

Understanding Zero-Energy Buildings

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The U.S. Department of Energy's (DOE) Building Technologies Program has set a research goal of making commercial zero-energy buildings (ZEBs) marketable by 2025.¹ In concept, a ZEB has greatly reduced energy loads such that renewable energy can supply the remaining energy needs. This immediately begs some questions: "This is a far stretch from our current energy-efficient buildings—is it even possible?" "Are there examples out there that are even close?"

To address these questions, the National Renewable Energy Laboratory (NREL) conducted an assessment of the commercial sector to evaluate the technical potential for meeting this goal based on possible technology improvements for 2025. NREL also evaluated seven low-energy commercial buildings to determine with respect to their ability to meet a zero energy goal.²



Photo courtesy of the National Renewable Energy Laboratory

Photovoltaic array on the roof of the Lewis Center at Oberlin College in Oberlin, Ohio.

Justification for Zero-Energy Buildings

Why are ZEBs important? Residential and commercial buildings consume 40% of the primary energy and 71% of the total electricity in the United States.³ That is a huge burden on the electrical system, energy resource availability, emissions, and economic viability.

To make matters worse, energy use in the U.S. commercial sector is expected to grow by 1.6% per year—twice as fast as in the residential sector. It is being driven by economic expansion and population growth, which require more and more space each year.⁴ The total building area and its energy impact are increasing faster than all the energy conservation measures being taken and retrofits being made to buildings.

So how can new commercial buildings be constructed so that they are, in fact, ZEBs? And how can older buildings be retrofitted to be environmentally sound, comfortable, economical, and energy efficient? In most cases, an older building cannot be a ZEB. However, research has shown that energy consumption and costs can be reduced significantly by applying some fairly simple energy-efficiency principles.^{2,5}

Definitions of Zero-Energy Buildings

When energy goals are set as percent savings, an energy scale is implied. The question of “savings from what?” is

often asked. Answers include: “savings from ANSI/ASHRAE/IESNA Standard 90.1-2004, *Energy Standard for Buildings Except Low-Rise Residential Buildings*.” The other end of the scale is implied to be zero. A 30% energy goal is measured from Standard 90.1-2004 on the path to zero.

Zero is the crossover point between a building that consumes a resource and one that produces the resource. Conceptually, it is envisioned as the point where the energy needs of the building has no impact.

First, on the definition front—the word “zero” is really “net zero.” The sums of the flows in and out are equal and opposite. This does not imply zero flows.

If a building owner has the goal of creating a building that has a net zero, the design team first must define what that means, as it is open to interpretation. What do you mean by *energy*—is it source energy, site energy, energy cost, or emissions as a result of using energy? At least four ZEB definitions, which are incorrectly assumed to be interchangeable, are in use today.⁶

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This article will examine:

- Net zero source energy building;
- Net zero site energy building;
- Net zero energy cost building; and
- Net zero energy emissions building.

A *net zero source energy building* produces as much energy as it uses compared to the energy content at the energy source. The system boundary is drawn around the building,

the transmission system, the power plant, and the energy required getting the fuel source to the power plant. It tends to be a better representation of the total energy impact. However, it is challenged by difficulties in acquiring site-to-source conversions and by the limitations of these conversions. Fixed conversion factors do not account for dispatch of energy with time of day, and the changes in dispatch as new buildings and the new power plants to supply them come on-line. This definition can depend on how the utility is buying or producing the power, rather than on the energy performance of the building. So, if someone wants to construct a building in an area with a large percentage of hydroelectric energy, it may have a low source energy impact. However, placing the building in that location may necessitate new fossil fuel generation plants and the building may actually use the new generation capacity, which is coal. This analysis is very difficult.

A *net zero site energy building* produces as much energy as it uses when measured at the site. This definition as a goal is useful, as it can be verified through on-site metering. It tends to encourage energy-efficient designs. However, it does not distinguish between fuel types or account for inefficiencies in the utility grid. The site must also be defined.

Is the site just the building footprint, or does it include the entire property? What happens if you cover a parking lot with photovoltaic (PV) panels to achieve your zero energy building, only to develop that space later into a new building? This would give higher priority to PV systems that are within the building footprint because it is always part of the building.

Building owners are typically most interested in *net zero energy cost buildings*, and tend to use energy efficiency and

renewable energy as part of their business plans. This definition, like the site ZEB definition, is easy to verify with the utility bills. Market forces provide a good balance between fuel types based on fuel availability. Costs also tend to include the impact of the infrastructure. Reaching zero may be difficult or impossible because of utility rate structures. Many rate structures will give credit for energy returned to the grid, but will not allow this number to go below zero on an annual basis. As a result, no way exists to recover costs incurred by fixed and demand charges. Finally, imagine a day when all buildings approach zero energy. Utility rates will need to be changed to maintain a reliable utility grid.

The fourth definition, a *net zero emissions building*, looks at the emissions that were produced by the energy needs of the building. This is probably a better model for sustainable energy sources. However, like the source ZEB definition, it can be difficult to calculate.

Why is this important? People often use definitions to meet their own needs. The design team must determine, as part of the goal setting process, which definition is being used. Later, we will compare these definitions on actual low-energy buildings. The next section discusses how a few of these definitions play out in actual building performance.

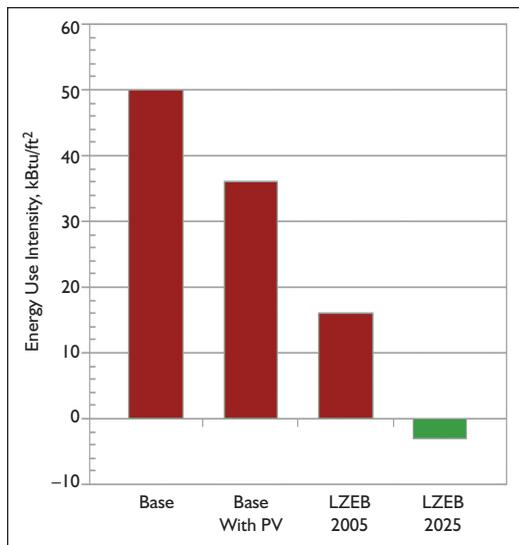


Figure 1: Energy use intensity for four scenarios of the commercial building stock.

Using a Whole-Building Design Process

Each building we studied has a unique purpose and function, and all have commonalities. These buildings are successful because they are good energy performers. All had owners who pushed low-energy or sustainability goals and considered energy efficiency part of the decision-making process. The architects and engineers created a design to implement the vision, which required a whole-building design process.

The whole-building design process requires that the team responsible for the building design—the architect,

engineers (lighting, electrical, and mechanical), energy and other consultants, and the building's owner and occupants—work together to set and understand the energy performance goals. The purpose of the whole-building design approach is to enable the entire design team to interact throughout the design process to understand system interdependencies. A systematic analysis of these interdependencies can help ensure that a much more efficient and cost-effective building is produced.

Could All Buildings Have Zero Energy Impact?

Are ZEBs possible on a wide scale? To answer this question, NREL researchers took 5,375 buildings in 1999 Commercial Buildings Energy Consumption Survey (CBECS) public use data,⁷ extracted the key energy-related building parameters, and created energy models to simulate the energy performance representing the entire commercial building sector. We used Standard 90.1-2004 performance requirements for all of the building models to use as a baseline, then applied a set of readily available energy conservation measures and covered 50% of each simulated roof with photovoltaic (PV) panels.⁸

The PV was limited to the roof area and was the only supply-side source analyzed. Other sources were considered, but not used for this analysis. With a broad scan of the building's sector, technologies needed to have the potential to be applied to large number of buildings. For example, on-site wind generation is limited by wind regime. Biofuels, such as woodchips, must be imported to the building site. Microturbines and fuel cells purchase energy and convert it to heat and power. These units may improve overall efficiency, but energy still enters the boundary of the defined system. PV can be applied to almost any building.

Figure 1 shows the results of this analysis by displaying the net site energy use intensity for the entire commercial building sector for four different scenarios. The Base scenario represents the energy use intensity (EUI) if all buildings were built to Standard 90.1-2004. The EUI for this scenario is 49.7 kBtu/ft² (564 MJ/m²), which is a 41% reduction from the actual 1999 EUI for the commercial building stock of 84.2 kBtu/ft² (956 MJ/m²). This result indicates that if we rebuilt and operated all buildings to current standards, we could save a significant amount of energy. Adding PV to the roofs enables

us to reduce energy consumption by an additional 28%, to 35.8 kBtu/ft² (407 MJ/m²). This is represented in Figure 1 by the scenario Base with PV.

Next, we applied a set of energy-efficiency measures—elongated the buildings along the east-west axis, applied daylighting strategies within 15 ft (4.6 m) of exterior surfaces, added overhangs to block high summer sun, reduced the lighting power density by 17%, and made modest improvements in HVAC efficiency. This yielded a saving of 41% over

the base scenario. Adding the PV results in an EUI of 15.5 kBtu/ft² (176 MJ/m²). This is scenario LZEB 2005.

Finally, we made additional improvements based on the DOE goals for technologies of the future. The assumptions in the Future Maximum Technology scenario represent an additional 20 years of research and development. Improvements in HVAC equipment and lighting technologies are accounted for in this case. Because of small buildings loads, improvements in PV technology allow the entire

sector to start exporting energy. This final case represents an EUI of -2.5 kBtu/ft² (-28 MJ/m²). (The minus sign means that energy is exported on an annual basis.)

Conceptually, we found that the entire commercial building sector could generate energy, based on aggressive energy savings and using the roof to generate electricity for the building. It does require technology improvements coupled with good integration and control of systems.

Some buildings can achieve zero energy more easily than others. Warehouses present a wonderful opportunity, as they are typically one-story buildings, have minimal plug loads, and can be easily daylighted. They can quite easily generate more energy than they consume, which helps those energy-intensive sectors, such as food service and health care.⁹

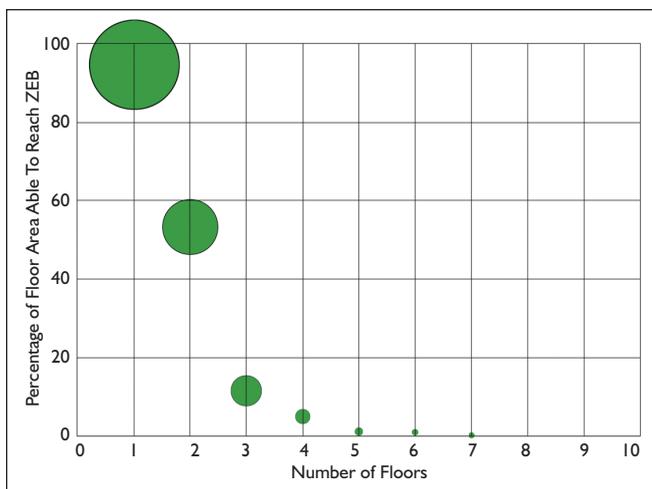


Figure 2: Fraction of commercial area that could reach zero energy in the LZEB 2025 scenario as a function of the number of stories.

Learning the Lessons of Zero-Energy Buildings

Documenting the performance of buildings helps us understand how close we are to achieving the ZEB goal. Even utility information by itself is useful. Experiences and lessons learned can help accelerate the adoption of technologies into the marketplace. Few people like to admit to the “dirty laundry,” but it helps the industry move forward and shows leadership in minimizing the energy impact of buildings. Standardized methods of reporting energy performance

are available through DOE, and guidance is available from ASHRAE standards. DOE also maintains a database to share case studies and experiences from leading-edge buildings (www.eere.energy.gov/buildings/database/). The database is set up to capture lessons learned and energy performance data. Others can search the database to get ideas, and to see what works and what does not. This will help improve the energy efficiency of the building stock.

An example of a more detailed analysis is to look at number of stories. *Figure 2* shows the percentage of commercial floor area that can reach net site ZEB as a function of the number of floors for the future LZEB 2025 case. As the number of stories increases, the ability to achieve ZEB decreases substantially because daylighting the space is difficult and the plug load density increases vis-à-vis the building's footprint. The amount of PV is fixed by the footprint of the building compounding the problem. The sizes of the green circles in *Figure 2* indicate the relative percentage of the building stock represented by the number of floors. We tend to build single-story buildings.

What Has Been Done Today?

To see how this applies to buildings today, we selected seven buildings that all had aggressive energy goals.¹⁰ Each was monitored to observe the energy performance. Six of the buildings had PV systems. The buildings represent a variety of uses and are located in a range of climates. Many similar energy-efficiency strategies were used in the buildings. *Table 1* has a summary of the characteristics of these buildings. Additional information about the buildings, including complete descriptions, can be found in the references.^{2, 11-13} *Table 2* shows the actual energy performance of these buildings,

Building Location	Stories	Size	Energy Savings*	Daylighting
Oberlin Oberlin, Ohio	2	13,600 ft ² (1265 m ²)	79%	Yes
Zion Springdale, Utah	1	Visitor Center: 8,800 ft ² (820 m ²) Restroom: 2,756 ft ² (256 m ²)	67%	Yes
Cambria Ebensburg, Pa.	1	34,500 ft ² (3205 m ²)	43%	Yes
CBF Annapolis, Md.	2	31,000 ft ² (2900 m ²)	25%	Yes
TTF Golden, Colo.	2	10,000 ft ² (930 m ²)	51%	Yes
BigHorn Silverthorne, Colo.	1	Retail Area: 18,400 ft ² (1700 m ²) Warehouse: 24,000 ft ² (2230 m ²)	53%	Yes
Science House St. Paul, Minn.	1	1,370 ft ² (127 m ²)	137%	Yes

* Compared to a substantially similar code-compliant building; includes PV contribution.

Table 1: Characteristics of selected low-energy buildings.

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Building and Installed PV System (DC Rating Size)	Building Footprint	Site Roof Area PV Fill Factor	Source ZEB Roof Area PV Fill Factor	Cost ZEB Roof Area PV Fill Factor	Emissions ZEB (Carbon Equivalent) Roof Area PV Fill Factor
Oberlin—60 kW	8,500 ft ² (790 m ²)	1.27	1.27	4.70	1.27
Zion—7.2 kW	11,726 ft ² (1089 m ²)	0.52	0.52	0.68	0.52
Cambria—17.2 kW	17,250 ft ² (1603 m ²)	2.16	2.16	Not Available	2.16
CBF—4.2 kW	15,500 ft ² (1440 m ²)	1.65	1.65	3.12	1.65
TTF—No PV	10,000 ft ² (929 m ²)	0.56	0.40	0.78	0.41
BigHorn—8.9 kW	38,923 ft ² (3616 m ²)	0.82	0.47	1.00	0.49
Science House—8.7 kW	1,370 ft ² (127 m ²)	0.73	0.73	Not Available	0.73

Table 2: Comparison of ZEB definitions that use the energy performance of seven buildings.

including PV production. Only one achieved ZEB status according to any of the definitions.

All the buildings use innovative combinations of “state-of-the-shelf” energy technologies to reduce their energy use and minimize their environmental impacts. The buildings all have thermal envelopes that exceed current energy codes. They

also use some or all of the following features: daylighting, radiant heating, natural ventilation, evaporative cooling, ground-source heat pumps, PV, and passive solar strategies. All use much less energy than comparable energy code-compliant buildings. We found that the buildings’ energy consumption was 25%–70% lower than code.

We used simulations for PV production to increase the amount of PV and achieve ZEB status using each of the definitions. *Table 2* compares the area required for the PV panel to achieve each of the ZEBs by definition. The roof areas have been normalized against the building footprint. A number of 1 would indicate that the PV must cover the roof. A roof area fill factor of 0.50 would imply that the roof is half covered. Fill factors greater than 1 imply that area is needed outside the building footprint.

Two of the buildings (TTF and BigHorn) use natural gas for heating. In this case, less PV is needed to meet a net source ZEB, compared to a net site ZEB. The remaining buildings are all electric, so the site and source definitions yield the same result.

The demand charges and metering charges become important to achieve a net zero cost building. In all cases, the amount of PV was greater than for a Net ZEB. Much variability exists in this number because of the local utility rate structures. The net zero emissions building was based on a carbon equivalent¹⁴ and is easier to achieve when natural gas is used for heating.

The loads in the TTF, Zion, BigHorn, and Science House are small enough that rooftop PV systems can meet them with the net energy source definition. However, a two-story building such as Oberlin does not have enough roof area for PV to meet the building loads. Single-story buildings have the advantage that most of the area can be daylit. Multistory buildings are harder to daylight because of the interior zones. This, combined with the plug load densities, determines a building’s ability to achieve ZEB status. Loads must be reduced to achieve ZEB status.

Conclusion

The decisions we make on design teams will influence the energy future of the world. We have the potential to change how buildings use energy, to the point of creating ZEBs in the coming decades. As a profession, we all need to strive to achieve this goal and help facilitate decisions that are economically responsible, environmentally sound, aesthetically pleasing, and occupant friendly.

As a starting point, we need to strive to create low-energy buildings. Constructing market-viable buildings that use substantially less energy is possible today. Many times it involves careful planning and creating an engineered system—something that requires the entire design team early in the process. As an engineer, you can encourage owners to follow this path.

Use case studies of buildings that have been built. At a minimum, follow the guidance in the Advanced Energy

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Design Guide series.⁵ Look for opportunities to create a good thermal envelope—especially look for thermal bridges at the corners and around steel beams. Implement daylighting with automated controls wherever possible and dim, or better yet turn off the lights. Consider natural ventilation. Size the HVAC system to match these reduced loads. Low-energy buildings can be built cost effectively. Most importantly, help the owner to set aggressive goals and follow through by helping shape the architecture and HVAC systems.

To create ZEBs we must:

- Set concrete and measurable energy goals for all building projects;
- Strive to meet those goals by using the envelope of the building to meet the comfort and programmatic needs of the occupants; and
- Measure and report the actual performance of buildings.

Finally, share your thoughts and lessons learned on your experiences to achieve ZEBs, and share areas of concern and needs for research. Research is needed to improve system performances and integrated designs if we are to have widespread ZEBs. Together we can dramatically change how buildings impact the energy future.

Acknowledgments

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