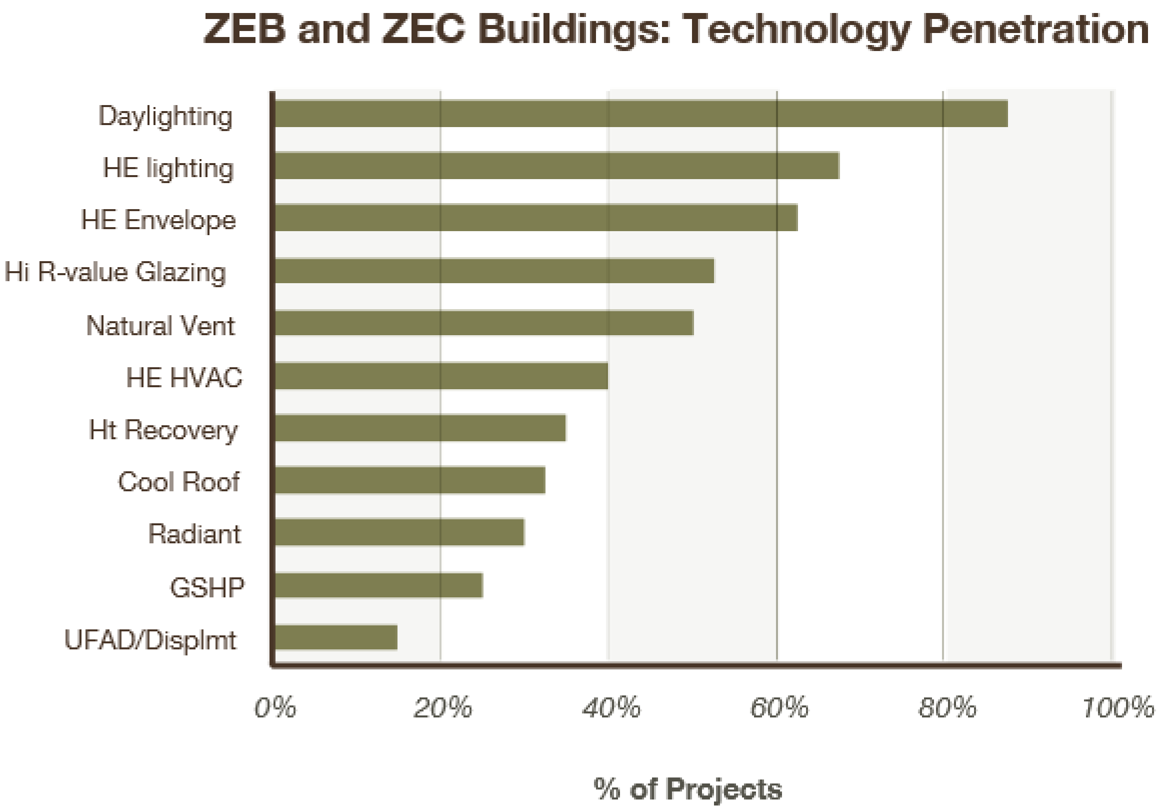


Figure 3-1: Technologies used in ZEB and zero energy-capable (ZEC) buildings [50]

In looking specifically at the features of ZEBs, four such buildings in mild climates eliminated traditional HVAC systems and utilize passive strategies to maintain thermal comfort. This includes natural ventilation, thermal mass to moderate temperature fluctuations, and night-time flushing with cold air.

When HVAC systems *are* used, about half of the ZEBs report using a radiant heating/cooling system, often in conjunction with ground-source heat pumps.

Multi-family building projects often draw domestic hot water via a solar thermal system; these can be large loads in certain commercial building types (e.g., restaurants, supermarkets, lodging facilities, laundries, health clubs, etc.). Pursuit of net zero necessitates consideration of use patterns and climate, as well. Anecdotal information suggests that a number of these net zero buildings are occupied primarily during daylight hours, reducing the need for artificial lighting.

Case studies of the NREL and IDeAs buildings, both large facilities occupied by working professional, show that net zero can be realized on a broader scale rather than being constrained to more niche applications (e.g. nature centers and boutique buildings). Design of the HVAC system technology

3.2 Design of the HVAC System Technology

3.2.1 A "Whole Building" Approach to Achieving Minimal Energy Consumption

DOE BTO has developed a system-engineered "whole building" approach to unite segments of the building industry that have traditionally worked independently. The BTO whole building approach promotes design of buildings from the ground up, considering the interaction between the building envelopes, mechanical systems, landscaping, neighboring houses, orientation, and climate [9]. BTO's ET Program accelerates the research, development, and commercialization of upcoming high-impact building technologies that are generally five years or less to market-ready. BTO sees these emerging technologies as having the potential to achieve up to 70% energy savings and playing an integral role in the "whole building" approach. The ET Program's current portfolio of research in advanced technologies includes:

- Advanced windows (e.g., dynamic windows, highly-insulating windows, advanced daylighting, window attachments)
- Advanced refrigerator technology
- Building energy models/calculators
- Low global warming potential refrigerants (i.e. working fluids)
- Heating, ventilating, air conditioning, and water heating
- Solid state lighting
- Sensors and controls
- Window air conditioning
- Advanced heat pump technology (e.g., ASHPs, cold climate heat pumps, GSHPs, heat exchangers)
- Building envelope (e.g., cool roofs, advanced attics, improved insulation)

Furthermore, BTO focuses on designing systems with an optimally-sized mechanical unit when taking a "whole building" approach. In low energy homes, significant reductions in heating and cooling loads allow for smaller space conditioning systems. Mechanical systems with capacities more closely matched to actual loads will provide greater comfort and save energy. DOE investigates ways to combine the operation and control of a building's equipment (for heating, cooling, and water heating) together with its thermal envelope, thermal delivery, and ventilation systems in a total system design approach.

3.2.2 Importance of HVAC System Technology Advancements

Ninety-six percent of respondents to McGraw-Hill's SmartMarket Report published in 2012 indicated that highly efficient HVAC systems and/or water heaters are important in achieving greener homes (see Figure 3-2). This is not surprising given that HVAC systems and water heaters account for over half of energy consumption in homes. Coming in at second on the survey is the importance of a properly sized/ installed HVAC. Because of the large impact that HVAC systems can have on a building's energy consumption, DOE and EPA have focused much attention on setting appropriate criteria and test procedures for HVAC, as well as most other major appliances [51].

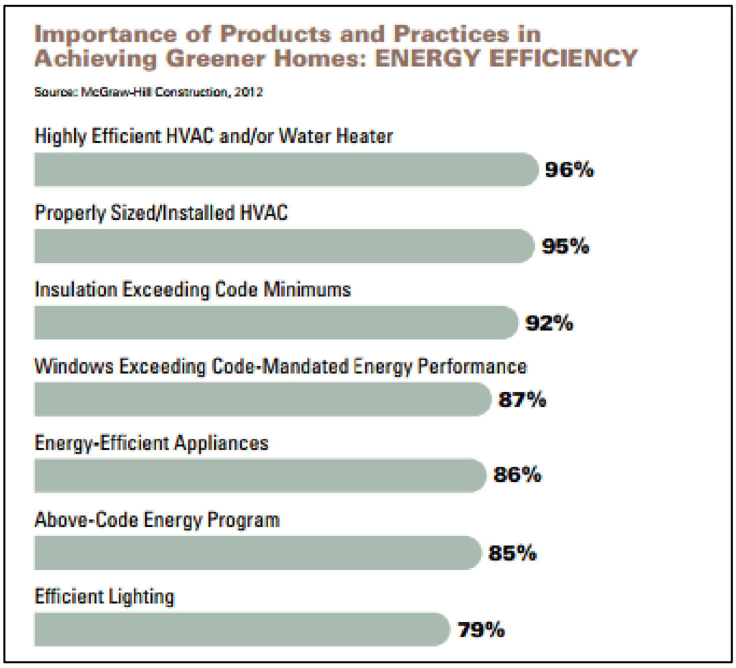


Figure 3-2: Importance of Energy Efficient Products and Practices in Achieving Greener Homes [51]

3.2.3.1 Residential Application

HVAC systems for residential buildings in the U.S. are generally done by small, local heat pump/AC contractors using procedures published by the Air Conditioning Contractors of America (ACCA) [52]. ACCA publishes and maintains a series of documents related to residential HVAC system design. These include Manual J (Residential Load Calculation – 8th edition), Manual D (Residential Duct Systems), and Manual S (Residential Equipment Selection). ACCA also publishes a document for existing home retrofits – ACCA Existing Home Evaluation and Performance Improvement (ACCA Standard 12). The organization runs a certification program for quality residential HVAC installation (http://residentialdesignhvac.com/).

3.2.3.2 Commercial Application

New buildings. Collaboration by ASHRAE, AIA, Illuminating Engineering Society of North America, USGBC, and DOE has resulted in the development of the *Advanced Energy Design Guide* series, which provides prescriptive energy guidance for builders and retrofitters for achieving energy savings over the minimum code requirements of ANSI/ASHRAE/IESNA/

Standard 90.1. The initial set of Guide Books provided recommended measures for achieving 30% energy savings over the 1999 version of 90.1 for small office buildings, small hospitals, highway lodging facilities (small motels up to 80 rooms), warehouses & self-storage buildings, K-12 schools, and small retail buildings. A more recent set of Guide Books with energy savings of 50% over the 2004 version of 90.1 are available for the following building types:

- Large hospitals [standard mid- to large-size hospitals, typically at least 9,300 m^2 (100,000 ft^2) in size]
- Medium to big box retail buildings [about 1,800 to 9,300 m^2 (20,000 to 100,000 ft^2)]
- Small to medium office buildings [about 1800 to 9,300 m^2 (20,000 to 100,000 ft^2)]
- K-12 school buildings (elementary, middle, and high school buildings)

Each Guide Book includes design and construction recommendations for all major aspects of high performance / low energy buildings (including HVAC), and they have all been tailored to each U.S. climate zone. Both the 30% and 50% guides are available for free download from ASHRAE [53].

Detailed recommendations and "Good Design Practice" tips for implementing HVAC and WH equipment and systems typically used in each building type are provided in designated chapters of the Guide Books. These reports are free to download at www.ashrae.org/freeaedg.

Retrofits. Like the *Advanced Energy Design Guide,* the *Advanced Energy Retrofit Guide (AERG)* series – created from a collaboration of E Source, RMI, the National Association of Energy Service Companies, PECI (originally Portland Energy Conservation, Inc.), and DOE – offers commercial building energy managers with comprehensive guidance for planning and executing successful retrofit projects. Currently, four AERGs have been complete:

- AERG for Office Buildings
- AERG for Retail Buildings
- AERG Small to Medium Office Buildings [about 1,800 to 9,300 m^2 (20,000 to 100,000 ft^2)]
- AERG K-12 School Buildings (elementary, middle, and high school buildings)
- *A healthcare guide is currently under development.*

Major differentiating factors taken into consideration in the AERGs are the building type, level of energy savings / depth of retrofit, and the climate zone. HVAC measures are among those recommended for each level of retrofit. A sample of recommended HVAC measures is shown in Table 3-1, from the "AERG for Office Buildings" document [54]. Similar tables for other building types can be located in the corresponding AERGs available for free download at https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20761.pdf.

Table 3-1: Summary of HVAC Recommended Measures in "AERG for Office Buildings," Specific to the Level of Retrofit [54]

System	Measure Description	Climate Zones
Existing Building Commissioning (EBCx) Recommended Package Measures		
HVAC - Air Side	HA1. Revise air filtration system	All
HVAC - Air Side	HA3. Calibrate air sensors	All
HVAC - Air Side	HA4. Re-enable supply air temperature setpoint reset	All
HVAC - Air Side	HA5. Reduce HVAC equipment runtime, close outside air damper during unoccupied periods	All
HVAC - Air Side	HA7. Reduce economizer damper leakage	All, except hot-humid
HVAC - Water Side	HW4. Calibrate water sensors	All
HVAC - Water Side	HW6. Shut down cooling plant when there is no cooling load	All
Standard Retrofit Recommended Package Measures		
HVAC - Air Side	HA11. Widen zone temperature deadband (replace pneumatic thermostats)	All
HVAC - Air Side	HA12. Lower VAV box minimum flow setpoints (rebalance pneumatic boxes)	All
Deep Retrofit Recommended Package Measures		
HVAC - Air Side	HA13. Widen zone temperature deadband, add conference room standby control (upgrade to DDC zone control)	All
HVAC - Air Side	HA14. Lower VAV box minimum flow setpoints, reset duct static pressure (upgrade to DDC zone control)	All
HVAC - Air Side	HA15. Add demand-controlled ventilation	All
HVAC - Air Side	HA16. Replace supply fan motor and VFD	All
HVAC - Water Side	HW7. Shut down heating plant when there's no heating load	Hot-humid, Hot-dry
HVAC - Water Side	HW8. Increase efficiency of condenser water system	Hot-dry
HVAC - Water Side	HW9. Increase efficiency of condenser water pumping system	Hot-humid, Hot-dry
HVAC - Water Side	HW10. Change cooling plant pumping system to variable primary.	Hot-humid, Hot-dry
HVAC - Water Side	HW12. Add a VFD to one chiller	Hot-humid, Hot-dry
HVAC - Water Side	HW15. Replace boilers and change heating plant pumping system to variable flow primary	Marine, Cold, Very cold

* Detailed implementation plans are provided in the AERG for each recommended measure, identified by the "HA" or "HW" number.

Technical Tools

3.2.3 Applied Design and Calculation Methods

3.1.1.1 Whole Building

Multiple technical tools are available to support researchers and building industry professionals in ensuring consistent research results for new and existing buildings. These tools aid in evaluating building designs, accessing performance and cost data, executing field tests, and tracking research progress. Descriptions of these research tools are provided below:

- EnergyPlus: EnergyPlus is a whole-building energy simulation program that enables engineers, architects, and researchers to optimally design a building to use less energy and water. Aspects of a building that EnergyPlus can model include heating, cooling, lighting, ventilation, other energy flows, and water use [55].
- Spawn of EnergyPlus Unlike EnergyPlus, SOEP is an equation-based simulation engine, based on the equation-based modeling language Modelica. This next-generation EnergyPlus rests on a stable IT platform based on open standards, reduces EnergyPlus maintenance effort, connects energy simulation with control design, optimization, and implementation, and closes the simulation technology model gap by supporting vendor-defined models [56].
- Open Studio is a cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source (LGPL) project to facilitate community development, extension, and private sector adoption. OpenStudio includes graphical interfaces along with a Software Development Kit (SDK) [57].
- Building Energy Optimization Software (BEopt): BEopt, developed by NREL, is designed to evaluate residential building designs for new and existing homes, and to identify the most optimally efficient designs with the lowest cost at various levels of whole-house energy savings. BEopt considers specific house characteristics, such as size, architecture, occupancy, vintage, location, and utility rates when conducting simulation-based analysis. BEopt Version 2.0 includedmajor new features, including integration with the National Residential Efficiency Measures Database (see next bullet), improved retrofit analysis capabilities, photovoltaic, whole-house efficiency incentives, and HPXML export [58].
- National Residential Efficiency Measures Database: This database also developed by NREL, houses information on residential building retrofit measures and associated estimated costs for the U.S. building industry. This data can assist software developers and researchers in analyzing the trade-offs associated with incorporating various energy efficiency measures into their designs [59].
- Field Test Best Practices Website: This website, hosted by NREL, draws from Building America field research to provide a start-to-finish best practice guide for building science researchers participating in field evaluations of energy efficiency measures. For example, website viewers can find guidance on:
    - Defining the research objectives;
    - Planning for and conducting a field test;
    - Choosing, testing, and installing components; and
    - Selecting equipment and knowing when and how to use it [60].
- House Simulation Protocols Report: The purpose of this report is to help researchers compare progress of multi-year, whole-building energy reduction against research goals for new construction and existing homes. The report uses consistent reference points, which are preloaded into BEopt, enabling comparison between projects. [61]
- High Performance Buildings Database: This database, sponsored by DOE, collects information from residential and commercial buildings as well as whole campuses

and neighborhoods. Compilation of data (e.g., energy, materials and land use) is intended to improve building performance measuring methods [62].

3.1.1.2 Heat Pump

Many models have been developed in recent years that are specialized in the design and simulation of heat pumps and other HVAC equipment, as opposed to the whole building tools above. Most have originated from national laboratories or academia, although some manufacturers have built their own models in house. Below are summaries of several models:

- Heat Pump Design Model (HPDM): ORNL's Heat Pump Design Model is used in the steady-state design analysis of air-to-air-heat pumps and ACs using a standard vapor-compression cycle. Users can specify the heat exchangers, air flows, and the compressor. A variety of refrigerants can be modelled [63].
- TRaNsient System Simulation Program (TRNSYS): TRNSYS is an energy simulation program that uses a modular system approach and includes a graphical interface, a simulation engine, and a library of components that range from various building models to standard HVAC equipment to renewable energy and emerging technologies. The user can also create new components in TRNSYS that may not exist in the standard package. Recently, NREL researchers created a HPWH simulation model in TRNSYS capable of studying the interactions of HPWHs and space conditioning equipment, related to climate and installation location in the home [64]. TRNSYS is accessible at http://sel.me.wisc.edu/trnsys.
- ACMODEL: Purdue University developed this public domain program to model the system performance of unitary AC and heat pump systems. The program is modular, using separate subroutines to model specific components of an AC system or heat pump. ACMODEL is accessible at http://www.purdue.edu.
- System Design Simulator (SDS): Emerson Climate Technologies has developed this powerful software application that enables users to identify potential problems and address the issue early in the design process. A "what if" design analysis function allows users to quickly evaluate numerous design configurations and find the optimal setup for the application. SDS is available for purchase at http://www.emersonclimate.com.
- CYCLE_D: Developed by the National Institute of Standards and Technology (NIST), CYCLE_D is a vapour-compression-cycle design program that can simulate a basic subcritical or transcritical refrigeration cycle as well as a subcritical two-stage economizer cycle, a subcritical three-stage economizer cycle, and a subcritical two-stage compression cycle with intercooling. The model allows the user to select between 62 single-compound refrigerants and 66 pre-defined refrigerant blends. CYCLE_D is accessible at http://www.nist.gov/srd/nist49.cfm.
- VapCyc: The University of Maryland created VapCyc to enable advanced vapour-compression system design and simulation. The software can simulate a conventional four component system in addition to two-stage cycles and a variety of other cycle configurations. The user can build a larger system by adding components to a basic configuration. VapCyc is available for purchase at http://www.ceee.umd.edu/consortia/isoc/vapcyc.

- ThermCom (Thermal Comfort Design/Evaluation Tool): This tool is currently under development at the University of Maryland and was a part of the US contribution to Annex 40. Its purpose is to evaluate thermal comfort accounting for all radiative, convective heat transfer effects as well as local air properties. This tool is specifically intended as design tool for comfortable environments that employed heated/cooled surfaces such as heated/cooled floors, ceilings and/or walls, so that spaces can be conditioned with the most appropriate temperature heat transfer fluid maximizing heat pump efficiency.

3.2 "Smart" technology application in buildings

The use of variable capacity heat pumps for advanced utility demand response (DR) is becoming an area of active research, owing to the possibility for better comfort during demand response events—translated as less impact to the customer. The US Electric Power Research Institute (EPRI) and member utilities have several projects underway to investigate the DR potential of advanced heat pump systems [65]:

- **[Commercial HVAC Advanced Demand Response]** This project is characterizing the capability of advanced DR available through variable capacity commercial systems. The variable capacity nature of these systems enables throttling of output and power draw, while minimizing comfort impact to building occupants. The project is a pilot of systems in four regions of the United States: California, Mid-South, Deep-South and Hawaii. Each region will test several commercial building sites through actual (or simulated) utility demand response events, through Open ADR communications.

- **[Next-Generation Residential Heat Pumps]** The primary intent is to advance the attribute of variable capacity heat pumps for a variety of use-cases through utility energy efficiency and DR programs in the residential sector. A fundamental attribute of variable capacity systems is their ability to vary power draw and cooling/heating output. Advanced DR takes advantage of this attribute by maintaining some level of comfort conditioning while substantially reducing power draw of the HVAC equipment for peak periods. In support of the project EPRI has developed a specification for Next-Generation Heat Pumps [66]. The specification has two different levels or tiers. Under Tier 1 ASHP products must have a rated SCOPh 8.3 °C ≥2.93 (US HSPF ≥10) and a space heating capacity at -8.3 °C ≥80% of the rated capacity at 8.3 °C. Under Tier 2, products must have a rated SCOPh ≥3.81 (US HSPF ≥13) for US climate region IV and a space heating capacity at -15 °C ≥80% of the rated capacity at 8.3 °C. In addition, systems must be compliant with the new Air Conditioning, Heating, and Refrigeration Institute (AHRI) DR standard (see below).

- **Controllable Heat Pump Water Heaters]** This project is a demonstration of both the capabilities of electric HPWHs for grid support, and a demonstration of the standardized communication system based on the CTA-2045 standard. HPWHs have a limited, but growing presence in the U.S. for residential domestic water heating. Traditional electric resistance water heaters have been used for many years as a controllable load for demand response and grid support. If HPWHs gain significant market share and displace the installed base of controllable electric water heaters, then a major resource will need to be replaced.

  Some manufacturers have designed HPWHs with modular communications ports based on the CTA-2045 standard, which enables external communication to enable externally driven load control. This project will field evaluate multiple installations of these enabled HPWHs, with the aim of understanding the nuances of the communication system and the capability the HPWHs for providing load control

Draft Demand Response Standard for HVAC Equipment in Development

In late 2011 AHRI established the Smart or Connected Equipment Ad Hoc Committee. In 2014 they developed a framework document [67] [Ref: Smart Framework document from 2014]. A subcommittee was established to draft a standard based on this framework for DR performance and communication specifications for smart/connected variable capacity residential and small commercial unitary HVAC equipment. This effort will standardize how variable capacity HVAC equipment will perform in load management situations and what information the equipment will receive either from the utility, other load management entity, or from pre-programed instructions of building occupants depending on peak load pricing signals from utilities. The standard will include definitions; classifications; demand response performance requirements, test requirements; rating requirements; minimum data requirements for published ratings; operating requirements; marking and nameplate data; conformance conditions; and communication protocols. AHRI has issued the draft standard for public review and comment and expects to finalize the document in 2018.

Sensors and Controls and Buildings-to-Grid Research & Development

The U.S. Department of Energy Building Technology Office is coordinating strategies and activities with stakeholders to address the integration and optimization of homes and commercial buildings with the nation’s energy grid. BTO explores fundamental concepts of transaction-based energy systems, characterization of building end-uses, and the opportunities they bring to the larger energy system. It is also investing in VOLTTRON, an open source control and coordination platform that DOE is developing as a common platform for distributed control. VOLTTRON enables developers to quickly build secure applications and agents that can unlock more value from building devices through the delivery of end-use services, grid services, and energy market services [68].

DOE/BTO is conducting a “Smart Neighborhood” R&D and demonstration project that aims to validate a “smart,” neighborhood-level, buildings-to-grid integration strategy utilizing the VOLTTRON platform. The project is in collaboration with DOE’s Office of Electricity Delivery and Energy Reliability, electric utilities Alabama power, Georgia Power, and Southern Company, and manufacturers Carrier and Rheem. Two different transactive microgrid approaches to distributed power generation and storage with building level energy management are being compared. This management of complex systems is enabled through the integration of the VOLTTRON-based transactive controls platform: one approach will focus on aggregate renewable generation and distributed energy storage at the neighborhood level through community scale storage, solar photovoltaic (PV), and emergency distributed generation (i.e. Community Scale Microgrid); the second approach will focus on utilizing a fully distributed approach with rooftop solar PV and home energy storage (i.e. a Neighborhood of Home Scale Microgrids). The project began in late 2017 to evaluate several control and optimization strategies, including HVAC and WH integration and optimization, in a research house at ORNL. It will continue through 2020 with field evaluations in a 62-home microgrid-connected neighborhood in Alabama [69].

A separate DOE/BTO initiative, the Sensors and Controls sub-program, seeks to improve building energy management and optimize building operating conditions (i.e., heating, ventilating, and air conditioning (HVAC), lighting, and plug loads) through the development of low-cost and fully automated building sensors and controls systems that will improve data collection, monitoring and optimization of building energy use, as well as effectively integrate building energy loads with the rest of the electric grid and support energy-related transactions outside the building envelope. The sub-program is organized around the following areas: [70]

- Multifunction plug-and-play wireless sensors – fully automated and self-power sensing node packages that can be easily installed, operated and maintained.
- Occupant-centered and –comfort sensors and controls – at the zone or subzone level to enable accurate, real-time feedback on individual and group-level occupant presence and/or comfort.
- Whole-building submetering – pervasive and granular submetering such that all equipment and plug loads are being metered with sufficient accuracy for unique identification and monitoring-based commissioning.
- Adaptive and fault tolerant controls – Ongoing, automated commissioning that compares top-level or submeter information about building energy consumption to an appropriate baseline to automatically identify and diagnose operational faults.

Advancements in these sensor and control strategies will improve the efficiency and enable energy savings for other building technologies (i.e., HVAC, water heating, lighting and building envelope and windows).

3.3 Evaluation of applied technologies

DOE/BTO and others have been working toward developing more efficient HVAC/WH systems for application in highly efficient (including nZEB ready) residential and commercial buildings. The integrated heat pump (IHP) is a leading concept. IHPs basically combine the space, heating, space cooling, and water heating functions into one highly efficient system – dedicated dehumidification and ventilation functions can also be included in the package. Both ground source (GS-IHP) and air source (AS-IHP) systems have been developed and field tested, details of which are furnished in three reports published by ORNL and summarized below [71] [72] [73].

Two prototype AS-IHP designs were field tested near ORNL [72]. The first, developed in collaboration with Nortek Global HVAC, Inc., uses a single variable speed (VS) compressor and fans [72]. A field test prototype was installed in a 223 m^2 test house and monitored from May 2014 to May 2015. About 40% annual savings were estimated for the AS-IHP vs. a baseline suite of individual systems operating at DOE minimum efficiencies under at the test site. The second AS-IHP, developed in collaboration with Lennox Industries, combined a commercially available high-efficiency ASHP with a separate prototype module for water heating, demand dehumidification and ventilation [73]. A field test prototype was installed in the same house and tested from Oct. 2015 to Oct. 2016. Estimated total annual energy savings for the second AS-IHP prototype vs. the baseline system were also about 40% [74]. (Field performance for both system designs would have shown better results if the test house had better thermal envelope performance, e.g., near-zero-energy ready.) Additional work on equipment and packaging and optimizing controls is needed to further advance the AS-IHP designs toward commercial products.

GS-IHPs offer a similar combination of space heating and cooling and domestic water heating capabilities as AS-IHPs but use a very highly efficient variable-speed (VS) water-source heat pump (WSHP) coupled to a geothermal energy source/sink. Today one GS-IHP product is on the market: the ClimateMaster Trilogy 45 Q-Mode (https://www.climatemaster.com/residential/geothermal-heat-pumps/trilogy-packaged-systems) with a rated heating COP and cooling COP of 5.1 and 13.2, respectively, at minimum capacity [71].

Field tests of the GS-IHP product were conducted at two sites in Knoxville and Oklahoma City, respectively. For the 2015/2016 test year, the Knoxville site provided about 55% total energy savings compared to a baseline 3.8 SCOPc (13 SEER) electric ASHP and electric WH. Peak demand savings ranged from 54% to 78% per month. Energy cost savings of ~64% were achieved, with about 65% due to lower demand charges. For the Oklahoma City site, the GS-IHP demonstrated total site electricity savings of ~60%. Best applications of the GS-IHP system are buildings or specific small zones of buildings that have high hot water loads coincident with high space cooling loads. These demonstration sites allowed the GS-IHP to take advantage of its combined space cooling/water heating operating mode featuring extensive recovery of the normally wasted system condenser heat for water heating. It was estimated that if applied nationally to all appropriate commercial building spaces, the GS-IHP could save 0.084 quads of source energy vs. the all electric baseline system [71].

WH-only systems used in most highly efficient buildings (or nZEBs) in the US are currently either condensing type gas (with storage tank or instantaneous) WHs, solar WH systems (with gas or electric back up), or air-to-water HPWH products. Electric HPWHs are available from several manufacturers with EF ratings of 2.3 to 3.5 W/W [75]. Several gas HPWH products are under development but none are commercially available yet.

Concerning their “role” in current and future nZEBs, high-efficiency heat pumps will continue to help further reduce the overall energy consumption level of the building and enable achievement of nZEB performance. Heat pumps (or other HVAC technology options) cannot on their own bring a building’s energy consumption level below zero any more than increasingly heavily insulated thermal envelopes. Some renewable on-site energy generation technologies (e.g., solar/photovoltaic systems, etc.) must be incorporated to get to this level.

Finally, DOE’s Next Generation Rooftop Unit (RTU) R&D project sought to develop a commercial RTU design capable of providing cooling capacity of about 44 kW (150,000 BTU/hr) with an Integrated cooling COP (ICOP) of over 6.4. A lab prototype using R-410A reached 6.33 ICOP, while another lab prototype reached 6.6 ICOP using R-452B. A prototype was field tested in 2016, reaching 6.1 seasonal ICOP. More than half of U.S. commercial building space is cooled by RTUs. Existing RTUs consume more than 1.3% of total US energy annually (1.0 Quad source energy). If replaced by advanced RTUs at 6.4 ICOP, it is estimated that businesses would save over $1 billion each year in energy costs [14].

4 CASE STUDIES AND SAMPLE PROJECTS OF REALISED NZEB

4.1 Short description of realized nZEB on the national level

As part of its Zero Energy Ready Home program, the U.S. Department of Energy provides a "virtual tour" of 160 examples located throughout the country [76]. A review of those documented yielded the following results:

Nationally, 74% of these homes relied upon some type of heat pump system for primary heating (78% of these being air-source heat pumps, and 22% being ground-source heat pumps).

39% of these "heat pump" homes are located in the cold climate zone. 20%, 18% and 14% can be found in the marine, hot-humid, and mixed humid zones, respectively. Only 8% of Tour Zero heat pump homes exist in the cold/very cold, hot-dry and mixed-dry climates.

Heat pump efficiency ratings (COP) for ASHP systems (identified in 76 homes) ranged from 2.12 to 5.50, with a median of 2.84. GSHP COP system ratings (identified in 20 homes) ranged from 3.6 to 5.7, with a median of 4.9. Gas heating systems (identified in 30 homes) rated per AFUE (Annual fuel utilization efficiency) ranged from 91 to 98, with a median of 95.

8% of heat pump homes indicated a secondary gas heating system.

18% of homes relied upon cooling-only central air conditioning systems for cooling, with 7% indicating no cooling system or not specifying one and the balance relying on heat pump systems.

Cooling performance ratings ($SCOP_c$) of standard central AC systems (identified in 29 homes) ranged from 3.5 to 7.6, with a median of 4.4 (US SEER ratings range of 12 to 26, with a median of 15).

Table 4-1 summarizes the basic characteristics of the 160 Tour Zero homes. Five best practice examples are highlighted in sections 4.1.1-4.1.5.

Table 4-1: Summary Characterization of Homes Featured on Tour of Zero Website [76]

		MIXED-HUMID	HOT-DRY	COLD	HOT-HUMID	MARINE	MIXED-DRY	COLD/ VERY COLD	ALL REGIONS
Number and Size of Characterized Home	# of Characterized Homes	24	8	71	24	26	6	1	160
	Minimum Size (m^2)	114	178	43	75	36	182	111	37
	Median Size (m^2)	245	274	325	175	210	199	111	256
	Maximum Size (m^2)	473	6002	638	737	415	206	111	6002
Primary Heating System Type (# of Homes)	Heat Pump	71%	63%	66%	88%	92%	67%	100%	74%
	Gas	21%	25%	30%	8%	4%	33%	0%	21%
	Other	0%	13%	4%	0%	0%	0%	0%	3%
	Not Specified	8%	0%	0%	4%	4%	0%	0%	3%
Secondary Heating System Type (# of Homes)	Heat Pump	0%	13%	4%	4%	4%	0%	0%	4%
	Gas	0%	0%	15%	4%	0%	0%	0%	8%
	Other	0%	0%	0%	0%	4%	0%	0%	1%
	Not Specified/None	100%	88%	80%	92%	92%	100%	100%	88%
Primary Cooling System Type (# of Homes)	Heat Pump	71%	75%	69%	83%	85%	67%	100%	74%
	Cooling-only Central AC	21%	25%	24%	13%	0%	33%	0%	18%
	Other	0%	0%	0%	4%	0%	0%	0%	1%
	None/Not Specified	8%	0%	7%	0%	15%	0%	0%	7%
Median Primary Heating System Efficiency	Gas Systems AFUE	95	92	98	96	93		-	95
	ASHP $SCOP_h$	2.74	2.93	2.81	2.55	3.81	2.79	2.91	2.84
	GSHP COP	-	-	5.60	-	4.50	-	-	4.90
Median Primary Cooling System Efficiency	Cooling-only Central AC SEER	16.0	15.5	14.0	19.0	-	16.5	-	16.0
	ASHP $SCOP_c$	5.28	4.69	5.03	4.69	4.54	4.91	7.62	4.98
	GSHP COP	-	-	5.95	6.19	4.5	-	-	5.84

4.1.1 Best Practice: McKinley Project (Carl Franklin Homes & Green Extreme Homes)

One of 75 affordable homes constructed by builder Carl Franklin Homes in collaboration with non-profit Green Extreme Homes Community Development Corporation, this home was awarded a U.S. DOE Zero Energy Ready Home Housing Innovation Award in 2015.

Table 4-2: Key Features of McKinley Project

Name	McKinley Project.
Location	Garland, TX, U.S.A.
Layout	3 bedrooms, 2.5 baths, 2 floors.
Conditioned Space	148 $m^{2.}$
Climate Zone	IECC 3A, hot-humid.
Completion	January 2015.
Category	Affordable.
HERS Index	Without PV 56, with PV 26.
Projected Annual Utility Costs	Without PV $1,875, with PV $1,167.
Projected Annual Energy Cost Savings (compared to 2009 IECC)	Without PV $1,450, with PV $1,905.
Builder's Added Cost (Over 2009 IECC)	Without PV $2,000, with PV $10,000.
Annual Energy Savings	Without PV 22,298 MJ (6,194 kWh), with PV 46969 MJ (13,047 kWh).
Walls	11.43 cm (4.5 in) SIPs RSI 3.17 (R-18); wood chip-resin siding; bottom sill gasket.
Roof	21.20 cm (8.35 in) SIPs RSI 6.69 (R-38); ice and water shield over roof; 30-year composite shingle.
Attic	Sealed conditioned attic or cathedral.
Foundation	Uninsulated slab.
Windows	Double-pane; composite-framed; argon-filled; low-e; U=0.29; SHGC=0.21.
Air Sealing	0.4 ACH 50.
Ventilation	ENERGY STAR-rated ERV; exhaust fans.
HVAC	Ductless mini-split; 3.68 COP (15.5 SEER).
Hot Water	Tankless water heater; 0.95 EF.
Lighting	CFLs, linear fluorescents and LEDs.
Appliances	ENERGY STAR-rated dishwasher, ceiling fans, and exhaust fans.
Solar	3.5 kW.
Water Conservation	Low-flow fixtures; 2-button toilets; native drought-tolerant plants.

4.1.2 Best Practice: Hickory Drive (Glastonbury Housesmith)

Completed in April of 2015 by builder Bob Dykins, this home not only met DOE Zero Energy Ready Home program standards, but also achieved a National Association of Home Builders (NAHB) National Green Building Standards emerald level and was selected as a CT Zero Energy Homes Challenge 2014 Grand Winner, in addition to achieving LEED for Homes platinum certification at the homeowner's request. A summary of the technology and systems incorporated into this house appears below:

Table 4-3: Key Features of Hickory Drive

Name	Hickory Drive.
Location	Glastonbury, CT, U.S.A.
Layout	4 bedrooms, 4 baths, 2 floors, finished basement.
Conditioned Space	398 m^2.
Climate Zone	IECC 5A, cold.
Completion	April 2015.
Category	Custom.
HERS Index	Without PV 29, with PV -23.
Projected Annual Utility Costs	Without PV $2,331, with PV $-1,864.
Projected Annual Energy Cost Savings (compared to 2006 IECC)	Without PV $2,763, with PV $6,958.
Builder's Added Cost (Over 2006 IECC)	Without PV $215/$m^2$, with PV $301/$m^2$.
Annual Energy Savings	Without PV 11,711 MJ (11.1 MMBtu), with PV 95,588 MJ (90.6 MMBtu).
Walls	Advanced framing; 50.8 mm x 152.4 mm (2 in x 6 in) 40.6 cm (16 in) on center; open 3-stud corners; right sized headers; ladder blocking at intersecting walls; 13.97 cm (5.5 in) blown-in fiberglass cavity insulation; taped coated sheathing; 6.98 cm (2.75 in) rigid mineral wool; 1.90 cm (.75 in) vertical furring drainage plane; fiber cement siding; spray foam from sill to floor joists. Total wall RSI 6.16 (R-35).
Roof	Breathable waterproof underlayment; taped coated sheathing; metal roofing.
Attic	Unvented and conditioned attic; 12.7 cm (5 in) closed-cell spray foam RSI 6.16 (R-35); 16.51 cm (6.5 in) blown-in fiberglass RSI 10.21 (R-58); insulated on underside of roof.
Foundation	25.4 cm (10 in) concrete basement walls; 10.16 cm (4 in) XPS foam RSI 3.52 (R-20); rigid fiberglass on slab edge RSI 3.52 (R-20), rigid glass foam under slab RSI 2.99 (R-17).
Windows	Triple-pane; argon-filled; aluminium-clad wood frame; low-e; U=0.23-0.26.
Air Sealing	0.57 ACH 50.
Ventilation	ERV; MERV 13 filters.
HVAC	Geothermal heat pump; COP 4.4; EER 29.5.
Hot Water	Heat pump water heater; desuperheater.
Lighting	100% LED.
Appliances	ENERGY STAR-rated refrigerator, clothes washer, dishwasher, heat pump clothes dryer, induction cooktop, and ceiling fans.
Solar	13.8 kW; rotates on pole.
Water Conservation	All EPA WaterSense-rated fixtures.
Other	Electric vehicle charging stations; storm shelter; gravity-fed rainwater irrigation.

4.1.3 Best Practice: Fishers Circle (Amaris Homes)

Amaris Homes built the first home in Minnesota certified to the DOE Builders Challenge program, the precursor to the DOE Zero Energy Ready Home program. This home, built in Vadnais Heights, MN, continues that commitment to energy efficient design.

Table 4-4: Key Features of Fishers Circle [76]

Name	Fishers Circle
Location	Vadnals Heights, MN, U.S.A.
Layout	3 bedrooms, 2 baths, 1 floor.
Conditioned Space	175 m^2.
Climate Zone	IECC 6A, cold.
Completion	March 2015.
Category	Custom.
HERS Index	Without PV 47, with PV 22.
Projected Annual Utility Costs	Without PV $1,262, with PV $663.
Projected Annual Energy Cost Savings (compared to 2006 IECC)	Without PV $776, with PV $1,366.
Builder's Added Cost (Over 2006 IECC)	Without PV $20,000, with PV $37,660.
Annual Energy Savings	Without PV 73,692 MJ (20,470 kWh); with PV 97279 MJ (27,022 kWh)
Walls	50.8mm x 101.6mm (2 in x 4 in); 60.96 cm (24 in) on center aligned with roof trusses; 2.54 cm (1 in) rigid foam exterior insulation; 7.62cm (3 in) closed-cell spray foam in cavity RSI 4.23 (R-24); house wrap; engineered wood siding.
Roof	Ice and water shield 91.44 cm (36 in) past wall line; valley metal flashing; metal roof edging; step flashing at house and wall connections; kick-out flashing; continuous ridge vents; 15# felt; architectural asphalt shingles.
Attic	40.64 cm (16 in) energy heel trusses; 5.08 cm (2 in) closed-cell spray foam on attic floor; 38.1 cm (15 in) blown-in cellulose RSI 11.53 (R-65.5).
Foundation	Slab on grade; 5.08 cm (2 in) rigid foam insulation at foundation walls and below slab RSI 4.23 (R-10).
Windows	Double-pane; argon-filled; PVC framed; low-e; U=0.25; SHGC=0.16.
Air Sealing	1.64 ACH 50.
Ventilation	HRV; motion detector-controlled exhaust fans; 70 watts; 0.035 m^3/s (75 ft^3/m); MERV 16 filter.
HVAC	Air-source heat pump with variable speed; rigid metal HVAC ducts in conditioned space; 3.53 COP (14.5 SEER).
Hot Water	Natural gas boiler for radiant floor heat and domestic hot water; 95% efficient.
Lighting	100% LED ENERGY STAR-rated refrigerator, dishwasher and three exhaust fans.
Solar	4.9 kW PV.
Water Conservation	Low-flow faucets, showerheads and toilets.
Other	Energy management system; programmable thermostat, low-VOC.

4.1.4 Best Practice: Casa Aguila

With its three dual-axis PV trackers, wind turbine and battery storage, this Ramona, CA home's projected annual energy cost is -$9,900. Additional ZEB technologies and features include:

Table 4-5: Key Features of Casa Aguila [76]

Name	Casa Aguila.
Location	Ramona, CA, U.S.A.
Layout	4 bedroom, 5 bath, 1 floor.
Conditioned Space	291 m^2.
Climate Zone	IECC 3B, hot-dry.
Completion	April 2016.
Category	Custom.
HERS Index	NA.
Projected Annual Utility Costs	Without PV $1,000, with PV $-9,900.
Projected Annual Energy Cost Savings (vs typical new homes)	Without PV $1,400, with PV $11,700.
Builder's Added Cost (Over 2012 IECC)	NA.
Annual Energy Savings	Without PV 35,280 MJ (9,800 kWh), with PV 232,200 MJ (64,500 kWh).
Walls	5.08 cm x 40.64 cm (2 in x 16 in) oc. Double-stud advanced frame walls with RSI 9.86 (R-56) blown cellulose. 3-coat stucco over liquid-applied weather-resistant barrier. Phase-change material under drywall.
Roof	Synthetic underlayment; standing steam metal roof with 0.52 SRI (R-3).
Attic	5.08 cm x 20.32 cm (2 in x 8 in) rafters filled with dense-blown cellulose and topped with OSB roof decking, liquid waterproofing, then 15.24 cm (6 in SIPs); phase-change material behind dropped ceiling drywall.
Foundation	Slab-on-grade; 2.54 cm (1 in) R-5 EPS rigid foam and vapor barrier under slab.
Windows	Triple-pane, tilt-and-turn RSI 0.88 (R-5) windows with impact-resistant glass; U=20, SHGC=0.30.
Air Sealing	0.32 ACH 50.
Ventilation	HRV with humidity control.
HVAC	Radiant floor heat; fan coil cooling, ducted mini-split heat pump.
Hot Water	Solar and air-to-water heat pump for space and DHW; backup heat pump WH.
Lighting	100% LED.
Appliances	ENERGY STAR clothes washer, refrigerator, dishwasher, ceiling fans.
Solar	22.1-kW PV (three dual-axis trackers); 3.2-kW wind turbine. 40-kW battery storage.
Water Conservation	Four 37,854-liter (10,000-gal) rainwater cisterns for potable water. Four storm water tanks and one greywater tank of the same 37,854-liter capacity for irrigation and fire suppression.

4.1.5 Best Practice (Commercial): 435 Indio (SHARP Development)

Within the commercial space, the New Buildings Institute regularly publishes case studies of buildings which meet their criteria for Verified ZNE status. One such example is a one-time Hewlett Packard research and development laboratory in California, which at the time had been vacant for several years [77]. The building owners contracted with the SHARP Development Company with the goal of renovating to ZNE status while being a better financial investment than a typical code-minimum building by standard real-estate development metrics.

To maximize operational efficiency, SHARP installed several passive and active systems:

Table 4-6: Key Features of 435 Indio [77]

Lighting and Daylighting	Forty-three daylight cupolas carved out of the roof minimize heat loss and gain while allowing more direct sunlight. 186 m^2 (2,000 ft^2) of electrochromatic windows were installed. Suspended LED fixtures spaced further apart than normal supplement typical daylight levels when necessary.
Envelope	As night ventilation of thermal mass is a primary strategy, 14.29 cm (5-5/8 in) thick polystyrene insulation was added to exterior walls so the thermal mass was exposed on the interior and available to exchange with cool air in the evenings. The walls have an RSI 3.52 (R-20) insulatory value. The roof was improved with insulated foam for better insulation and additional support for a new PV system and daylighting design. A cool roof coating was applied over the foam and 25.4 cm (10 in) batt insulation was added; all told, the roof has an RSI of 7.04 (R-factor of 40).
HVAC & Natural Ventilation	Two air-source heat pumps serve as the backup heating and cooling for the building's passive systems. The HVAC system is 22% of a traditionally sized system. Actuators open the skylights and ground-level windows and rising hot air is moved by eight-foot steel fans as part of a night flushing program for tpre-cooling of the thermal mass in winter months.
Plug Loads	The building's use as an open space for tech firms results in plug loads being the biggest energy end use, at 58%. Installed circuit metering provides real-time information to tenants about plug use.
Controls	A Master System Integrator and building controls company advised on the controls system starting early in the design process; they developed an "omni-controller" to monitor how all passive systems worked in tandem. Building controls can be operated manually, automatically, and remotely turning fans on and off, opening/closing windows, and performing other control related tasks.
Renewable Energy Generation & Storage	A 113.2-kW flat-panel PV system rests across the roof, along with two solar panels for hot water. The PV system generates 957,000 MJ (266,000 kWh) per year and the solar thermal system generates 1,800 MJ (500 kWh) per year; all told this system is generating 113% of the building's annual energy usage.

The thoughtful design and comprehensive set of ZNE measures allowed this renovation to meet the owners' original goals. Accelerated lease-up times, increased rent and lower operational costs realized at 435 Indio highlight that ZNE renovations can make financial sense for developers, and SHARP Development has gone on to complete three other projects that leased up either during or before construction started.

5 SUMMARY OBSERVATIONS

5.1 Brief summary of state-of-the-art

As documented throughout this report, the United States is committed to reducing energy consumption in new and existing buildings and has set aggressive goals for doing so. The BTO strategic goal is to reduce average US building energy use intensity (EUI, kWh/m^2 or Btu/hft^2) by 50% compared to a 2010 baseline [9]. Sub goals for the HVAC, water heating (WH), and Appliances R&D activities are to develop technologies by 2020 with potential EUI reductions of 60%, 25%, and 15%, respectively, vs. a 2010 baseline. A key element of achieving these and other goals is to develop appliances, including heat pumps that are as efficient as possible.

Government-sponsored programs and non-profit organizations, such as ENERGY STAR, LEED, and the New Buildings Institute (NBI) have played a pivotal role in developing certifications and rating systems and publicizing ZEB developments in the United States that aid building owners and contractors in building and retrofitting low energy, high performance buildings. In 2016, NBI reported a total of 395 ZEB or nZEB commercial buildings in the United States; 53 were “zero energy buildings” (ZEB), 279 were ZEBs under construction or had limited data to verify zero energy performance, and 62 were classified as “ultra-low energy verified buildings”, meaning they could be zero energy if final steps were taken to implement on-site renewable generation [25].

In the residential market, over 1,700,000 ENERGY STAR-certified homes have been built, with estimates for 2016 ranging from about 72,000 to more than 92,000. According to ENERGY STAR, savings from the construction of these homes is the equivalent of [28]:

- Eliminating the emissions from over 22,000 passenger vehicles,
- The carbon sequestered by nearly 3,000,000 tree seedlings over ten years.
- Saving the environment 105,000 metric tons of CO_2.

The national market share in the new homes sector of ENERGY STAR-certified homes reached 10% in 2016.

5.2 US contributions to IEA HPT Annex 49

As IEA HPT Annex 49 progresses, the United States has identified a few ways to contribute in subsequent Task 3.

- Center of Environmental Energy Engineering (CEEE), University of Maryland: Prof. Reinhard Radermacher and his CEEE colleagues are developing an individual cooling system called the Roving Comforter (RoCo). The objective is to develop a mobile personal conditioning system that employs a phase change material (PCM) to capture cooling cycle waste heat so that it is not rejected to the interior building space. By employing personal cooling systems like RoCo, the general building space temperature level can be set to a higher level and overall building energy consumption lowered without sacrificing comfort for the occupants. RoCo development will be documented for Annex 49 in the US country report for Task 3.

- National Institute of Standards and Technology (NIST): Dr. Vance Payne and his colleagues at NIST are conducting a field evaluation of two air-to-air air-source heat pumps (ASHP) with different air distribution systems at the NIST Net Zero Energy Residential Test Facility (NZERTF). One system will use a traditional central air duct distribution system based on relatively large duct sizes and low air velocities (aka, big duct). The second will employ small diameter ducts with high-speed air flow (aka small duct). Field testing of the two systems began in 2017 and will continue into 2018 with results reported to Annex 49 in the US country report. (See Figure 5-1 for an overview of NZEB features in the NIST test residence.)
- Oak Ridge National Laboratory (ORNL): Since the conclusion of HPT Annex 40, ORNL has continued development and evaluation of several integrated heat pump (IHP) systems. For Annex 49 we plan to contribute the following
    - Field demonstration results for a commercialized electric ground-source (GS-IHP) in a commercial and a multi-family building application,
    - Final field tests of prototype electric air-source (AS-IHP) versions, and
    - Cost reduction progress for a prototype engine driven AS-IHP version.

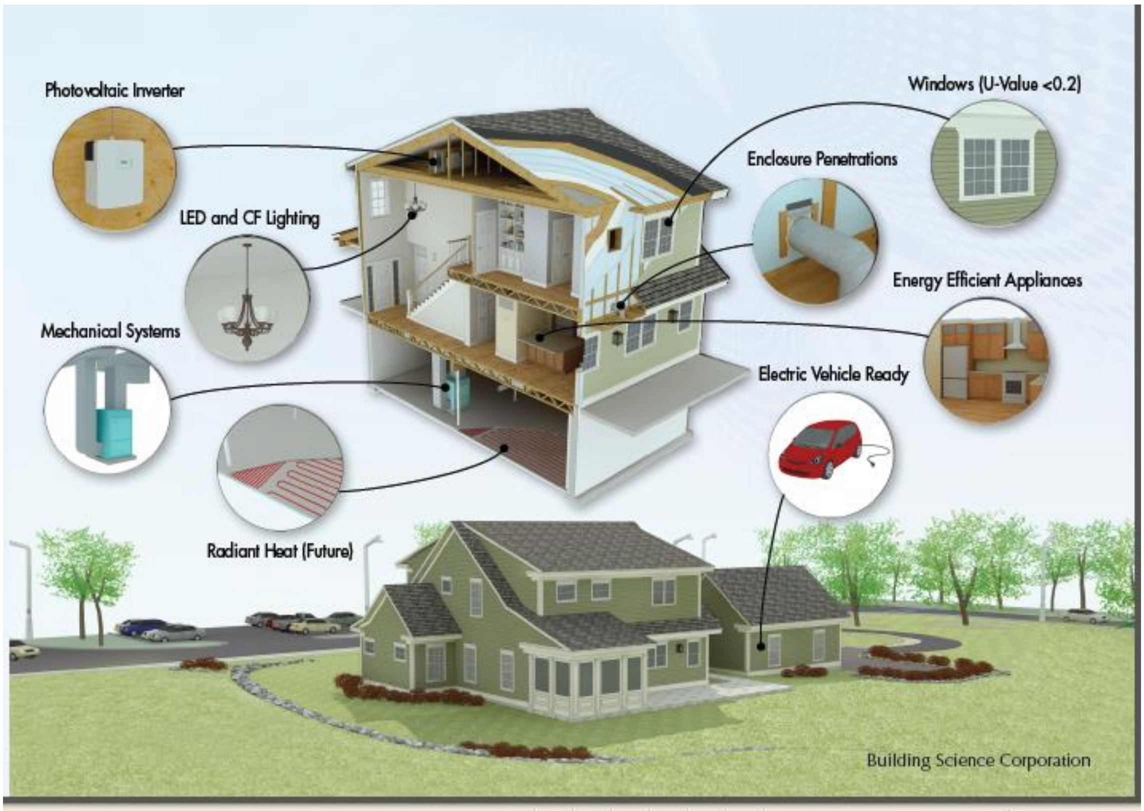


Figure 5-1: Overview of Key NZEB Features at the NIST Net-Zero Energy Residential Test Facility [78]

6 ACKNOWLEDGEMENT

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