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Assessment of the Technical Potential for Achieving Zero-Energy Commercial Buildings

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B. Griffith, P. Torcellini, and N. Long
National Renewable Energy Laboratory

D. Crawley and J. Ryan
U.S. Department of Energy

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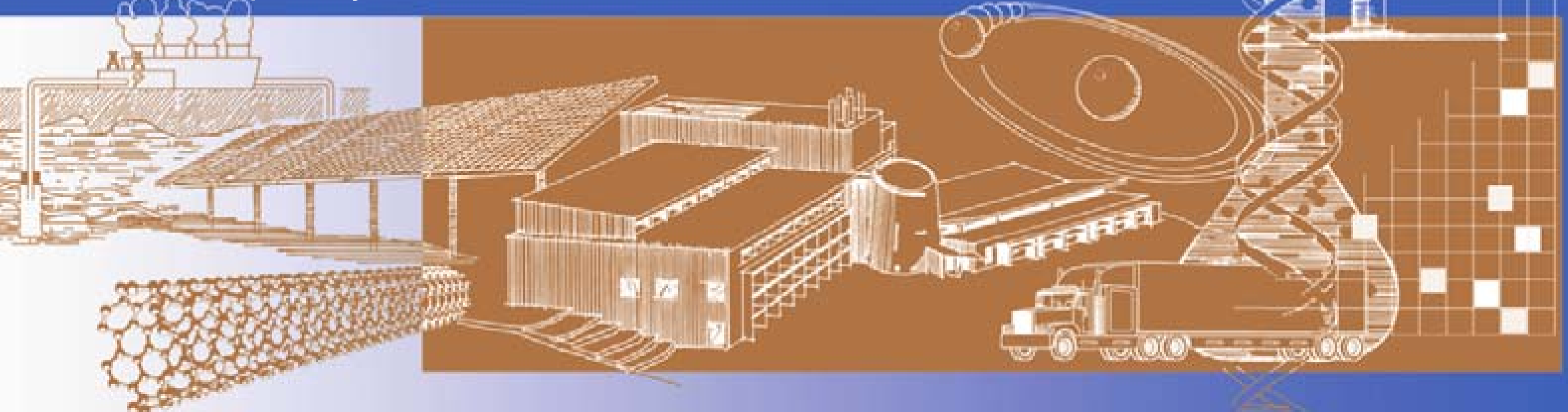

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Assessment of the Technical Potential for Achieving Zero-Energy Commercial Buildings[1]

Brent Griffith, Paul Torcellini, and Nicholas Long,
National Renewable Energy Laboratory

Drury Crawley and John Ryan,
U.S. Department of Energy

ABSTRACT

The U.S. Department of Energy's (DOE) Building Technologies Program has adopted the goal of making zero-energy commercial buildings (ZEBs) marketable by 2025. The National Renewable Energy Laboratory (NREL) conducted an assessment of the entire commercial sector to evaluate the technical potential for meeting this goal with technology available in 2005 and projected forward to possible technology improvements for 2025. The analysis looked at the technical feasibility of ZEBs, limitations in market penetration and utility grid structures notwithstanding.

The core of the evaluation was based on creating 15-minute, annual simulations based on 5,375 buildings in the 1999 Commercial Buildings Energy Consumption Survey Public Use Data and the current ANSI/ASHRAE/IESNA Standard 90.1-2004. These baseline-building models were then used to develop alternate ZEB scenarios by applying sets of available technologies and practices and projected improvements after 20 years.

The results show that the ZEB goal is technically achievable for significant portions of the commercial sector. Using today's technologies and practices, the technical potential is that 22% of the buildings could be ZEBs. With projected 2025 technologies, the technical potential is that 64% of the buildings could be ZEBs. If excess electricity production could be freely exported to the grid, then with the projected 2025 technology in every building, the commercial sector could generate as much as 37% more energy than it consumes. The results suggest that the ZEB goal is feasible for the sector as a whole and that research should be implemented to overcome hurdles to achieving the goal.

Introduction

The Energy Information Agency's (EIA) *Annual Energy Outlook 2006* (AEO 2006) predicts that energy use in the commercial sector will grow by 1.6% per year, driven by the increasing floor area needed for economic expansion and population growth. AEO reports that the commercial sector is the fastest growing demand sector—its growth rate is twice that of the residential sector. To address the resulting problem of increasing burden on the nation's energy system, the U.S. Department of Energy's Building Technologies (BT) Program has adopted the goal of market-viable, new commercial buildings with zero net energy impact (ZEBs) by 2025 (DOE 2005). Successfully meeting the ZEB goal would allow commercial sector energy demand to be decoupled from economic growth and help to mitigate risks to economic expansion that may arise from possible future constraints on energy supply and fossil fuel-related emissions.

This paper looks at the potential to achieve ZEBs in the commercial building sector. What might be achieved if all commercial buildings strived toward the ZEB goal? How low can energy use go within the sector? Which subsectors can meet the goal and which need additional energy savings to achieve the goal?

This assessment determines the technical potential for the commercial sector as a whole by evaluating collections of known technologies and practices and carefully modeling system interactions with whole-building simulation.

Methodology

For an assessment of the ZEB goal to be valuable to BT, national-scale results are required. To meet this need, we used a method with a large number of individual building models that were intended to represent the entire commercial sector. Various researchers have used this approach, which has been referred to as stock aggregation, bottom-up, and backcasting (Briggs, Crawley, and Belzer 1987; Briggs, Crawley, and Schliesing 1992; Crawley and Schliesing 1992, Huang and Franconi 1999). We developed a set of building models that represent all building types and locations based on the 1999 Commercial Buildings Energy Consumption Survey (CBECS) public use data (EIA 2002). Our analysis takes parameters from the CBECS dataset, creates building models, and determines the technical potential for energy performance based on current technologies and practices and on projected performance levels 20 years hence. Such technical potential studies establish the maximum technically achievable energy savings. They do not include any consideration of economic feasibility. Technical potential studies are useful in establishing broad research goals and targets of opportunity for energy R&D programs. Economic analysis can be used later to establish the initial cost levels needed to achieve significant market penetration. Multiple scenarios were used to develop an understanding of the relative importance of various technologies for achieving high performance.

The essence of the ZEB concept is a building designed in such a way that on-site energy consumption is reduced to a level that can be entirely met by on-site renewable energy production over a typical one-year period. This study assumes that the building can export energy to the utility grid—realistically, grid limitations may prohibit this. Photovoltaic solar electric power systems (PV) were selected as the technology for on-site energy production because it is the probably the most widely applicable renewable technology—the roofs of virtually all buildings are viable sites for PV. For this research, we used a net site energy definition. A *net site ZEB* produces as much energy annually as it uses when accounted for at the site (natural gas energy use is offset with on-site electricity generation at a 1:1 ratio).

Analysis Framework

Because building energy use is complex, simulation tools are needed to model all the interactions between systems, components, occupants' activities, and weather. This is especially important when evaluating the combined performance of collections of technologies and practices. EnergyPlus (Crawley et al. 2001) was selected because it can model PV systems and advanced building technologies in an integrated manner. In some cases alternate scenarios were evaluated by comparing the annual simulation results for baseline building models to the results for models that reflect the addition of ZEB technologies and practices.

Although simulations can model the energy performance of buildings, simulation studies often deal with only a handful of buildings in a few locations. This limitation makes it difficult to extrapolate results and draw valid conclusions for the sector as a whole. This study overcame this limitation by using a methodology based on a large set of 5,375 models derived directly from the sample buildings in the public use data from 1999 CBECS. The primary benefit of directly using CBECS is that the CBECS weighting factors provide a robust way of obtaining national results from simulations of individual buildings. For example, to aggregate results for the national average for percent savings in net site energy (*netEUI*) for a particular LZEB scenario, we use the weighting factor and floor area data from CBECS in the following manner:

$$\%\ savings = \frac{\sum_{i=1}^{N}\left(\left(\frac{(netEUI_{i,base} - netEUI_{i,LZEB})}{netEUI_{i,base}}100\right)\times Floor\ area_i \times Weighting\ Factor_i\right)}{\sum_{i=1}^{N}\left(Floor\ area_i \times Weighting\ Factor_i\right)}$$

where, i is the result for each individual model and N is the total number of model results.

Using a set of models aligned with CBECS solves the problem of how to credibly assess the sector as a whole, but it also presents several challenges: (1) the number of CBECS buildings results in an extremely large number of simulations, (2) CBECS contains much less information on the sample buildings than is needed for building energy modeling, and (3) CBECS characterizes the existing building stock, not new construction—the target buildings for the ZEB program. The most severe technical challenge was how to deal with some 32,250 simulations and the demand for computing resources and data management. These challenges were overcome by creating EnergyPlus input files based on a set of high-level building parameters and managing the simulation input and output in a database. To address the large computational needs, routines for dispatching and executing models on a 200 processor computer were developed. Finally, data mining methods were developed for reducing and analyzing results into manageable forms for reporting.

Many technical problems were overcome by using a preprocessor that automates the creation of input files. Algorithms were developed to implement rules that define exactly how each building would be modeled from a set of high-level parameters. These rules included thermal zoning, HVAC system configuration and operation, overhang creation, and the use of multipliers to reduce simulation execution time for large, complex buildings.

Basing the set of models on the 1999 CBECS provided a set of data that is limited compared to the detailed descriptions required for simulation. In addition, the assessment focused on the potential for new construction. Applying the current ASHRAE Standard 90.1-2004 (ASHRAE 2004) enabled much of the detail on envelopes and equipment to be defined. This required developing large sets of data and algorithms for automatically applying Standard 90.1-2004 to any commercial building. We also wanted to capture much of the variability of buildings, so we used probabilistic assignments (applying the central limit theorem) to create many details such as distribution of plug and process electrical loads, orientation and aspect ratio, and infiltration. Because exact locations are masked in the CBECS data, we developed algorithms based on degree-day information to assign locations to each building. Finally, the CBECS statistical model for existing stock (building type, floor area, number of floors, geographical location, weights etc.) was used as a proxy for a statistical model of the buildings being built in 2005 and beyond.

Scenarios

NREL ran EnergyPlus models for each of 5,375 prototypes under six scenarios:

1. **Base** produced reference baseline results by applying Standard 90.1-2004 to define characteristics that affect energy performance. This is the same as rebuilding the entire commercial building stock to current energy standards.
2. **Base with PV** examined the impact of applying PV to **Base**. The systems applied 10% efficient PV panels with an area equal to 50% of the total roof area for every building.
3. **LZEB 2005** (Low-/Zero-Energy Building) examined what can be achieved when an aggressive package of currently available technologies and practices is applied. Each building was reoriented and elongated along an east-west axis for good daylighting and passive solar design. Exterior fixed overhangs were added to south-facing glazing. Tubular daylighting devices were added to core zones. The facade was modeled with superinsulation and superwindows. The HVAC system was changed to a centralized, chilled-water-based variable air volume system with economizer and heat recovery ventilation (HRV) on the outside air system. Lighting power density (LPD) was reduced 17% from Standard 90.1-2004 by assuming the use of super T8 lighting (Sachs et al. 2004). The coefficient of performance (COP) of all chillers was set at 6.0. Gas heating efficiency was raised from 80% in the baseline models to 95% by assuming the use of condensing boilers.
4. **LZEB 2025** predicted the energy savings with all the same measures as the LZEB 2005 scenario with higher component performances. This could reflect reasonable outcomes after 20 years of R&D. This scenario includes a doubling of the efficiency in rooftop PV panels and a slight improvement in inverter efficiency. LPD levels were reduced by 50% from Standard 90.1-2004 (DOE 2005). Chiller COP increased from 6.0 to 6.5, and heating efficiency increased from 95% to 97%. Fan static pressure decreased slightly, and minor improvements in HVAC systems are forecast.
5. **LZEB 2025 LPD75** modeled an optimistic level of success in the development of improved lighting sources such as solid-state lighting. It is identical to the **LZEB 2025** scenario except that the design LPD is reduced by 75% from Standard 90.1-2004. This is an improvement over the **LZEB 2025** scenario, which modeled an LPD reduction of 50%, which includes the impact of solid state lighting devices at 160 lumens/watt. The 75% reduction level was developed from the efficacy projections of 199 lumens/watt for laboratory solid-state devices by 2025 and assumes that such devices and other technologies could further reduce lighting energy use.
6. **LZEB 2025 PlugProcess25** modeled the reduction in energy use by appliances and all types of electrical equipment, collectively referred to as plug and process loads. Plug and process power densities were reduced by 25% from the LZEB 2025 models and all other

scenarios. The intent is to model how the technical potential for ZEB might be affected by improvements in the efficiency of appliances and devices that use electricity inside commercial buildings (computers, copiers, cash registers, refrigerators, elevators, etc.).

Results and Discussion

The assessment study produced new data from simulation on the technical potential for ZEB technologies and practices to reduce the impact of commercial buildings on the U.S. energy system. The study developed quantitative estimates to answer this question: How low can you go?

ZEB Goal and Percent Savings for Sector as a Whole

Figure 1 shows the percentage of the commercial sector that can meet the ZEB goal under the five scenarios, in terms of both overall floor area and overall number of buildings. The ZEB goal was found to be achievable for portions of this sector—with 2005 technologies and practices, 22% of commercial buildings could reach net zero. Projections for technology improvements by 2025 increase this percentage to 64%. Calculated according to floor area, rather than by number of buildings, the percentages that can reach the ZEB goal are 23% for 2005 and 53% for 2025.

Figure 2 shows the potential percent savings in site energy for the sector as a whole. These results are presented in terms of net savings (which includes PV power production) and total end use savings (which includes only changes in efficiency).

Figure 1. Percentage of U.S. Commercial Sector that Can Reach the ZEB Goal for Various Scenarios

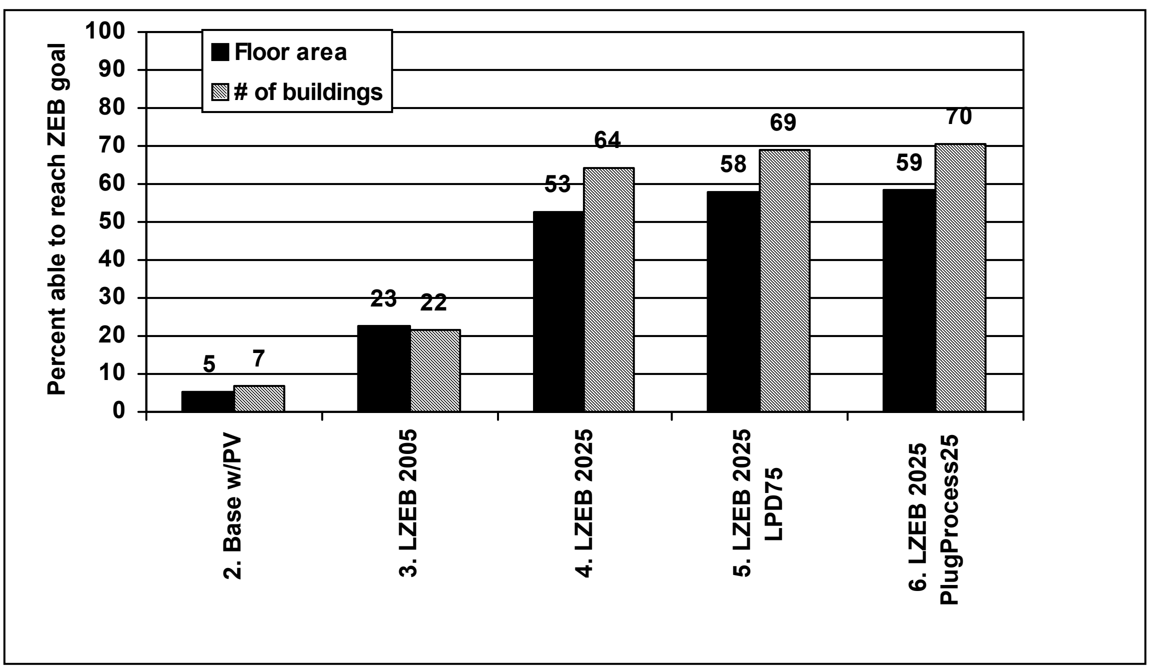
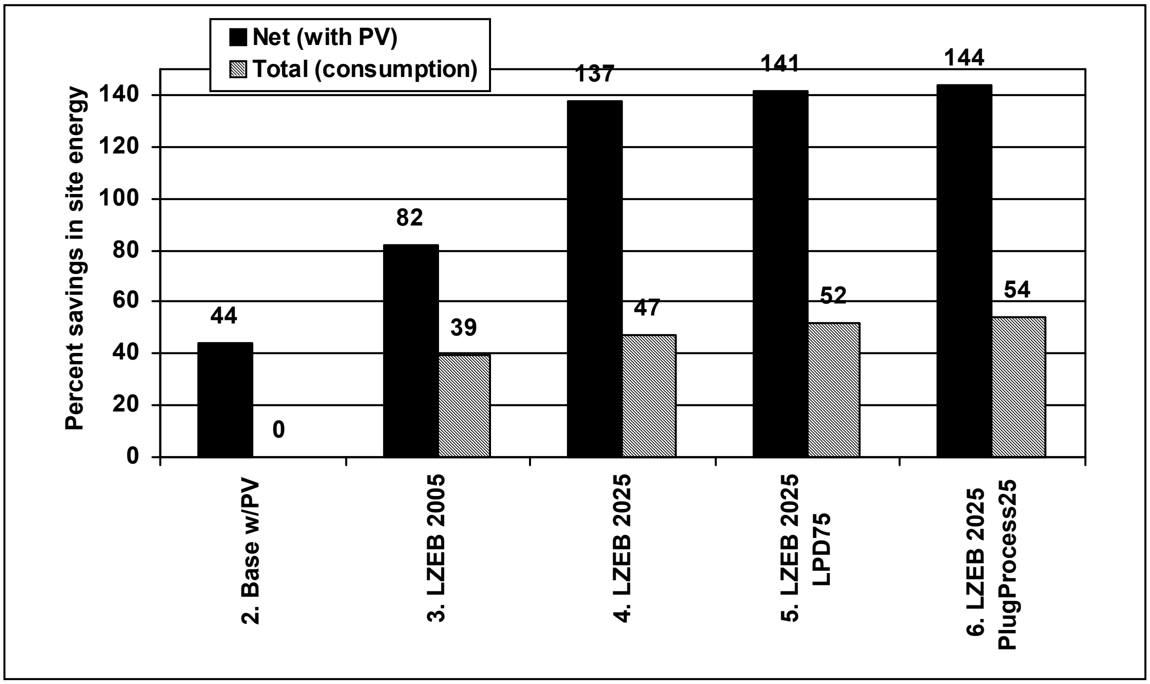


Figure 2. Percent Savings in Site Energy for U.S. Commercial Sector for Various Scenarios (100% represents ZEB)



The **Base with PV** scenario examined what can be achieved by adding only PV to cover 50% of the roof area of each baseline-building model. The results show that 5% of the commercial floor area could reach the ZEB goal and that, for the sector as a whole, 44% of the site energy use could be offset with PV power.

The **LZEB 2005** scenario examined what can be achieved if an aggressive package of current technologies and practices to improve energy efficiency were also applied. This scenario showed that the amount of floor area that could reach ZEB reaches 23% and, for the sector as a whole, 82% of site energy could be saved.

The **LZEB 2025** scenario reflected two main performance differences—a doubling of the output available from rooftop PV panels and a 50% reduction in LPD. Under this scenario, 53% of the commercial floor area could achieve net zero and, for the sector as a whole, 137% of the site energy could be saved or 37% more energy could be produced than consumed by all the buildings in the sector.

The **LZEB 2025 LPD75** scenario showed an additional 25% reduction in LPD compared to the **LZEB 2025** scenario (for a 75% reduction compared to Standard 90.1-2004). Under this scenario, 58% of the commercial floor area could achieve net zero and, for the sector as a whole, 141% of the site energy could be saved.

The **LZEB 2025 PlugProcess25** scenario also showed a 25% reduction in plug and process power density compared to the **LZEB 2025** scenario. Under this scenario, 58% of the commercial floor area could achieve net zero and, for the sector as a whole, 144% of the net site energy could be saved.

The results of the **Base with PV** scenario show that efficiency improvements make the ZEB goal much more attainable. Adding rooftop PV systems to baseline buildings could allow 5% of commercial floor area, and 7% of commercial buildings, to reach ZEB. But when efficiency measures are also added, these numbers increase: 4.1 times more by floor area, and 3.2 times more by number of buildings, can reach ZEB than could with only PV. From an energy savings point of view, the 2005 vintage PV systems can reduce site energy use by 44%, on average; efficiency improvements can reduce site energy use by 39% for the **LZEB 2005** scenario and 47%−54% for the **LZEB 2025** scenarios. This indicates that the amount of energy that can be saved by efficiency measures is comparable to the amount that can be generated by rooftop PV panels and that pursuing both is important for reaching the ZEB goal.

Analysis of the **LZEB 2025** and **LZEB 2025 LPD75** scenarios showed that the lighting system improvement saved 1.70 kBtu/ft^2·yr in lighting energy use. However, this improvement leads to a reduction in the total site energy use intensity of 2.11 kBtu/ft^2·yr. This shows that (in the ZEB context) the added HVAC savings is 24% of the lighting energy savings, for the sector as a whole. Similarly, the **LZEB 2025 PlugProcess25** scenario showed an average added benefit of 18%. (This means that reducing lighting or plug energy use by one unit will, on average, reduce whole-building site energy use by 1.24 and 1.18 units, respectively, because of the indirect effects on HVAC system energy use.)

ZEB Goal by Geography

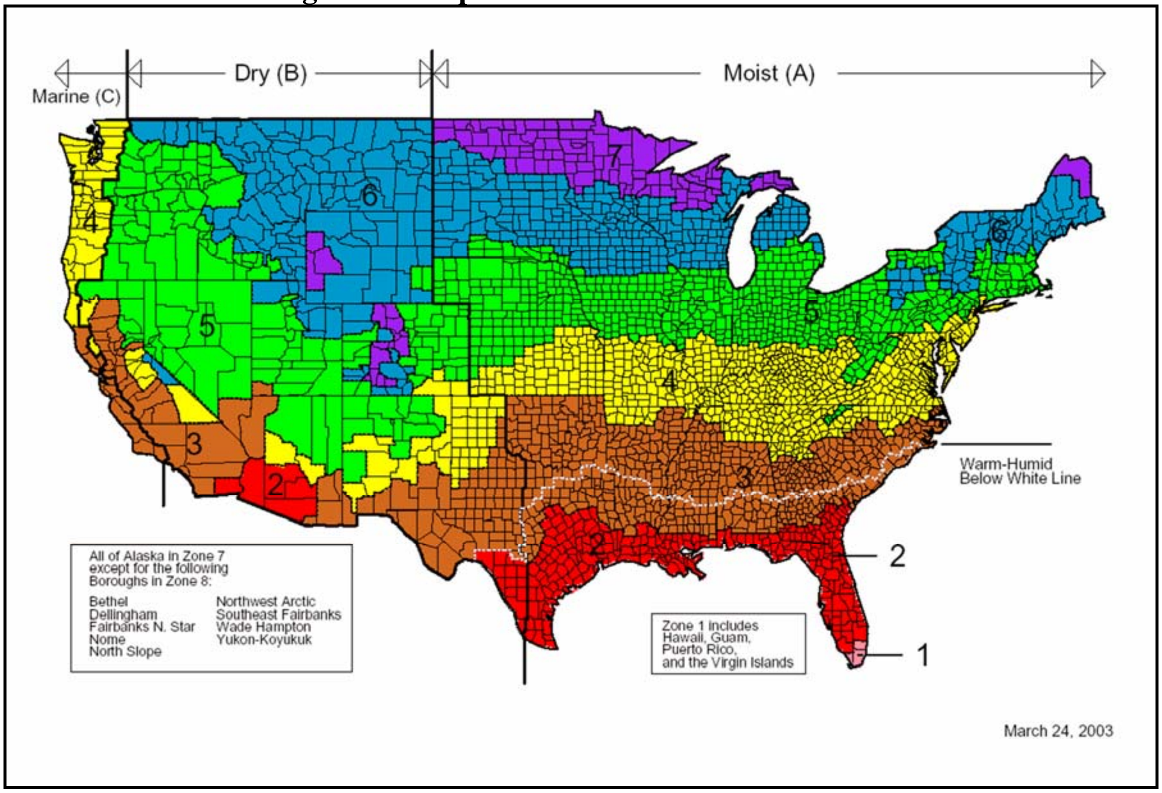
The results can also be analyzed for geographic variation at the climate zone and census division levels.

Standard 90.1-2004 uses a climate classification system with eight major zones. Results were sorted and weighted among all the buildings in each climate zone. Table 1 shows the percentage of floor area that can reach the ZEB goal for the climate zones and selected LZEB scenarios. Figure 3 shows the distribution of the climate zones. No buildings were assigned to climate zone 8 (because this applies only to portions of Alaska with sparse populations) and relatively few buildings are in climate zones 1 and 7. Climate zones 1, 2, and 3 show the best prospects for achieving the ZEB goal.

Table 1. Percentage of Floor Area Able to Reach ZEB by Climate Zone

Standard 90.1-2004 Climate Zone	2. Base with PV	3. LZEB 2005	4. LZEB 2025	5. LZEB 2025 LPD75	6. LZEB 2025 PlugProcess 25
All	5	23	53	58	59
1	16	40	61	62	65
2	12	38	73	76	77
3	10	36	64	68	72
4	3	16	44	51	51
5	1	13	43	48	48
6	0	12	45	54	50
7	0	0	19	19	19

Figure 3. Map of ASHRAE 90.1-2004 Climate Zones



Source: www.energycodes.gov/implement/pdfs/color_map_climate_zones_Mar03.pdf

The 1999 CBECS public use statistical data distinguish geography by the nine census divisions defined by the U.S. Department of Commerce (see Figure 4). Results were sorted and weighted among all the buildings in each census division. Table 2 shows the percentage of floor area that can reach the ZEB goal for the census divisions and selected LZEB scenarios. The results show less dependence than on climate. Prospects for reaching the ZEB goal are lower in the Midwest and Northeast regions.

Figure 4. U.S. Census Bureau Divisions

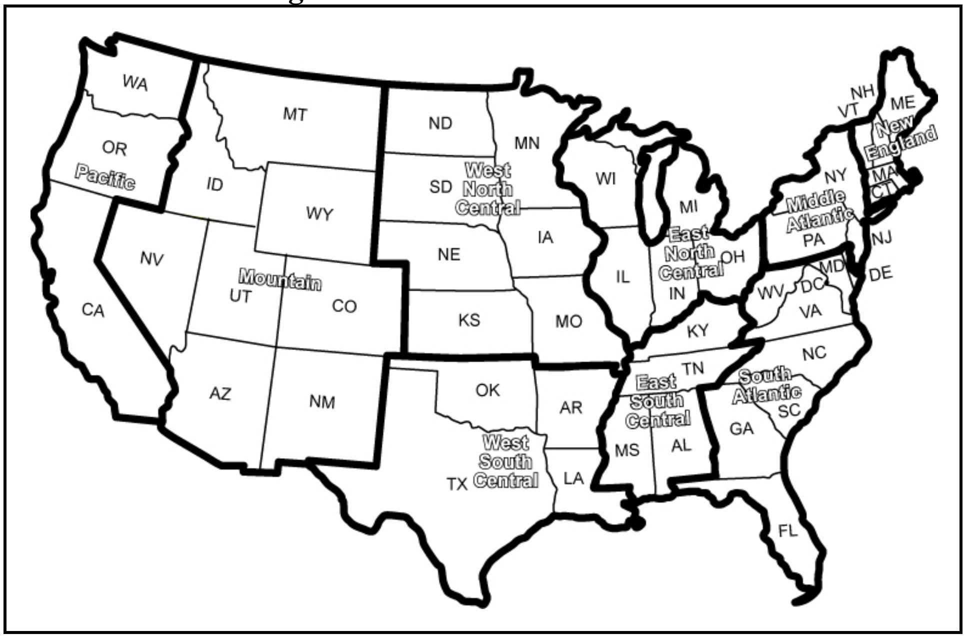


Table 2. Percentage of Floor Area Able to Reach ZEB by Census Division

U.S. Census Division	2. Base with PV	3. LZEB 2005	4. LZEB 2025	5. LZEB 2025 LPD75	6. LZEB 2025 PlugProcess 25
All	5	23	53	58	59
1 New England	0	5	34	40	39
2 Middle Atlantic	1	8	34	39	39
3 East North Central	1	17	45	52	51
4 West North Central	2	14	48	55	54
5 South Atlantic	9	31	61	63	65
6 East South Central	8	29	66	74	76
7 West South Central	10	33	67	71	72
8 Mountain	10	32	62	65	67
9 Pacific	8	29	56	61	63

ZEB Goal and Energy Savings Potential by Subsector

The results can also be analyzed by subsector, also called the principal building activity. The two basic criteria evaluated here are (1) the ease with which the ZEB goal can be met and (2) the sector-wide energy savings that could be achieved through ZEB technologies and practices. Figure 5 plots results by subsector for the portion of floor area in the commercial sector that could reach the ZEB goal under the LZEB 2005 and LZEB 2025 scenarios. Figure 6 plots the results for the aggregated net site energy savings if these two scenarios were applied to every commercial building in the country.

The relative potential of all subsectors can be examined by studying these figures. Offices have historically received the most research attention because they constitute the largest subsector. However, these results show that nonrefrigerated warehouses constitute an important subsector because they are the most likely to reach the ZEB goal and offer the highest total savings opportunity.

Figure 5. Percentage of Floor Area that Can Reach ZEB Goal by Subsector

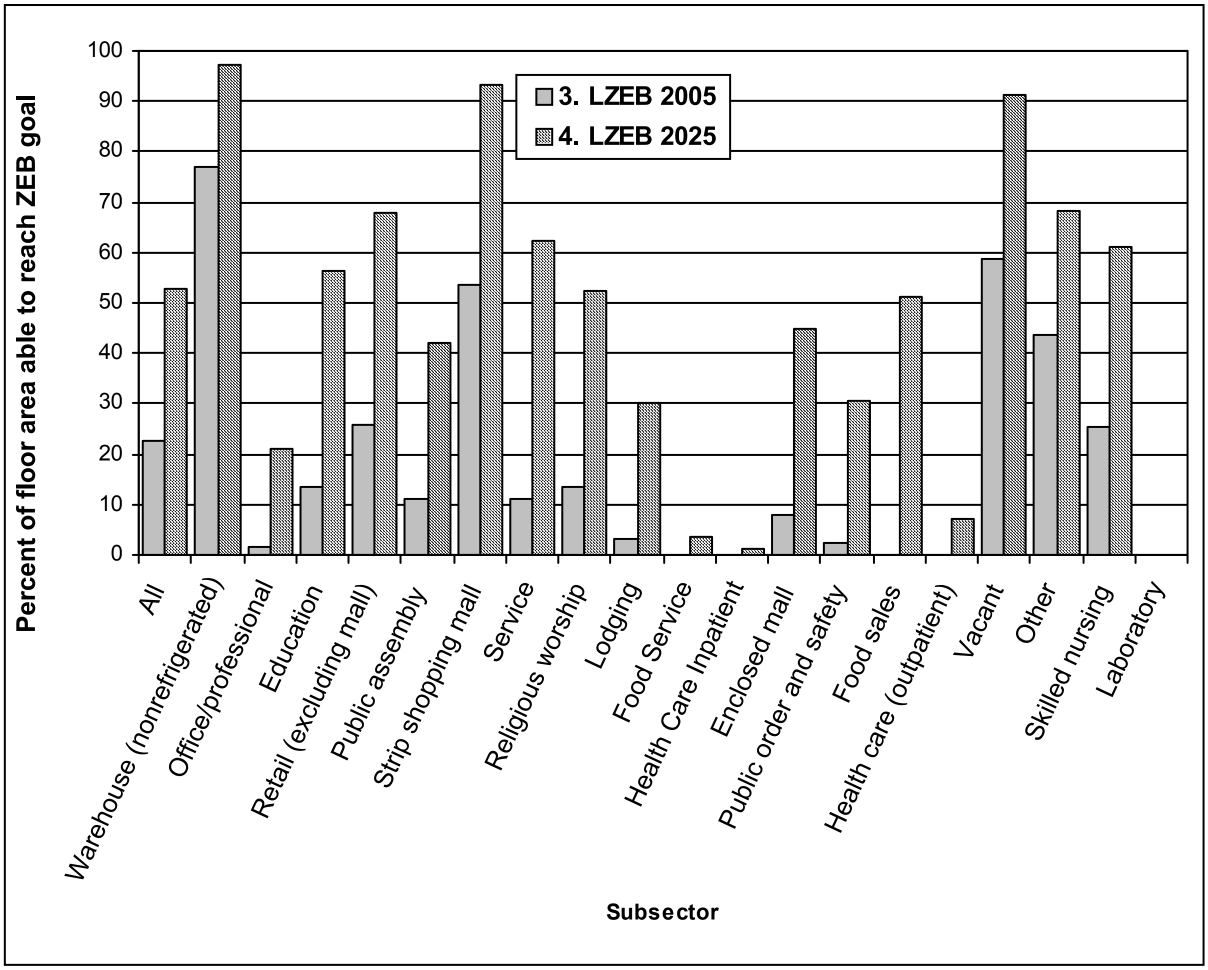
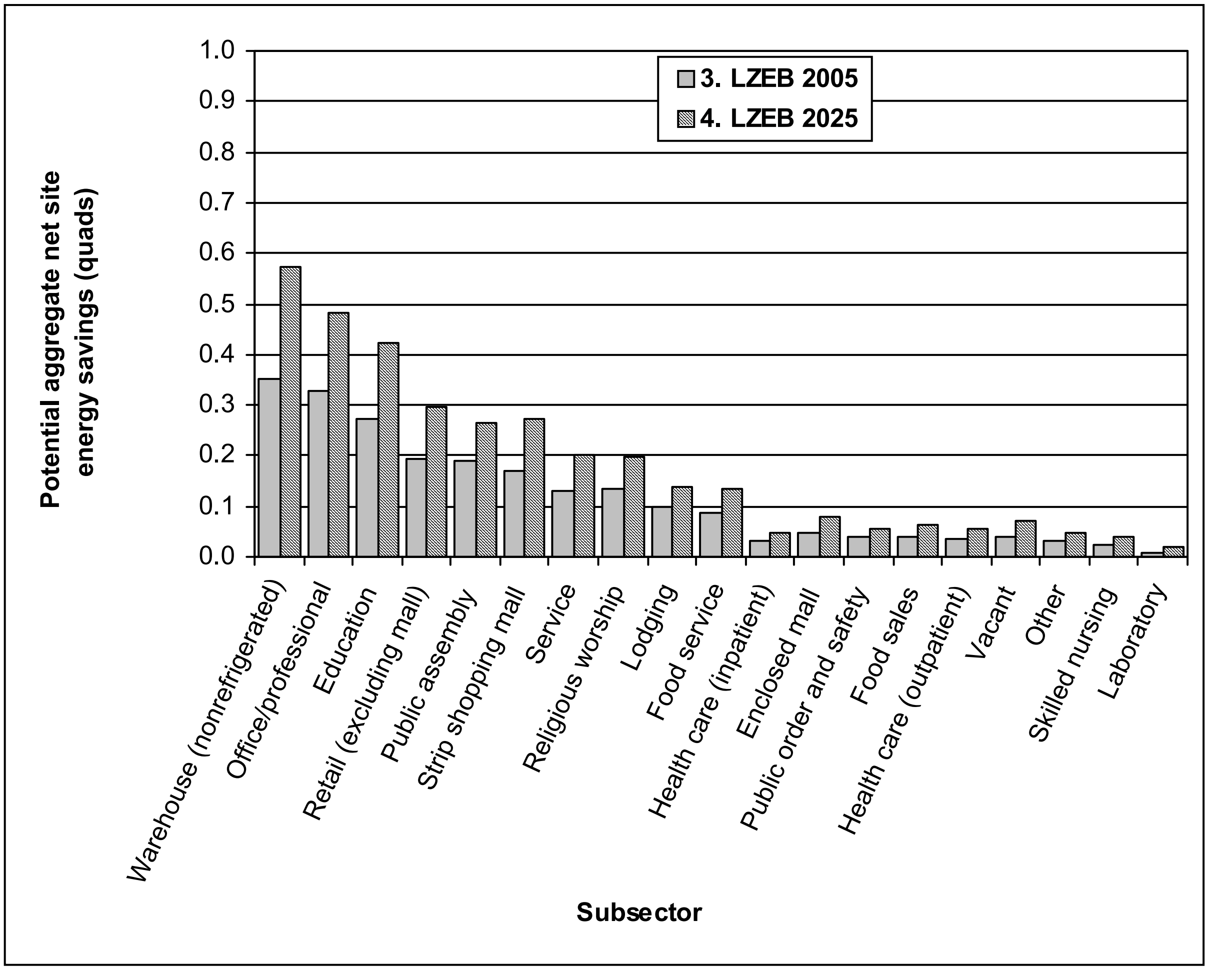


Figure 6. Aggregated Potential Net Site Energy Savings from ZEB Technologies and Practices by Subsector



Conclusions

Analyses conducted to date have led to the following conclusions and subsector priority recommendations.

The ZEB goal is technically achievable for significant portions of the commercial sector. This suggests that a ZEB goal is feasible and this goal can be used to direct research and other activities.

Efficiency measures are important for reaching the ZEB goal. The amount of energy that can be saved by efficiency improvements is comparable to the amount that can be generated by current rooftop PV panels.

A targeting strategy for selecting portions of the sector on which to focus should be developed based on two priority criteria: (1) how easily the ZEB goal can be met and (2) how much sector energy use can be reduced. The warehousing subsector offers the best opportunity for successfully meeting the ZEB goal because warehouses are often single-story buildings with low plug and process loads. Warehouses also represent the greatest opportunity for reducing energy use in aggregate. Office and professional buildings, educational, and retail buildings are the next most significant subsectors in terms of the potential for aggregated savings.

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