Analysis of 50 Energy Efficient Net Zero Energy Buildings

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Energy efficient building design and decarbonization have become a high priority in the quest to reduce the effects of pollution, conserve natural resources and slow climate change. Many engineers and stakeholders want to reduce energy consumption and related carbon emissions from buildings but may not know how to do so. This article analyzes existing net zero energy buildings (NZEBs), buildings that produce as much electricity as they consume on a yearly basis, to determine if any patterns exist that can be learned from existing buildings and be applied to current and future buildings.

Most buildings studied were found in the 2020 Getting to Zero Buildings List[1] published by the New Buildings Institute. The list provides building site and source energy use intensity (EUI), net energy use intensity, building size, location and year constructed. The list is also exclusively for buildings that have all-electric heating and cooling systems.

The 2020 Getting to Zero Buildings List has 136 buildings with EUIs ranging from 1.4 kBtu/ft^2·yr (15.9 MJ/m^2·yr) to 91.8 kBtu/ft^2·yr (1043 MJ/m^2·yr) with a median of 23 kBtu/ft^2·yr (261 MJ/m^2·yr). Since efficient building analysis is this project's goal, only buildings with an EUI of less than 30 kBtu/ft^2·yr (341 MJ/m^2·yr) were studied. All EUI data in the analysis are site energy and do not take credit for renewable energy.

This project's focus was to determine if there are noticeable design patterns used in energy efficient net zero buildings for a variety of building types, sizes and climates. The hope was that there would be patterns in the data that could be used as a starting point when designing net zero energy buildings for a wide range of building types, sizes and climates.

Data was gathered on 50 NZEBs through websites, magazine publications and trade journals such as Newbuildings.org, *ASHRAE Journal*, *High Performing Buildings* and many others. *Table 1* is an overview of the buildings included in the analysis.

EUI by Building Type—NZEBs vs. U.S. Average

The Commercial Buildings Energy Consumption

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Survey (CBECS) is a national sample survey by the U.S. Energy Information Administration that collects information on U.S. commercial buildings, including their energy-related building characteristics and energy use data.[2] *Table 2* compares energy consumption of CBECS buildings versus the energy efficient net zero buildings in this study.

The CBECS buildings use 2.0 to 3.7 times more energy than the NZEBs. The following will investigate how the NZEBs were able to be much more efficient than the average building.

Building Orientation. Newly constructed buildings were commonly oriented on an east/west axis with window shading to optimize the amount of solar heating in the winter and reduce cooling loads in the summer.

Building Envelope. Most of the buildings use highly insulated walls and roofs along with tight construction for low building infiltration. Roof insulation values ranged from R-23 for a Hawaii building to an R-67 roof on a Denver building. Energy efficient windows were a key feature with some buildings using electrochromic glazing or triple-pane windows. In one case, using triple-pane windows enabled elimination of a perimeter heating system, substantially reducing the mechanical system cost.

Lighting. Windows, skylights, solar tubes and clerestories were commonly used to decrease the need for electric lighting during the day. Electric lighting was usually by LED, but a few older buildings used fluorescent light. Natural and LED lighting were often combined with occupancy sensors and light level sensors to automatically turn off or dim lights for energy conservation.

Electrical Loads. Plug loads were reduced with occupancy sensor-controlled outlets, energy efficient office equipment such as using laptops instead of desktop computers, Energy Star-rated equipment and energy efficient elevators. The general design philosophy of these buildings was to have equipment turned off and only turn things on when they are needed, an on-demand consumption philosophy.

Domestic Water Heating

The following are the domestic water heating systems used by the NZEBs: air source heat pump, ground source heat pump, electric, electric instantaneous, heat pump water heater and solar thermal water heater. Only about half the buildings studied note the type of domestic hot water system used, and many use solar thermal. This may be because the buildings that use solar thermal hot water wanted to highlight it, and other buildings that use systems such as electric tank or instantaneous water heaters did not consider these systems noteworthy.

TABLE 1 Overview of the buildings included in this study.

	YEAR CONSTRUCTED OR RENOVATED	SIZE (ft²)	EUI (kBtu/ft²·yr)	NO. OF STORIES
Range	2001 – 2020	924 – 222,000	2.3 – 29.6	1 – 6
Average	2013	38,834	16.8	1.8

TABLE 2 Comparison of energy consumption of CBECS buildings versus the energy efficient net zero buildings in this study.

BUILDING TYPE	NO. OF BLDGS.	NZEB MEDIAN EUI (kBtu/ft²·yr)	CBECS MEDIAN EUI (kBtu/ft²·yr)[2]	DIFFERENCE IN EFFICIENCY
Education	15	13.2	48.6	73%
Multifamily	4	15.2	52[3]	71%
Office	21	16.5	53.5	69%
Public Assembly	4	17.5	53.2	67%
Public Service	1	26.6	75	65%
Retail	2	20.9	40.8	49%
Warehouse	3	11.6	23.2	50%

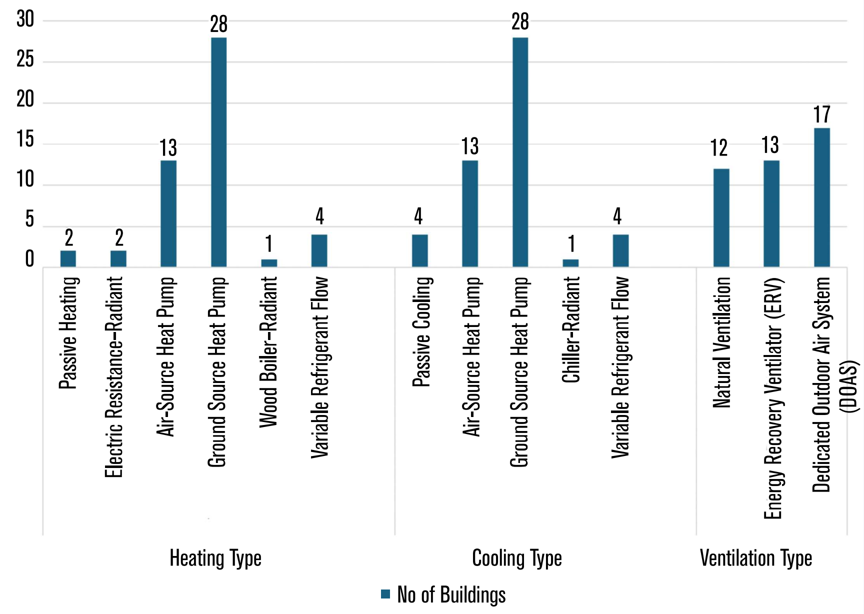
Many of the principles used by these NZEBs can be learned about in more detail from "The Advanced Energy Design Guide—Achieving Zero Energy"[4] series produced by ASHRAE, the American Institute of Architects (AIA), the Illuminating Engineering Society (IES) and the U.S. Green Building Council (USGBC), with support from the Department of Energy (DOE). These guides are available as a free download through ASHRAE's website.

Mechanical System Analysis

Heating, cooling and ventilation can have a significant impact on building energy use depending on climate zone, so what system types did the NZEBs in this study use to reduce energy consumption? *Figure 1* shows the number and type of heating, cooling and ventilation systems studied.

Ground source heat pumps were the most widely used system followed by air source heat pumps and VRF. These three systems were used in 45 of the 50 buildings. Passive cooling was in four buildings via operable windows with either automated or manual control. This

FIGURE 1 Number of systems studied by type.



isn't completely passive, but it doesn't use a refrigeration cycle to cool air, so it was included with passive.

The active cooling and heating systems were the same for most buildings except for the chiller coupled with radiant slab tubing, which was one of the higher energy users.

Of the buildings that listed how they provided and treated outdoor air, there were three main methods: energy recovery ventilator (ERV), natural ventilation and dedicated outdoor air system (DOAS). Natural ventilation was typically enabled through windows and was combined with a mechanical ventilation system. Examples are using automatically opening windows for nightly building cooling and during moderate daytime temperatures. ERV in this study is considered a dedicated source of outdoor air that recovers energy from the building exhaust airstream to pretreat outdoor air but does not have any active heating or cooling system. DOAS indicates a dedicated supply of outdoor air with active heating or cooling. DOAS units usually included energy recovery also.

It is notable that most buildings used a dedicated source of outdoor air instead of combining it with the room heating and cooling systems. By ventilating the building with a separate system from the building heating and cooling, it allows the heating and cooling systems to be turned off when space temperatures are acceptable. Only turning on the heating/cooling as needed reduces the amount of time building equipment is operating and the associated energy consumption.

In some instances, the amount of outdoor air was controlled by carbon dioxide (CO_2) levels or occupancy sensors in the spaces. When CO_2 levels were low, the outdoor air was reduced for energy savings.

Building EUI by Mechanical Distribution System

The way energy is distributed through a building can have a substantial impact on energy consumption. As heating or cooling is distributed throughout the building, thermal and friction losses occur through piping and ductwork. Recirculation losses are a major concern of central systems, especially with the distribution of hot water, but also with large central air distribution systems.

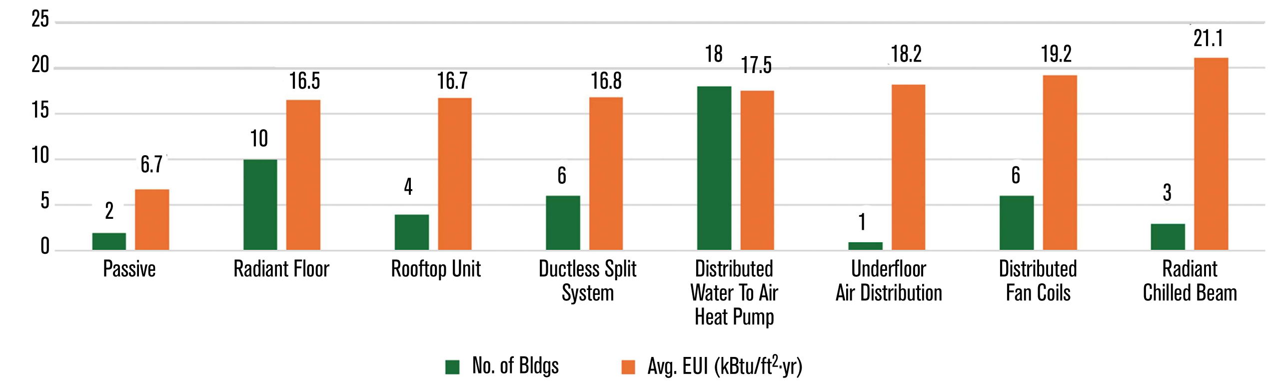
A study done by the University of California—Berkeley found that the losses associated with hot water recirculation systems can be 44%.[6]

No NZEBs in this study (*Figure 2*) used centralized air distribution to heat and cool the building. Some used centralized hot and chilled water distribution, and those had the highest average energy use of systems analyzed with the notable exception of radiant floor systems. The higher energy use of centralized systems may be the result of thermal energy losses in the piping or the increased energy required to pump hot and chilled water through the building.

The distribution systems with lower energy use were ones where the heating and cooling did not need to travel far from the source to the spaces, such as with small rooftop units, ductless split systems and distributed water to air heat pumps. These systems can also turn on and off as needed, reducing equipment run time and energy consumption.

The analysis so far has only considered EUI as a function of system types but has not considered the climatic effects of energy consumption on the building. The following looks to see if there are any patterns in EUI or system type as a function of geographic location.

FIGURE 2 NZEB EUI by mechanical distribution.



Net Zero Building EUI by Geographic Location

The following analysis breaks down energy consumption by location based on the U.S. Census Regions (*Figures 3a* and *3b*),[5] similar to what CBECS uses, but without including the subregions, with the exception of the Pacific West and Mountain West. The Mountain and Pacific subcategories were used because the climates in many of the Mountain areas, such as Utah, Idaho and Colorado, are considerably colder than California, Oregon and Coastal Washington.

The Pacific West NZEBs have the lowest EUI, which is likely a result of a moderate coastal climate. The Mountain West and Northeast NZEBs have cold winters and moderately hot summers, resulting in higher energy consumption. The Midwest NZEBs have the highest average EUI, which corresponds with the cold winters, hot summers and humidity.

FIGURE 3A U.S. census regions and divisions.

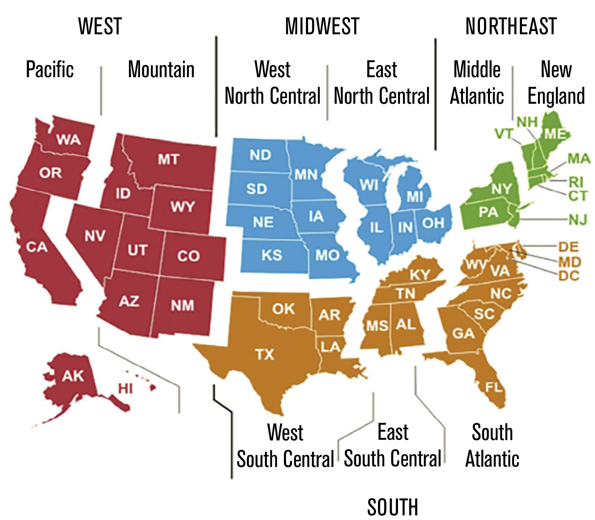
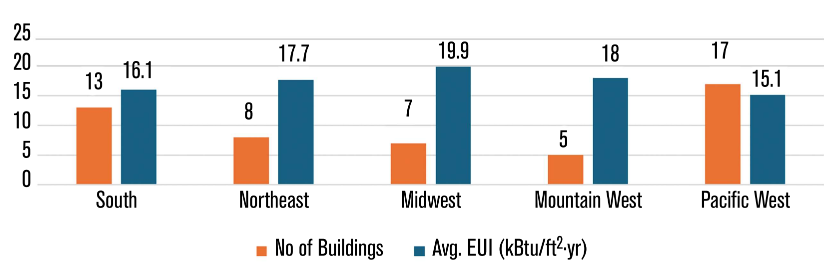


FIGURE 3B NZEB EUI by geographic region.



Net Zero Building Heating and Cooling Type By Geographic Location

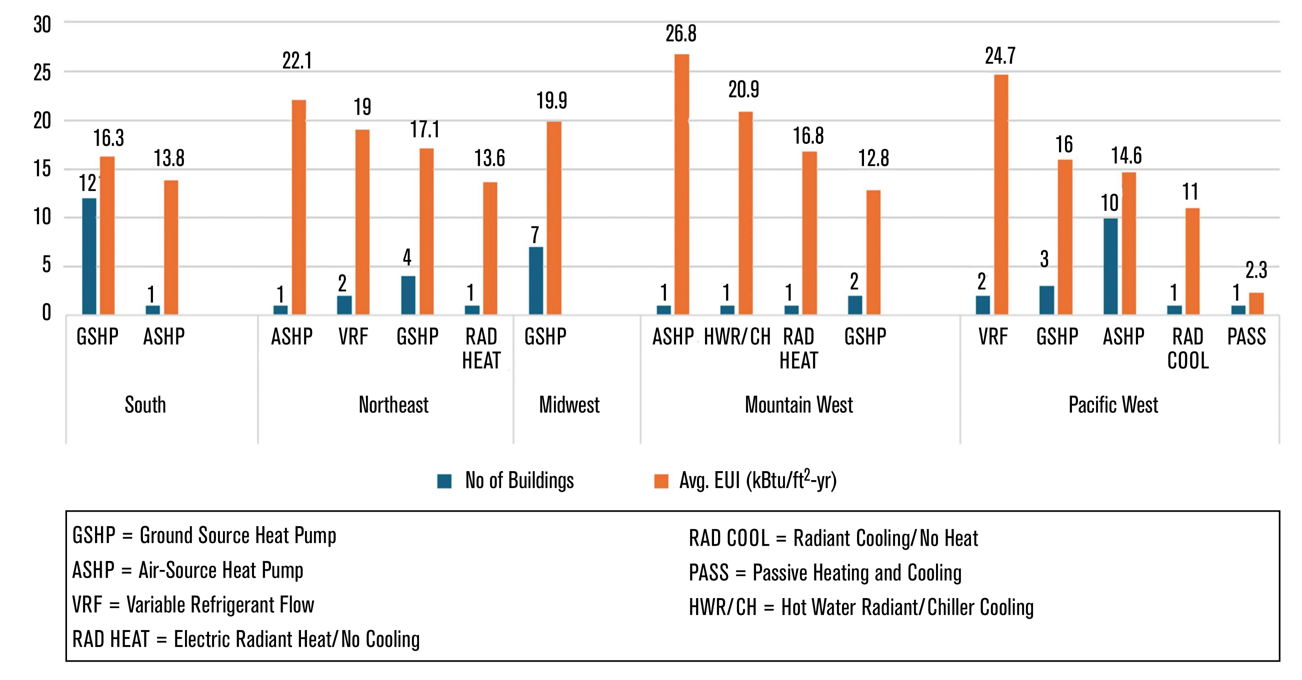
Breaking down the type of mechanical system by geographic location (*Figure 4*) revealed patterns for system types. All the buildings in the Midwest were geothermal, but by contrast the Pacific West Region used five different mechanical system types, likely a function of the moderate West coast climate.

Midwest. Buildings used 100% ground source heat pumps (GSHP). Other all-electric heating systems such as electric resistance and air source heat pumps (ASHP) are less efficient than GSHPs in cold climates.

South. Buildings used 92% GSHP and 8% ASHP. This was a little surprising because of the high cooling load in this region compared to heating, which makes a GSHP system more expensive due to the increased borefield size required to dissipate heat. It is also surprising because ASHPs can work well in moderate winter climates, but they are less efficient than ground source heat pumps.

Northeast. The most efficient used radiant heating, but this building did not have any cooling. GSHPs were the most efficient heating and cooling

FIGURE 4 Mechanical system type by geographic location.



system followed by variable refrigerant flow (VRF) and ASHP, which were less frequently used in this colder climate.

Mountain West. GSHPs and radiant heating were used in Utah and Colorado. That is not surprising with cold mountain winters. Only a single ASHP was used, in Arizona.

Pacific West. The predominant system is ASHP. There are 10 buildings in California, and nine of them use ASHPs or VRF.

Ventilation Type by Geographic Location

Are certain types of ventilation used more frequently based on climate? *Figure 5* shows a breakdown of ventilation strategies used by location.

A mix of ventilation strategies were used in different regions of the country, but definite patterns also existed.

- **South.** Dedicated outdoor air systems (DOAS) were prominent.
- **Northeast.** Energy recovery ventilators (ERV) were commonly used.
- **Pacific West.** Natural ventilation was prevalent.

Net Zero Energy Building EUI by Building Size

Buildings (*Figure 6*) smaller than 10,000 ft^2 (929 m^2) all had a similar EUI and were the most efficient. As the building size increased beyond 10,000 ft^2 (929 m^2), the EUI increased but there was still a significant variation. Many large buildings in this study were designed with mechanical systems that would traditionally have been reserved for smaller buildings, such as distributed heat pumps, which on average are more efficient than the centralized systems in this study.

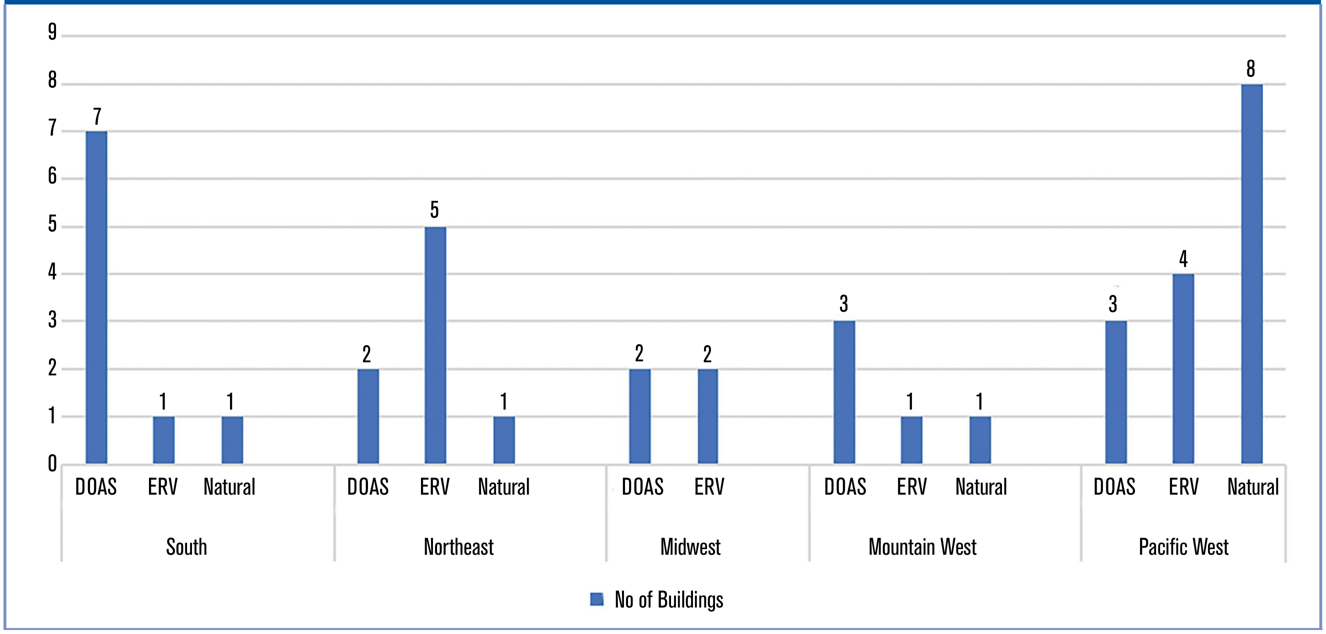
On-Site Renewable Energy

The buildings used solar photovoltaics (PV) to offset the building energy consumption. Most were roof-mounted except for three buildings with ground-mounted PV, and four buildings with parking canopy PV systems. One building used PV for building and window shading. One building used solar PV and a vertical axis wind turbine, but the solar PV was designed to provide all the electricity needed for the building.

Commissioning

Many of the buildings required adjustments after occupancy to optimize efficiency and performance. Buildings that used distributed ground source heat pumps tended to have fewer post-occupancy adjustments than other types of system, but most buildings required monitoring and adjustments to achieve energy efficiency goals and occupant comfort.

FIGURE 5 Ventilation type by geographic location.



Hiring a commissioning agent and having the design team be actively involved in the building performance for the first year after occupancy were common themes.

Cost

Often owners and engineers think that designing an energy efficient building requires spending significantly more on construction cost. The following is the cost data from NZEBs studied (*Figure 7*). Only data for 37 of the buildings could be found since not all building cost information is publicly available.

The first five buildings listed are renovations, and the remainder are new construction. There is a large range of construction costs for new buildings, from $171/ft^2 ($1841/m^2) to $857/ft^2 ($9225/m^2). Additionally, there is an interesting jump in cost from building 29 ($363/ft^2 [$3907/m^2]) to 30 ($556/ft^2 [$5985/m^2]), which we will look at more closely in the following paragraphs.

The lower-cost buildings were predominantly distributed mechanical systems (blue in *Figure 7*) such as water-to-air ground source heat pumps, rooftop units, VRF and ductless split systems. The higher-cost buildings were predominantly centralized mechanical systems

FIGURE 6 Building size EUI.

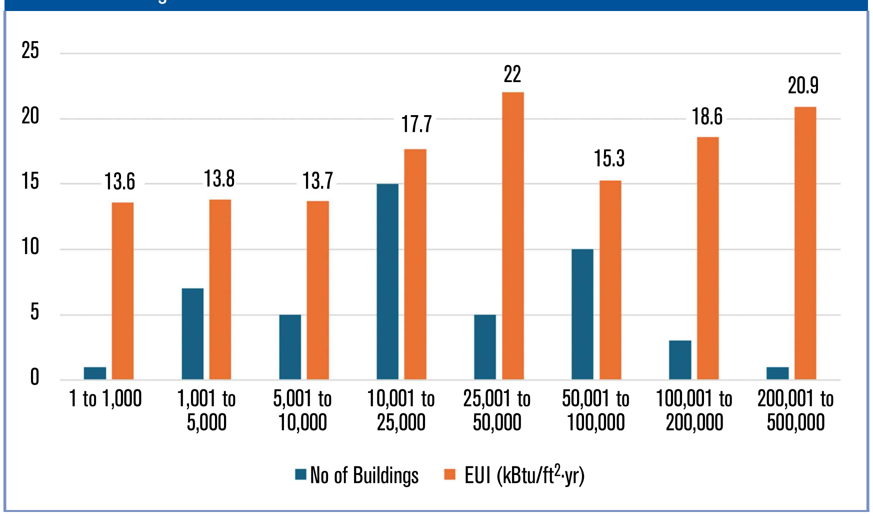


FIGURE 7 Construction cost $/ft^2.

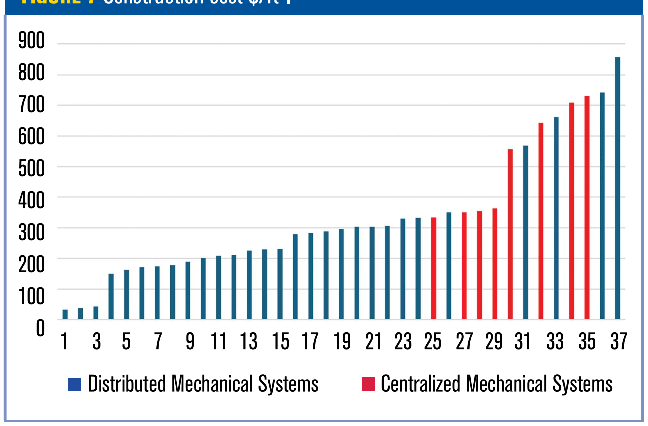


TABLE 3 $/ft²

	NUMBER OF PROJECTS	AVERAGE CONSTRUCTION COST ($/ft²)
Renovations	5	$85
New Construction	32	$374

(red in *Figure 7*) such as radiant floor and hot/chilled water fan coils. This is not the only explanation since many other factors exist in building construction cost, but it is a pattern worth noting. Some of the buildings that were more expensive included specially harvested wood or other features that increased the cost of the project but were not directly related to energy efficiency.

The overall average cost of the projects is shown in *Table 3*.

Modern commercial building construction costs range on average from $240/ft² ($2583/m²) to $870/ft² (9365/m²).[7] These costs are similar to the NZEBs studied.

It is interesting to note that a building's cost was not correlated with its energy efficiency. The least expensive group of buildings has an EUI of 17 kBtu/ft²·yr (193 MJ/m²·yr) compared to an EUI of 17.9 kBtu/ft²·yr (203 MJ/m²·yr) for the most expensive group.

Conclusion

The author's goal when starting this project was to determine if patterns exist in existing energy efficient building design and apply these to current and future projects. There were patterns such as GSHPs in the Midwest, DOAS units in the South or ASHPs in the Pacific West along with many other patterns.

Most buildings used decentralized air distribution systems, such as water-to-air heat pumps or fan coils and separated the heating and cooling system from the outdoor air. Distributed equipment reduced distribution losses. Dedicated outdoor air also allowed the individual heat pumps and fan coils to turn off when not needed on small and large buildings.

The fundamental design principles in these buildings are conserve energy through well insulated buildings with good natural lighting. Then design systems to be turned off as much as possible through decentralized HVAC systems, occupancy sensors for lighting, equipment with automatic sleep modes and plugs that automatically de-energize when rooms are unoccupied. Finally, when electricity needs to be used, it is conserved with efficient electric lighting and HVAC systems.

Hopefully the data presented will be used by engineers for increased adoption of energy efficient net zero buildings.

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