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Lessons Learned from Field Evaluation of Six High-Performance Buildings

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ABSTRACT

The energy performance of six high-performance buildings around the United States was monitored in detail. The six buildings include the Visitor Center at Zion National Park; the National Renewable Energy Laboratory's Thermal Test Facility, the Chesapeake Bay Foundation's Merrill Center, the BigHorn Home Improvement Center; the Cambria DEP Office Building; and the Oberlin College Lewis Center.

Evaluations began with extensive one-year minimum monitoring and were used to calibrate energy simulation models. This paper will discuss differences between the design energy targets and actual performance, common mistakes in implementing "state-of-the shelf" building technologies, commissioning experiences, policy implications, and lessons learned for future buildings. Overall, energy performance of the buildings will be compared to each other and to code compliant, base-case buildings.

The owners and design teams for each building had aggressive energy saving goals ranging from 40% to a net-zero energy performance. Some of the design teams also had ambitious goals regarding other dimensions of sustainability such as water management, building materials selection, or obtaining a high LEED™ score. The focus of this paper is on energy performance. Computer simulations were used for each building during the design process. All buildings used daylighting and good thermal envelopes as part of their high-performance features. Other high-performance features include mechanical and passive evaporative cooling, radiant heating, natural ventilation, mixed-mode ventilation, ground source heat pumps, photovoltaic, and passive solar strategies. A set of performance metrics are presented and discussed. All of the buildings used much less energy on an annualized basis than comparable code compliant buildings.

Introduction

The performance of six high-performance buildings around the United States was monitored in detail for more than a year. The short titles for each building are shown in parentheses for reference in the Lessons Learned portion of this paper. The six buildings include the Visitor Center at Zion National Park, Springdale, Utah (Zion); the National Renewable Energy Laboratory Thermal Test Facility, Golden, Colorado (TTF); the Chesapeake Bay Foundation Merrill Center, Annapolis, Maryland (CBF); the BigHorn Home Improvement Center, Silverthorne, Colorado (BigHorn); the Cambria Department of Environmental Protection Office Building, Ebensburg, Pennsylvania (Cambria); and the Oberlin College Lewis Center, Oberlin, Ohio (Oberlin).

Each building was new construction and used a design process that included a strong interest in creating low-energy buildings, including stating low-energy use as a goal in the program documents. All pieces of the building design were thought of as a single system from the onset of the conceptual design through the completion of the commissioning process [Torcellini 1999, 2002]. The design team created building envelops that minimized energy use followed by mechanical systems that complemented the load requirements for the building.

Energy flows were monitored for a minimum of one year including lighting loads, HVAC loads, and plug loads. In some cases, additional monitoring was used to further disaggregate end-loads and better understand the physics of the building. Data were tabulated every 15 minutes. The data were used to calibrate computer simulation models of the buildings. A set of common metrics was established for the analysis such that comparisons could be made. Part of analysis was creating and simulating code compliant, base-case buildings. Complete building descriptions as well as analysis techniques are available [DOE 2004].

The Six Commercial Building Case Studies

Lewis Center for Environmental Studies, Oberlin College

The Oberlin College Lewis Center for Environmental Studies is a two-story, 13,600-ft^2 classroom and laboratory building (Figure 1). The building contains four classrooms, a small auditorium, atrium, staff offices, and kitchenette. The vision for this building was to create a building that has the potential to be a net-zero-energy building either now or in the future as technologies improve. The building was funded through private donations and although cost was a concern, it was not a primary driver. The object was to promote technologies and serve as an educational tool for the Environmental Studies Program at the College.

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, an energy management system, and a system to process building waste water without sending the waste to the municipal sewage treatment plant. Because of the zero-energy vision, the building was designed to be all-electric, such that onsite energy could potentially offset 100% of the energy consumed. The building's roof is covered with a grid-tied, 60-kW photovoltaic (PV) array.

Figure 1. Oberlin South Facade Showing the PV Array on the Roof

The measured annual site energy use was 29.8 kBtu/ft^2/yr, or 47% less than the ASHRAE 90.1-2001 code compliant building for a typical meteorological year (TMY2). PV panels provided 45% of the total electric load of the building [Torcellini, 2002] for a net site energy use of 16.4 kBtu/ft^2/yr. As a point of reference, the energy use is less than half of the average Midwest educational building use of 79 kBtu/ft^2/yr [EIA 1999]. The source energy requirements of the Lewis Center are also very low at 39.7 kBtu/ft^2/yr, or 77% less than the code compliant building.

A high-performance academic building is possible in a heating dominated climate such as 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, extending beyond the footprint of the building, and better control algorithms would be required to meet the zero-energy vision.

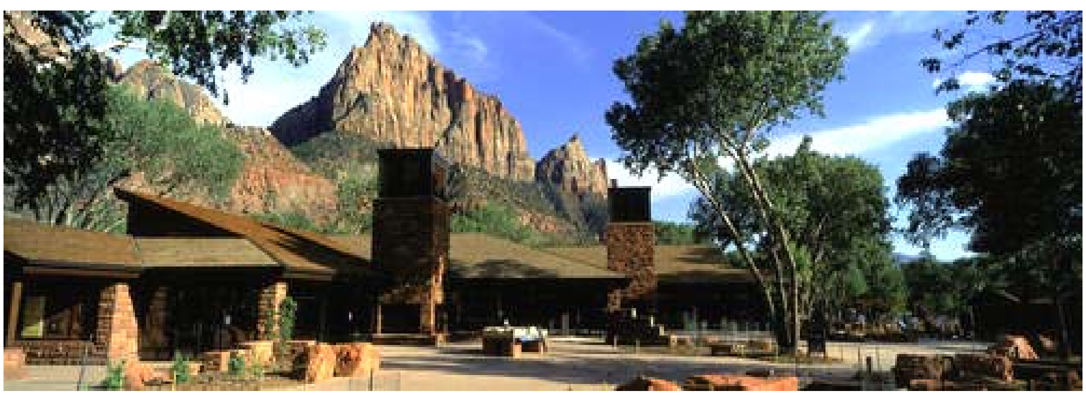
Zion Visitor Center

The Visitor Center Complex at Zion National Park (southwest 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, evaporative cooling (using passive cooltowers), passive solar heating, solar load control with engineered overhangs, computerized building controls, and an uninterrupted power supply (UPS) system integrated with the 7.2-kW PV system (Figure 2).

Two conditioned buildings were constructed: an 8,800-ft^2 main Visitor Center building that contains a retail bookstore, visitor orientation, and staff support areas; and a 2,756-ft^2 Comfort Station. Landscaping in the outdoor exhibit areas and between the buildings creates outdoor rooms, increasing the effective space available for visitor amenities.

The building's energy performance has been evaluated since it was occupied in May 2000. The integrated design resulted in a building complex that costs \$0.43/ft^2 to operate and consumes 27.0 kBtu/ft^2/yr. During the monitored year, the PV system produced a net 7,900 kWh (building normalized to 2.3 kBtu/ft^2/yr) or 8.5% of the annual energy use. The cooltowers eliminated the need for conventional air-conditioning. Localized electric heating systems augment passive solar heating. The heating system is controlled to purchase electricity for heating when demand charges will not be incurred. This system eliminated all ductwork and fuel storage from the project.

Figure 2. Zion Visitor Center North Elevation Showing Cooltowers and Plaza



BigHorn Home Improvement Center

The BigHorn Home Improvement Center consists of an 18,400-ft^2 hardware store retail area and a 24,000-ft^2 warehouse. The owner was committed to using renewable energy and a building design optimized for minimal energy use. Aggressive daylighting and smart envelope design in the retail area allow the use of natural ventilation to meet all the cooling loads. The lighting load is reduced by extensive use of natural light and switching arrangements of the fluorescent lamps. 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. The warehouse is heated by a transpired solar collector and gas radiant heaters.

Figure 3. BigHorn Home Improvement Center

The integrated design of the BigHorn Home Improvement Center produced source energy savings of 54%, energy cost savings of 53%, and annual energy costs of $0.43/ft^2/yr. The lighting design and daylighting reduced lighting energy by 93% in the warehouse and 67% in the retail and office areas. The reference case is based on ASHRAE 90.1-2001. The PV system provides 2.5% of the annual electrical energy with a highest monthly percent of 7.3% in July 2002. Operating problems with the PV system have reduced the annual performance by approximately two thirds of expected amounts.

NREL Thermal Test Facility

The NREL Thermal Test Facility is a 10,000-ft^2 building located in Golden, Colorado. The building has a steel frame structure typical of many small buildings, including professional buildings, industrial parks, and retail. The building features extensive daylighting through clerestory windows, two-stage evaporative cooling, overhangs for minimizing summer gains, T-8 lights, instantaneous hot-water heaters, and a well-insulated thermal envelope.

Figure 4. NREL Thermal Test Facility

The integrated design and energy features of the TTF have resulted in an energy cost saving of 51% and a site energy saving of 42%. The reference case was 10CFR435-1995 (Federal Energy Code) [USGVMT 1995]. Daylighting provided the most significant energy savings. The lighting design and daylight harvesting reduced lighting energy by 75%. In this dry climate, indirect/direct evaporative cooling provides sufficient cooling capacity with a better coefficient of performance than conventional cooling systems.

Cambria Office Building

The Cambria Office Building in Ebensburg, Pennsylvania, has an area of 34,500 ft^2 and serves as the district office for Pennsylvania's Department of Environmental Protection (DEP). The design team used the U.S. Green Building Council's 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 under-floor air distribution system, heat recovery ventilators, an 18.2-kW PV system, daylighting, motion sensors, additional wall and roof insulation, and high-performance windows. The DEP further reduces the impact of the building operations by purchasing 100% utility-based renewable energy. Finishes, including carpets, walls, furniture, and paints were based on recycled content and low-emissions.

Figure 5. South Facade of the Cambria Office Building

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

Chesapeake Bay Foundation Merrill Center

The Chesapeake Bay Foundation (CBF) is dedicated to restoring and protecting the resources of the Chesapeake Bay. In 2000, CBF built the 31,000-ft^2 Philip Merrill Environmental Center on 31 acres of a defunct beach club site. Its construction touched no previously undisturbed areas, maintained native landscaping, and used mostly native and recycled materials. CBF also promotes environmentally sound transportation options for its employees (showers, lockers, and bicycle storage enable people to walk, bike, or kayak to work), and provides electric, natural gas, and hybrid vehicles for errands. Videoconferencing and a telecommuting policy minimize transportation, and CBF arranges carpooling and has lunch delivered daily.

Figure 6. Photo of the Chesapeake Bay Foundation North Facade

The Merrill Center uses a ground-source heat pump system for heating and cooling. Forty-eight wells, each 300-ft deep, use the earth as a heat sink in the summer and a heat source in the winter. A glazed wall of windows facing south contributes daylight and passive solar heating. Sensors automatically turn off lights when daylighting is strong. The shed roof allows rainwater to be collected easily and used for fire protection, landscape watering, clothes and hand washing. Composting toilets also minimize water usage. Motor- and manually operated windows allow for natural ventilation. Fans are used to augment the natural ventilation system.

The performance of the Merrill Center was assessed by comparing measured performance to ASHRAE 90.1-2001. 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%. The water loop that serves the ground-source heat pumps shows higher than expected temperatures indicating HVAC efficiency is below expectations. On the second floor, lighting fixtures and controls are not harvesting daylight to its full potential.

Lessons Learned

There were many lessons learned in the design, construction, and operation of these buildings. The results of monitoring and evaluating the energy performance of the six building are shown in Table 1 and Figure 7. *Site* energy refers to energy consumption measured at the building location. *Source* energy refers to primary energy with a conversion of 3.167 for electricity and 1.084 for natural gas. These numbers were calculated from the 2002 Annual Energy Review [EIA 2003]. Numbers reported are facility totals including plug loads and site lighting. *Net site* includes on-site generation (utility meter). Table 2 presents a summary of the important lessons learned from the projects, which are divided by processes and systems.

Each building's performance was less than expected. This was due to a number of factors. First, design teams were optimistic about the behavior of the occupants and their acceptance of systems. Occupant loads (mostly plug loads) are often much higher than anticipated during the design process. There is always occupancy before or after the scheduled time. Building systems do not operate ideally and typically, simulations predict ideal operating conditions; therefore, the buildings consume more energy or generate less energy than expected. Building space temperatures are not set back as much as anticipated for the lengths of time that were expected. Insulation values are often inflated when designing the building. In the case of the TTF, the thermally broken window frames were not installed. In all cases, thermography indicated thermal leaks in the building, especially at corners and where the building hits the ground—a very difficult area to insulate. These results are similar to those found by other researchers [Branco 2004; Norford 1994].

Monitoring systems should be separate from the energy management systems. BigHorn, Cambria, CBF and Oberlin had dedicated monitoring systems. The systems in the BigHorn, CBF, and Oberlin buildings were easier to maintain and provided higher reliability than the other buildings. The goal of collecting energy performance is typically not an interest of facility personnel whose primary concern is control of the building for comfort. The system in the Cambria building was a commercially available system installed by the owner and was not reliable due to poor system design and poor maintenance. It takes an increased effort to maintain proper operation of detailed monitoring systems.

Integrating new technologies can be challenging. In all buildings, daylight sensors did not function properly with the lights and had to be either changed or reprogrammed. Success was achieved by lowering light power densities in many cases. Even though lights may be on during the day, the daylighting augments the lights to provide visual comfort. At night, the expectation is that spaces can be set to lower light levels. The concept appears to be that the time of day influences the amount of light that is required.

One issue across all the buildings was the ability to consistently define metrics for the buildings. Even with the same staff evaluating each building, determining consistency for measuring energy consumption proved difficult. Methods had to be established to define base-cases, energy consumption, and conditioned area calculations. This has become the framework for a new set of performance metrics being developed.

What to include in the energy measurements was also an issue. The energy numbers for Oberlin include the on-site wastewater treatment, which make up 23% of the total building use. CBF processes black water on-site with minimal energy. None of the other buildings accounted for wastewater treatment as it was done offsite.

In all cases, (even covering the roof with photovoltaic panels) none of the buildings can be net energy exporters within their own footprint [Hayter 2002]. The buildings all have more loads than is available with current PV technology. Even with the high performance of some of these buildings, additional strides must be made to achieve net-zero performance—that is, create buildings that are not burdens to energy supplies.

Creating energy cost goals during design, and verifying the costs are difficult due to the instability in energy prices. For example, in the case of BigHorn, natural gas prices varied up to 40% in the three-year monitoring period and the electrical prices varied widely, mainly due to new pollution regulations and a partial shift from coal to natural gas electrical production.

Getting long-term weather data for the exact building site can be a problem. Microclimates can significantly change results.

Some projects did not complete simulation throughout the design process. Although simulation was used in all projects, none created a simulation based on the construction plans. Claims were made on energy performance based on incomplete plans or, in some cases, plans that changed substantially. Caution must be exercised in comparing the initial predictions, analysis, and actual data—these numbers can vary greatly.

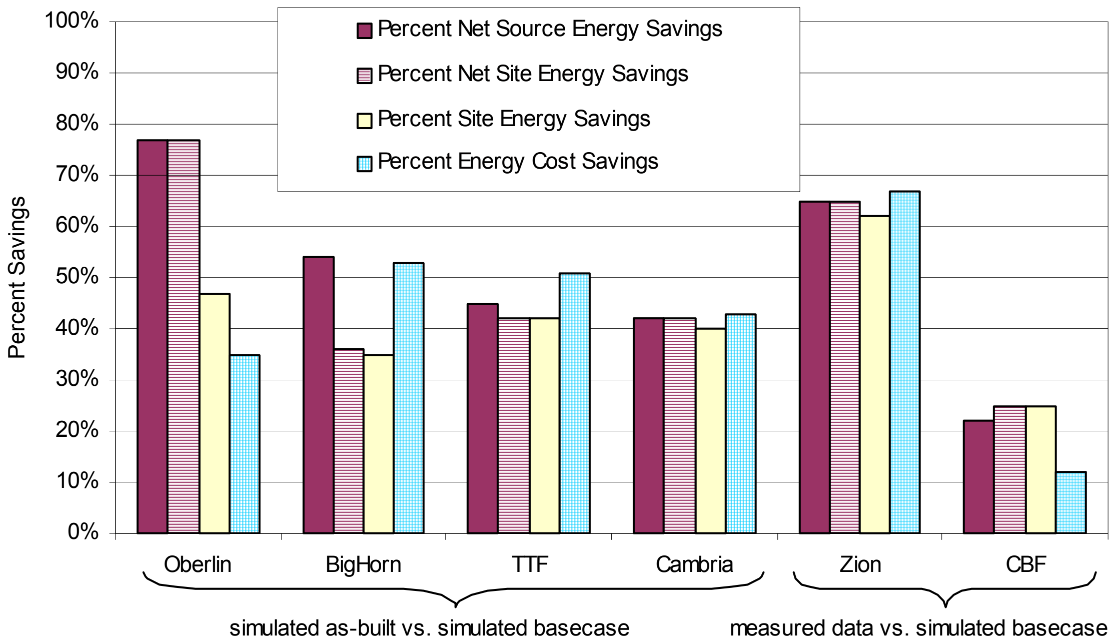
Measurable goals must be defined that can be used throughout the design process. Setting the goal can drive the project and can result in good performance against that metric. The building may not perform "well" when compared to buildings that used a different metric. For example, Zion had the largest energy cost savings in the group, and cost less to construct than a comparable code compliant building. Nevertheless, Zion is not the best performer on a source energy basis because of the use of electric resistance heat (even though it uses inexpensive off-peak electricity).

Table 1. Summary of Energy Use and Cost Performance

Metric		Oberlin	Zion	TTF[8]	CBF	Cambria	BigHorn
Benchmark	Revision of ASHRAE 90.1	2001	1999	1995[1]	2001	2001	2001
Annual Performance[9]	Energy Cost $/$ft^2$/yr	0.84	0.43	0.35	1.04	0.87	0.43
	Site Energy Consumption kBtu/ft^2/yr (kWh/ft^2/yr)	29.8 (8.7)	27.0 (7.9)	28.5 (8.4)	40.2 (11.8)	36.8 (10.8)	39.5 (11.6)
	PV Production kBtu/ft^2/yr (kWh/ft^2/yr)	13.4 (3.9)	2.3 (0.67)	0[3] 0	0.3 (0.09)	0.9 (0.26)	0.4 (0.12)
	Net Site Energy kBtu/ft^2/yr (kWh/ft^2/yr)	16.4 (4.8)	24.7 (7.2)	28.5 (8.4)	39.9 (11.7)	36.0 (10.6)	39.2 (11.5)
	Net Source Energy kBtu/ft^2/yr	53.0	80.0	65.7	124.0	116.1[7]	71.3
	Percent PV contribution to Site Energy	45%	8.5%	0%[3]	0.7%	2.7%	2.3%
Savings[10]	Percent Net Source Energy Saving	79%	65%	45%	22%	42%	54%
	Percent Net Site Energy Saving	79%	65%	42%	25%	42%	36%
	Percent Site Energy Saving	47%	62%	42%	25%	40%	35%
	Percent Energy Cost Saving	35%	67%	51%	12%	43%	53%
Actual Performance vs. Predicted Performance (goal comparisons)	Actual	Net site energy use: 16.4 kBtu/ft^2	Energy Cost Saving: 67%	Energy Cost Saving: 51%	Energy Cost Saving: 12%	Energy Cost Saving: 44%	Energy Cost Saving: 53%
	Design Goal or Predicted Performance	Net site energy use: 0.0 kBtu/ft^2	Energy Cost Saving: 80%	Energy Cost Saving: 70%[4]	Energy Cost Saving: 50%	Energy Cost Saving: 66%[6]	Energy Cost Saving: 60%[4]

Notes:
1. Code used was 10CFR435-1995 (Federal Energy Code).
2. Blank - data were not available to make calculation (not calculated).
3. No PV installed on building.
4. Goal was set on savings excluding plug loads.
5. Actual energy cost data changed tremendously over the monitoring year and these changes were not modeled.
6. The predicted energy costs were calculated prior to construction and may not be a good indicator of performance in the future because of volatile energy prices.
7. The Cambria office building purchases 100% green power (nonhydro renewable energy); therefore, the source energy was calculated assuming a 9% loss for transmission and distribution [EIA 2004].
8. TTF was only monitored for select periods. Actual data was used to calibrate simulations.
9. TTF annual performance data is based on simulations verified with actual data and run with typical weather. All other annual performance data is based on monitored performance.
10. Oberlin, BigHorn, TTF, and Cambria energy savings were calculated with simulations of as-built and basecase buildings with typical weather data. Zion and CBF savings calculated with measured data and basecase simulations run with measured weather data.

Figure 7. Summary of Building Energy Savings



Note: all bars include PV contribution except Percent Site Energy Savings.

Table 2. Summary of Key Lessons Learned

Observation	Recommendation
Design and Construction Process	
Design teams that established energy as a high priority at the outset produced buildings with better energy performance. (Zion, TTF, BigHorn, Oberlin)	Set aggressive energy goals early and follow through with all members of the design team. Impact of design and construction decisions on energy performance should be evaluated throughout the design and construction process.
Lighting Systems	
On/off switching can be disturbing to occupants. (TTF, Zion)	Control lights to minimize cycling especially on partly cloudy days. On/Off lighting works best in hallways and retail areas. It does not work as well in offices. Use dimmers if possible. Use dimmable ballasts that reduce power use relatively linearly with reduced light output.
Daylighting design resulted in less light than anticipated. (All). At Zion and Oberlin, darker than expected ceiling beams and ceilings reduced daylighting. At Zion and Bighorn, the operable windows had less glass area than as designed. At Bighorn, dark rows of merchandise absorbed the daylighting.	Coordinate with interior designers to make sure finishes and furniture reflectances are well understood and accounted for in daylighting design—white ceilings perform best. When modeling daylighting performance, make sure that glass properties are simulated correctly including reduced visible transmission because of frames, mullions and window screens, and consider the affects of exposed structural elements such as columns and beams and the eventual contents of the space.

Observation	Recommendation
Daylighting was not harvested to its full potential (Zion, Cambria, CBF) because of poor controls or control algorithms.	Make sure controls and lighting fixtures are designed to modulate electric lighting to the minimum required for visual comfort in the space. Daylighting only saves energy when it displaces electric lighting use. Occupancy, photo-sensors, and the associated control systems must be carefully calibrated and commissioned to make sure they work properly under occupied conditions. Occupants should be polled to determine if problems need to be corrected.
TTF, Zion, Bighorn used central control systems to manage lighting. Although this increased first cost, these systems were easier to program and maintain.	Too many photocells in the space can be difficult to calibrate. To eliminate these problems, we found that single photocells can often be used in large spaces to control multiple zones of lights if proper control logic is developed. System bugs must be worked out before occupancy to minimize occupant complaints.
Lower lighting power densities (LPDs) than for conventional buildings were found to be acceptable by occupants. For example, Bighorn had 36% LPD than code in the retail area, and 50% less in the warehouse. Cambria had 38% lower LPD than code. All buildings in this study were below code in LPD.	Design building for a given lighting level and not to code maximums. Use daylighting as part of the system to offset electric lighting. Less lighting is required at night and on cloudy days because of limited window glare and favorable contrast ratios. Human needs for lighting vary according to conditions in the entire visual field, not just to levels on the work surface.
HVAC Systems	
Natural ventilation systems at BigHorn, Oberlin, Zion, and CBF all required extra efforts because automated windows did not operate properly—operable windows have been an operational problem.	Consider using traditional dampers for providing natural ventilation as they are standard HVAC equipment. Product manufacturers should develop insulated dampers and robust window operating hardware with EMS interface. Control logic for natural ventilation systems needs to be carefully thought out and integrated with the control logic for other HVAC systems in the building.
Energy recovery ventilators are not always effective. Oberlin and TTF both have exhaust fans that don't allow for full heat recovery. CBF has a desiccant system that is not used because of the need to operate a boiler in the summer.	Design and balance air streams to use equipment as designed taking into account exhaust fans. This must be part of the design. Integrated control logic for innovative combinations of systems must be carefully thought out and refined once the building is occupied.
Under-floor air distribution system in Cambria had slow response times.	Plan operating strategies for smaller night set backs and longer start-up times. Restrooms and other areas without under-floor distribution may need supplemental heat.
Ground-source heat pumps in CBF showed higher than expected temperatures. In Oberlin, an electric boiler was reheating the ground loop because of erroneous control logic (resulting in selection of a wrong temperature set point) related to the integration of the ground-source heat pump system with the electric boiler.	Use detailed, short, time-response models for designing ground source heat pumps. If additional heat is added to system to meet capacities, bypass the ground loops when operating. Additional research is needed to better understand real world operation and pitfalls associated with combining innovative combinations of components or systems.
Construction and Commissioning	
Commissioning is valuable, but does not guarantee good operation of innovative systems.	Commissioning did not address the unique control logic required to obtain optimal performance from the integration of innovative systems. Commissioning created buildings that met the specifications, but this does not help when the logic behind the designs and specifications needed to be changed based on actual operations.

Observation	Recommendation
Changes made during construction affected energy performance.	TTF: slab insulation removed and exhaust damper located in the wrong place changing building airflows. Watch design changes closely and assess energy impact when changes are made.
Commissioning can be done internally or by third party agents.	As long as the work is done methodically, both provided good results in terms of making sure the building was built and operated according to plan.
Monitoring and Evaluation	
High-performance buildings often include difficult-to-model features such as cooltowers, ground-source heat pumps, natural ventilation, and complex controls.	Whole-building energy modeling programs should be continually extended to allow simulating the wide variety of innovative systems that are constantly being developed.
Dedicated monitoring systems provided better reliability than using energy management systems to collect data.	Use dedicated, self-contained monitoring equipment rather than storing data collected by EMS. Current generation EMS's have limited memory, and are designed for control, not for in-depth analysis and diagnosis. Also, many facility managers prefer to limit access to the control systems.
Robust and complete data sets improved the analysis.	Formulate a detailed monitoring plan during design. Allow for more than one year of monitoring to collect a full year of data.
Consistent metrics across buildings is difficult due to an assortment of constraints.	Metrics must be clearly defined and codified and standardized procedures to measure them established.

Conclusions

The evaluation of the six buildings presented in this paper shows that they all have better energy performance than standard practice. Three of the buildings, Oberlin, Bighorn and Zion, have a net source energy saving that exceeds 50%. Three of the buildings, Bighorn, TTF and Zion, have an energy cost saving that exceeds 50%. Overall, net source energy savings among the six buildings ranged from 77% (Oberlin) to 22% (CBF), and energy cost savings ranged from 67% (Zion) to 12% (CBF). The performance of these buildings can be traced to the setting of goals and the design process used. Each of the design teams followed a whole-building design process. This included (to a greater or lesser extent) the use of detailed building energy simulation software to help quantify goals and evaluate impacts of design alternatives.

Performance goals are an important part of the design process, and different owners and teams will necessarily have different goals [Deru 2004]. Even with the best of intentions owners goals may not be entirely congruent with the greater societal good, and it is not always easy to define what is most beneficial to society. For example, the greatest source energy savings may yield the greatest emissions reductions, but not necessarily the greatest energy cost savings. To the extent that utility rate structures are rational, minimized energy costs may be the most beneficial from the societal perspective and the individual owner's economic perspective. However, when utility rates do not account for the externalities associated with emissions and other environmental impacts, it is not possible to quantify (in building engineering terms) which is the more laudable goal.

Some of the owners and design teams emphasized other dimensions of sustainable design besides energy. These included selection of sustainable materials, architecture that expresses connectedness to the outside, innovative water management systems, and use of symbolic amounts of on-site generation. In general, the design teams that set the strongest energy performance goals and paid more attention to the impact of design decisions on energy performance throughout the design had the best energy performance. 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. In some cases, the initial automated control algorithms reflected a flawed understanding of how the innovative systems in these buildings should function together. Commissioning did not always catch these problems because it 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 of the building requires a constant effort, which is absent in most buildings. Continually tracking building performance is expensive and requires motivated, trained staff. However, advances in metering technology, computerized communications, and automated controls offers hope for the future. Additional research work 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.

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The energy performance of six high-performance buildings around the United States was monitored in detail. The six buildings include the Visitor Center at Zion National Park; the National Renewable Energy Laboratory's Thermal Test Facility; the Chesapeake Bay Foundation's Merrill Center; The BigHorn Home Improvement Center; the Cambria DEP Office Building; and the Oberlin College Lewis Center. This paper discusses the design energy targets and actual performance.

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