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Evaluation of the Energy Performance of Six High-Performance Buildings

Preprint

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Abstract
The National Renewable Energy Laboratory (NREL) monitored and evaluated the energy performance of six high-performance buildings around the United States. The six buildings were the Visitor Center at Zion National Park, the NREL Thermal Test Facility, the Chesapeake Bay Foundation's Merrill Environmental Center, the BigHorn Home Improvement Center, the Cambria Office Building, and the Oberlin College Lewis Center.

Evaluations began with extensive one-year minimum building energy use monitoring; the data were then used to calibrate energy simulation models. Actual energy savings and common lessons learned are described. These real stories can highlight what should be repeated and avoided in future buildings. The energy performance was compared among the buildings and to code-compliant, base-case buildings. Features of the buildings include good thermal envelopes, advanced glazings, Trombe walls, photovoltaic systems, daylighting, ground-source heat pumps, and passive solar design strategies. A set of performance metrics used for the evaluations is presented and discussed. The buildings saved 40%–70% compared to typical code-compliant buildings.

Introduction
The energy consumption of commercial buildings continues to increase. Because buildings consume more than 39% of the nation's primary energy and more than 70% of its electricity (EIA 2003), architects and engineers must design new buildings that use considerably less energy than typical commercial buildings. Some building owners and designers have made great strides to significantly change the way commercial buildings use energy. Some of these early adopters have documented the performance of sustainable buildings with respect to energy and identified lessons learned from their experience. Publishing performance data and lessons learned encourages others to build low-energy buildings and can help to prevent errors from being repeated.

Recently, the U.S. Department of Energy (DOE) documented the operating performance of six high-performance buildings constructed over the past decade to understand how these buildings perform with respect to their design goals (Torcellini et al. 2004). All the design teams included sustainability in their initial project goals and worked to minimize the energy and environmental impacts of their projects through design. From the onset, the owners and design teams for each building set aggressive energy saving goals ranging from 40% better than code to a net zero-energy performance. Some of the design teams also had ambitious goals for other dimensions of sustainability such as water management, building materials selection, or obtaining a high LEED™ score (USGBC 2004). All buildings have thermal envelopes that exceed ANSI/ASHRAE/IESNA Standard 90.1. In addition, daylighting, radiant heating, natural ventilation, mixed-mode ventilation, ground-source heat pumps, photovoltaic (PV), and passive solar design strategies were used. Computer simulated design tools were also used to help reach energy saving goals. Simulations were used to help guide each design—first by evaluating envelope options, then by designing mechanical systems that matched the predicted loads of the low-energy building. Each project looked at the envelope as the first method of creating low-energy buildings, and the mechanical and lighting systems should provide the remaining thermal and lighting comfort needs. Low-energy architecture is not effective if mechanical systems have to solve problems from inadequate envelopes. In other words, the mechanical and lighting systems complement the envelope (Torcellini et al. 1999, 2002).

Postoccupancy evaluations began with extensive building monitoring for at least one year; energy flows established from the measured data were used to calibrate building models for energy simulation performance. A set of common metrics was also established so comparisons could be made. *Site energy* refers to energy consumed by the building, but it does not include PV generation. *Net site energy* includes on-site generation, in other words, what the utility meter reads. *Net source energy* refers to primary energy with a conversion of 3.167 for electricity and 1.084 for natural gas (EIA 2003). Facility totals include plug loads and site lighting. Part of the analysis was creating and simulating code-compliant, base-case buildings to determine how much the buildings exceeded code. A brief description of each building follows. Complete building descriptions and detailed case studies of each building are available at http://www.highperformancebuildings.gov/case_studies/.

The Six High-Performance Buildings Case Studies

Oberlin College Lewis Center

The Adam Joseph Lewis Center for Environmental Studies at Oberlin College in Oberlin, Ohio, is a two-story, 13,600-ft^2 (1,265-m^2) classroom and laboratory building. The vision was to create a building that has the potential to be a net zero-energy building as technologies improve. The integrated building design includes daylighting to offset lighting loads, natural ventilation to offset building cooling loads, massive building materials to store passive solar gains, a ground-source heat pump system to meet the cooling and heating loads, and an energy management system. Because of the zero-energy vision, the building was designed to be all-electric, such that on-site energy could potentially offset 100% of the energy consumed. The building's roof is covered with a grid-tied, 60-kW PV array (Figure 1).

Measured annual site energy use was 29.8 kBtu/ft^2·yr (338 MJ/m^2·yr), or 47% less than the ASHRAE 90.1-2001 comparable code-compliant building for a typical meteorological year. The PV system provided 45% of the total electricity load of the building for a net site energy use of 16.4 kBtu/ft^2·yr (186 MJ/m^2·yr). The net source energy requirements of Oberlin are also very low at 39.7 kBtu/ft^2·yr (451 MJ/m^2·yr), or 77% less than the code-compliant building.

These results show that a high-performance academic building is possible in a climate that has heating loads, cooling loads, and humidity, such as in northern Ohio. A zero-energy building in this climate will be very difficult to realize, especially with on-site wastewater treatment loads. Additional PV capacity that extends beyond the footprint of the building and better control algorithms would be required to meet the zero-energy vision with today's technology.


Figure 1. Oberlin College Lewis Center

Zion National Park Visitor Center

The Visitor Center at Zion National Park in southwestern Utah exemplifies the National Park Service's commitment to promote conservation and to minimize impact on the natural environment. The building design incorporates energy-efficient features, including daylighting, natural ventilation, cooltowers, Trombe walls, solar load control with overhangs, computerized building controls, and an uninterrupted power supply (UPS) system integrated with the 7.2-kW PV system (Figure 2).

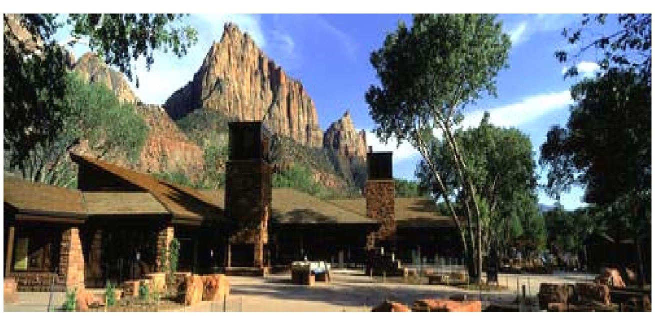


Figure 2. Zion National Park Visitor Center

The cooltowers use a wet medium at the top of a tower; cool air naturally "falls" down the tower and into the building without fans. Two fractional horsepower water pumps drive the entire cooling system. The cooltowers eliminated the need for conventional air-conditioning. Trombe walls were integrated into the envelope, providing passive solar heating without introducing light and glare into these commercial spaces. The Trombe wall supplies

20% to 40% of the annual heating, depending on the winter. Localized radiant electric heating augments passive solar heating. The heating system is controlled to purchase electricity when demand charges will not be incurred. This system eliminated all ductwork and fuel storage from the project. Because heating, ventilation, and air-conditioning (HVAC) equipment was reduced, the building was constructed for less money than a conventional visitor center.

The integrated design resulted in a building that costs $0.43/ft^2·yr ($4.63/m^2·yr) to operate and consumes 27 kBtu/ft^2·yr (307 MJ/m^2·yr). The PV system produced a net 7,900 kWh (building area normalized to 2.3 kBtu/ft^2·yr (26 MJ/m^2·yr) or 8.5% of the annual energy use.

BigHorn Home Improvement Center

The BigHorn Home Improvement Center in Silverthorne, Colorado, consists of an 18,400-ft^2 (1,710-m^2) hardware store retail area and a 24,000-ft^2 (2,230-m^2) warehouse (Figure 3). The owner was committed to minimizing energy use in his building. Natural ventilation provides all the cooling loads, which was enabled by reduced internal gains from lighting and envelope design. The lighting load is reduced by extensive use of daylighting. The retail area uses a hydronic radiant floor system with natural gas-fired boilers. An energy management system controls the lights, natural ventilation, and heating system. A transpired solar collector and gas radiant heaters heat the warehouse.

Figure 3. Bighorn Home Improvement Center

The integrated design of BigHorn yielded a source energy saving of 54%, an energy cost saving of 53% with annual energy costs of $0.43/ft^2·yr ($4.63/m^2·yr). The lighting design and daylighting reduced lighting energy use by 93% in the warehouse and 67% in the retail and office areas. The reference case is based on Standard 90.1-2001. The PV system provides 2.5% of the annual electrical energy with the highest monthly percentage of 7.3% in July 2002. The additional building cost was approximately 10% compared to conventional construction. Most of the increase in cost can be attributed to the architecture of the building; this architecture was designed to help the energy performance.

NREL Thermal Test Facility

The NREL Thermal Test Facility (TTF) in Golden, Colorado, is a 10,000-ft^2 (930-m^2) steel frame building typical of many small commercial buildings, such as professional buildings, industrial parks, and retail spaces. The building features extensive daylighting through clerestory windows, two-stage evaporative cooling, and overhangs for minimizing summer gains, T-8 lamps, instantaneous water heaters, and a well-insulated thermal envelope (Figure 4).

Figure 4. NREL Thermal Test Facility

The integrated design and energy features have resulted in an energy cost saving of 51% and a site energy saving of 42%. Daylighting provided the most significant energy savings, reducing the lighting energy use by 75%. In this dry climate, two-stage evaporative cooling provides sufficient cooling capacity for less energy than conventional cooling systems. The building was built at the same cost as a conventional building; however, an overall evaluation of the project by an independent estimator showed an approximate increase of 3.5% because of the energy features. Like BigHorn, some of these features also enhance the architecture of the building.

Cambria Office Building

The Cambria Office Building in Ebensburg, Pennsylvania, has an area of 34,500 ft^2 (3,205 m^2) and serves as the district office for Pennsylvania's Department of Environmental Protection. The design team used LEED™ 2.0 requirements and standards as design guidelines and goals. Among the low-energy design features used in this building are ground-source heat pumps, an underfloor air distribution system, heat recovery ventilators, an 18.2-kW PV system, daylighting, motion sensors, additional wall and roof insulation, and high-performance windows (Figure 5).

The integrated energy design of this all-electric building produced an energy saving of 40% and energy cost saving of 43% compared to Standard 90.1-2001. The lighting and HVAC efficiencies contributed most to the energy saving. Some daylighting was used, but the energy saving was minimal. The PV system covers about 40% of the roof and provides approximately 2.7% of the annual energy. Operational problems with the PV system have been corrected and the energy production is expected to double.

Figure 5. Cambria Office Building

Chesapeake Bay Foundation Phillip Merrill Environmental Center

The Chesapeake Bay Foundation (CBF) built the 31,000-ft^2 (2,900-m^2) Philip Merrill Environmental Center in Annapolis, Maryland, to serve as the foundation headquarters (Figure 6). Early in the design process, CBF's design team established a goal of achieving a Gold or Platinum (Version 1.0) LEED™ certification. The LEED™ certification goal had a strong influence on the building design; however, conserving the Chesapeake Bay is the organization's first priority.

Figure 6. CBF's Philip Merrill Environmental Center

CBF uses a ground-source heat pump system for heating and cooling. A glazed wall of windows on the south contributes daylight and passive solar heating. The shed roof collects rainwater for fire protection, landscape watering, and clothes and hand washing. Composting toilets also minimize water use. Operable windows are used for natural ventilation when feasible. Fans are used to augment the natural ventilation system. For the monitoring period, the total site energy use saving was 24.5%, the source energy saving was 22.1%, and the energy cost saving was 12.1%.

Lessons Learned

Many lessons were learned in the design, construction, and operation of each building to reach the stated energy performance. In some cases, information gained from building monitoring resulted in changes to the building to improve performance. Ultimately, each building broke new ground to help the future design, construction, and operation of all commercial buildings. The performance results and design goals of the six buildings are summarized in Figure 7. Even though each building is a good performer, a number of factors caused the energy performance to be lower than expected. First, design teams were too optimistic about the behavior of the occupants and their acceptance of systems. Simulations create idealistic controls—actual performance showed different set points and less setup and setback of space temperatures. Energy consumption was higher and energy production was lower than simulations predicted. In particular, daylighting was less than predicted, which meant more electrical lighting was used. Actual peak demands were often higher than predicted, resulting in increased energy costs. Insulation values are often inflated when designing the building. Thermal bridging was partially accounted for in the models during the design process, but construction details and specifications are not always installed as designed.

In the five buildings with PV systems (the TTF does not have PV), the actual PV production was less than predicted. Inverter integration problems at Cambria, Oberlin, and Bighorn resulted in unexpected downtime (Hayter et al. 2002). Continuous monitoring and identification of problems during typical operation resulted in inverter and software upgrades, improving PV system output in these cases. An automatic monitoring system for PV system operation should be installed in future low- and zero-energy buildings (LZEB). There is no way to know whether grid-tied PV systems are operating correctly without manually checking the inverter output on its display terminal. Continual manual monitoring is not practical, and a simple automated system could be put in place that alerts the building operators when the system is down. Shading of PV arrays by snow, trees, and the buildings themselves also reduced actual PV production. Understanding actual performance of PV systems during typical operation will allow for better design predictions in future LZEB.

Although PV system performance in the five buildings was lower than predicted, these systems were successful overall. The PV-integrated UPS system at Zion provided backup power for more than 40 power outages in a year and met more than 8% of the total site energy use. The Oberlin PV system met 45% of the site energy requirements and helped the building realize significant source and net site energy savings. The Bighorn PV system is a highly visible feature that enhances the company's green image.

For the five buildings with PV systems, the on-site power generation did not directly reduce monthly peak demand charges. During summer months, when peak demands are due to peak cooling loads, peak demands typically result when a cloud shades the PV array. This results in minimal PV production during periods of peak cooling loads, and the consequential peak demand charges. Peak demands can also be shifted to nighttime in daylit buildings, when PV is not available. Daylighting reduces peak daytime lighting loads, but cleaning staff may turn on all the lights at night, which can result in monthly peak demands when no PV is available. Demand responsive controls at Zion, which considers available on-site generation, historic demand levels, and loads that can be shifted, have successfully limited peak demands. In future generations of LZEB, it will be difficult to reduce peak demands with PV systems without demand responsive controls combined with on-site thermal storage, such as capacitance in the building or ice storage.

Starting at the design process, it was easier for the design team to achieve a larger percentage energy saving when concrete energy goals were established. Concrete goals not only provided targets for the design, but also provided a means for evaluating success. Oberlin has a goal of a net zero-energy building, which would result in a 100% net source energy saving; Zion, TTF, Cambria, and Bighorn all set energy cost savings design goals. In some cases, the targets were set without knowing if those targets could be achieved. Setting the goals also infers establishing the metrics. Different metrics yield different goals. A building that is successful in meeting its goal, might not fare well compared to other buildings that used other metrics for goals. As an example, CBF had a goal of building a LEED™ 1.0 Platinum building. It met this goal; however, energy was not an additional goal and although the building is a good energy performer, the energy use is greater than that of some of the other buildings. Oberlin had the most aggressive energy goal, which is evident in the results, but did not do as well in the energy cost category (which was not a part of its goals.) Goals drive projects and their establishment, and definition is critical early in the design process.

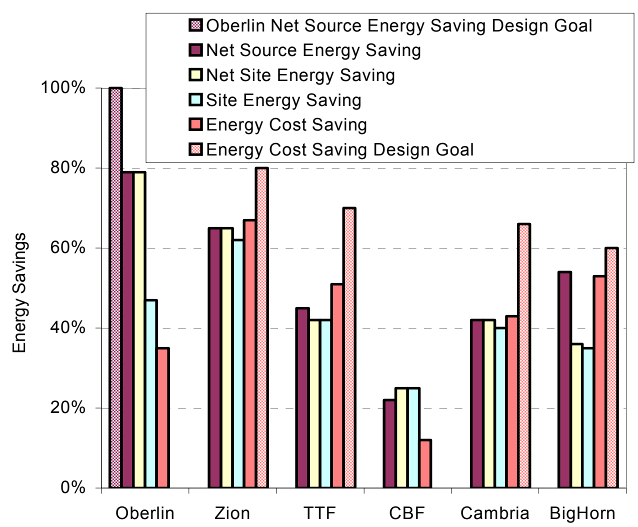
A key to all projects was using simple systems. Daylighting was accomplished with high windows and clerestories in all cases. To realize savings from daylighting, lights must be dimmed or turned off. In all six buildings, daylight sensors did not function properly and were either changed or reprogrammed to realize lighting savings. The reflectance of ceilings in daylit spaces should be greater than 80%, as darker ceilings in all cases reduced daylighting savings, especially when combined with indirect lighting. Glare from the daylighting fenestrations was also a problem in all cases. Diffusing films and light-deflecting panels have been successful at reducing glare issues without reducing daylighting savings. Central lighting controls tended to work better than distributed controls and allowed for easier commissioning and calibration. In all cases, lower lighting power densities (LPDs) were designed into the spaces. Even when the lights were on, savings were realized. Daylighting augmented the lighting, increasing the overall quality and quantity of interior illuminance. Appropriate placement and use of occupant-controlled task lighting are essential for daylit buildings with reduced LPD, especially for detailed task work. At night, the lower LPD resulted in less light. Few complaints were received, however, because people seem to adapt well to lower lighting levels at night. The concept appears to be that the time of day influences the amount of light that is required for human visual comfort.

Even though all of these buildings were commissioned prior to occupancy, commissioning did not always catch these problems. Typical commissioning primarily checks for proper individual system operation, but it does not address the optimal performance of the whole building once it is in operation. All of the buildings benefited from postoccupancy fine-tuning of system operations, resulting from building performance monitoring. Achieving and maintaining high performance require a constant effort, which is absent in most buildings.

Conclusions

All these buildings successfully saved energy because they integrated energy goals into the designs from the beginning. Use of whole-building energy simulation is a great help in setting goals, informing the design process, and evaluating the impact of design and construction decisions. It was critical that the envelope was designed first, followed by meeting remaining loads with HVAC equipment. Successful daylighting was vital to reducing lighting and HVAC loads.

Measured data from buildings provided feedback to building owners and design teams as to the success of their buildings. The monitoring results were used to compare results against the goals and identify areas that needed to be corrected to improve the energy performance. Based on good design and effective operation, buildings can be constructed that use significantly less energy than conventional buildings that are designed to meet code. Three of the buildings, Bighorn, TTF and Zion, had energy cost savings that exceeded 50%. Overall, net source energy savings among the six buildings ranged from 77% (Oberlin) to 22% (CBF). In all cases, none of the buildings could be net energy exporters within their own footprints. Even with the



Notes:

- CBF design goal was LEED certification and it reached this goal.

Figure 7. Energy Savings Summary

high-performance features of some of these buildings, additional strides must be made to achieve net zero-energy performance—that is, to create buildings that are not burdens to energy supplies. The performance of these buildings can be traced to goal setting and design processes. As with all building projects, not everything was achieved. Lessons learned from these projects, ranging from the design processes through the operation of the buildings, will help to improve all buildings.

Although all of the buildings have better than typical energy performance, none of them perform as well as predicted. The lower performance is mainly due to higher than expected occupant loads and systems not performing together in an ideal fashion. Additional research to reduce costs, better optimize control strategies, and improve reliability is needed to realize the full energy savings potential of high-performance buildings. In addition, whole-building energy simulation programs must be continually enhanced to keep pace with advances in new building energy technologies.

Performance goals are important to the design process, and different owners and teams may have different metrics for success (Deru and Torcellini 2004). However, some of the owners and design teams emphasized other dimensions of sustainable design besides energy. In general, the design teams that set the strongest energy performance goals and paid the most attention to the impact of design decisions on energy performance throughout the design had the best energy performance.

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