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BigHorn Home Improvement Center Energy Performance

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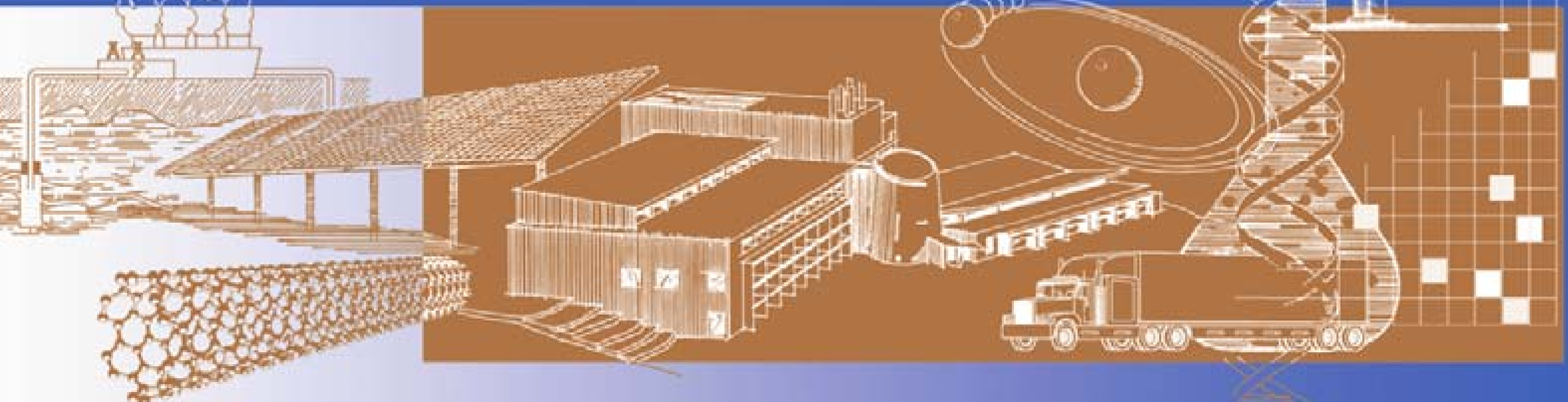

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BigHorn Home Improvement Center Energy Performance

ABSTRACT

The BigHorn Development Project, located in Silverthorne, Colorado, is one of the nation's first commercial building projects to integrate extensive high-performance design into a retail space. The BigHorn Home Improvement Center, completed in the spring of 2000, is a 42,366-ft^2 (3,936 m^2) hardware store, warehouse, and lumberyard. The authors were brought in at the design stage of the project to provide research-level guidance to apply an integrated design process and perform a postoccupancy evaluation. An aggressive energy design goal of 60% energy cost saving was set early in the process, which focused the efforts of the design team and provided a goal for measuring the success of the project. The extensive use of natural light, combined with energy-efficient electrical lighting design, provides good illumination and excellent energy savings. The reduced lighting loads, management of solar gains, and cool climate allow natural ventilation to meet the cooling loads. A hydronic radiant floor system, gas-fired radiant heaters, and a transpired solar collector deliver heat. An 8.9-kW roof-integrated photovoltaic (PV) system offsets a portion of the electricity.

After construction, the authors installed monitoring equipment to collect energy performance data and analyzed the building's energy performance for two and one-half years. The authors also helped program the building controls and provided recommendations for improving operating efficiency. The building shows an estimated 53% energy cost saving and a 54% source energy saving. These savings were determined with whole-building energy simulations that were calibrated with measured data. This paper discusses lessons learned related to the design process, the daylighting performance, the PV system, and the heating, ventilating, and air-conditioning system.

INTRODUCTION

Most builders of retail structures are concerned with creating a comfortable, inviting environment for their customers. Energy efficiency and sustainable design are usually not part of the design process. The BigHorn Home Improvement Center is an exception to this practice; it is one of the nation's first commercial buildings to integrate extensive high-performance design into a retail space (Hayter and Torcellini 2000). The project was completed in three phases. Phase I was a department store completed in February 1998. Phase II added smaller retail stores and was completed in 1999. Phase III is a 42,366-ft^2 (3,936 m^2) hardware store, warehouse, and lumberyard called the BigHorn Home Improvement Center. This final building was completed in the spring of 2000 and incorporated lessons learned from the first two phases. This paper documents the design process and the energy performance analysis of the Phase III efforts of the BigHorn Center and focuses on the energy aspects from the design phase through the first 2½ years of occupancy. The energy design process, including the energy simulation results and how they guided decision making, is described in detail. The energy monitoring system and the data recorded are described along with the performance analysis. A comprehensive set of lessons learned and recommendations is included at the end of this paper and in a detailed report on the project (Deru et al. 2005a).

The overall energy goal for this project was to design the building and its systems to save at least 60% in energy costs compared to a similar building built and operated according to the energy standards in 10 CFR 435 (FERC 1995) for lighting power densities (LPDs) and ANSI/ASHRAE/IESNA Standard 90.1-1989 (ASHRAE 1989) for all other parameters. To achieve this, a major design objective was to maximize the use of daylighting and achieve 100% daylighting under bright sky conditions. Additional design objectives included minimizing heating loads and peak electrical demand.

This paper is part of a series of six case studies to develop, document, analyze, and evaluate the processes by which highly energy-efficient buildings can be reliably produced. The following goals were established for working with the BigHorn Center:

- Achieve a 60% energy cost saving compared to a baseline building.
- Monitor and analyze the performance of the building and its subsystems for at least two years.
- Implement improvements to the building operation based on monitoring and analysis.
- Document lessons learned to improve future low-energy buildings.

BIGHORN DESIGN PROCESS

The authors were part of a multidisciplinary design team that was established to investigate innovative technologies and design strategies that were available in the market to produce an energy-efficient building. The authors were brought in at the design stage of this project to provide research-level guidance. The design team followed an integrated building design process developed from experience on previous projects. This process relies heavily on whole-building energy simulations to characterize the energy requirements, explore energy-efficient design alternatives, and analyze the as-built performance.

The design team for the Phase III building consisted of the owner/developer, building users, architect, mechanical engineer, electrical engineer, and the authors, who served as the energy consultants and design process facilitators. When the authors were approached about participating in the BigHorn project, building design was already underway.

Design Constraints

The constraints on the design process included the building program document, site restrictions, and climate variables. The building program called for a 36,980-ft^2 (3,436 m^2) building to house a hardware store and a warehouse/lumberyard building. The site dictated that the building be built with a long north-south axis, which required special consideration for solar load control and daylighting. The general look and feel of the building had to match the one that was built in the first two phases of the project and the rustic mountain character of the community. In addition, the Army Corps of Engineers restricted site development to preserve wetlands.

The climatic conditions in Silverthorne, Colorado, are different from most commercial building locations in the United States. Silverthorne is a mountain community at an elevation of 8,720 ft (2,658 m) with long winters and short summers. Based on long-term average weather data, there are 10,869 base 65°F (6,038 base 18°C) heating degree-days (HDDs) and 0 base 65°F cooling degree-days (CDDs). The average annual temperature is 35°F (2°C), and the average annual snowfall is 129 in (328 cm).

Energy Design Analysis

The authors developed an energy design process as a guideline for designing, constructing, and commissioning low-energy buildings (Hayter and Torcellini 2000). This process relies heavily on whole-building energy simulations to investigate the effectiveness of design alternatives. The energy design process is divided into three categories with ten steps. This is a recommended process—every building design evolves in different ways, so completing the process as presented may be unnecessary or impractical in some cases.

Pre-Design Steps

1. Simulate a baseline-building model and establish energy use targets.
2. Complete a parametric analysis of the baseline building.
3. Brainstorm energy-efficient solutions with all design team members.
4. Perform simulations on baseline variants and consider economic criteria.

Design Steps

5. Prepare preliminary architectural drawings.
6. Use simulations to design the heating, ventilating, and air conditioning (HVAC) and lighting systems.
7. Finalize plans and specifications, and perform simulations to ensure design targets are being met.

Construction/Occupation Steps

8. Rerun simulations of proposed construction design changes.
9. Commission all equipment and controls.
10. Educate building operators to ensure they operate the building as intended.

This process was developed during the course of working on the BigHorn Center and other projects. The steps were refined after the design was completed, so the design process used in the BigHorn project did not follow these steps exactly. All daylighting and thermal analyses in the design phase were performed with the building energy analysis program DOE-2.1E-W54 (LBNL 2003). DOE-2.1E is an hourly simulation tool designed to evaluate building system and envelope performance.

There is no Typical Meteorological Year (TMY2) weather file for Silverthorne (NREL 2004a). The closest station is in Eagle, Colorado, which is about 45 miles (72 km) away and 2,200 ft (670 m) lower in elevation. The temperature is the main difference between the two sites. Multiple weather files for the building simulations were created by modifying the Eagle, Colorado, TMY2 file. Weather file A was created to represent the long-term average conditions by adjusting the dry-bulb and dew-point temperatures in the Eagle TMY2 weather file with WeatherMaker (NREL 2001). The file was based on the 30-year average, daily high, and low temperatures as measured at a weather station near BigHorn (WRCC 2003). This weather file was used for all the design simulations and for predicting long-term energy performance of the as-built simulation models. Weather file B was created to represent the local weather conditions for the year from September 2002 through August 2003. The dry-bulb and dew-point temperature data were modified with the monthly average temperatures from the utility bills, and the solar radiation data were modified with five-minute solar data measured at a local weather station (NREL 2004b and Deru 2004).

Three main simulation models were created during the design process, with many variations of each model. In addition, two simulation models were created based on the as-built building. Table 1 lists these five models along with a description of each.

Table 1. Energy Simulation Models

Model	Description
Design Baseline	Building model based on the size and functionality of the building in the design phase and compliant with ASHRAE 90.1-1989 for the envelope and equipment and Federal Energy Code 10 CFR 435 for lighting
Original	This model was based on the original building design developed by the design team at the time the energy consultants joined the project
Optimized Design	Final building model from the design phase, including the most energy-efficient features from the design process
As-Built-Baseline	ASHRAE 90.1-2001 compliant model based on the size and functionality of the as-built building
As-Built	Calibrated model of the as-built building based on actual schedules and plug loads

Design Baseline Model

The Design Baseline Model represents a hypothetical building with the same size and function as the proposed design building. It is designed to meet the minimum requirements of the energy codes, and represents a baseline of energy performance to measure the effectiveness of the final design. The BigHorn baseline was a square two-zone building with one zone for the retail/office space and one zone for the warehouse. Equal window areas were used on all wall orientations. For this case, the energy standards were taken from ASHRAE Standard 90.1-1989 for the envelope and equipment requirements and from the Federal Energy Code 10 CFR 435 for the allowable LPDs. The LPDs in 10 CFR 435 are more restrictive than ASHRAE Standard 90.1-1989. The HVAC system was simulated as two packaged single-zone systems with economizers. Occupancy schedules were estimated with typical operation hours from a similar hardware store and expected customer density data provided by the owner. Hourly annual simulations were performed with weather file A, which represents an average weather year for Silverthorne. The results of the simulations are shown in Table 2 and Figure 1.

The Design Baseline Model is obviously dominated by the heating load, which is almost half the total building energy. The cooling load for this building can be almost entirely met by outside air economizers, which suggests that natural ventilation may meet the cooling loads. For this building with this system, the fans use a significant amount of energy to meet the ventilation needs. The high light levels in the retail area make the lighting almost one-quarter of the total. This analysis shows that reductions in the heating, fan, and lighting loads have the most energy saving potential.

Parametric Analysis of Baseline

The second step in the energy design process is to perform a series of parametric variations on the Design Baseline Model to determine which variables have the greatest impact on the building energy consumption. The parametric cases are formed by effectively removing each thermal energy path or energy source from the simulation one at a time. For example, thermal conduction through the walls is virtually eliminated by increasing the R-value to 99 $ft^2 \cdot °F \cdot hr/Btu$ (17 $m^2 \cdot K/W$). A summary of each parametric simulation follows.

- **R-99 Walls, Roof, Floor, and Windows:** Heat loss through the windows had the greatest impact on heating energy; additional insulation to the walls and roof should also be considered.
- **No Solar Gain:** Heating energy increased, which indicates that passive solar heating helps meet the building heating loads; however, glare in the retail area should be avoided.
- **No Outside Air or Infiltration:** This setting had the greatest impact on the building loads. Steps to minimize the infiltration and alternative controls for the outside air intake should be considered.
- **No Occupants:** This variation had little effect on the overall energy use.
- **No Lights:** Increased the heating energy but reduced the overall building energy use. Lighting energy should be reduced with careful design and daylighting controls.
- **No Plug Loads:** The internal equipment in a hardware store was assumed to be minimal; therefore, removing these loads had little impact on building energy requirements.

Optimized Energy Design

The third and fourth steps in the design process are to brainstorm solutions to improve the energy performance (based on the results of the parametric analysis) and to analyze the solutions with energy simulations. The design team used the Design Baseline Model as the starting point and worked to find energy-efficient solutions that fit within the physical and aesthetic design constraints. The cost implications of the variations were not explicitly part of the evaluation process; however, changes that carried a high price tag were not considered. In the end, the process of selecting the features for the final building design was based on economic, environmental, aesthetic, marketing image, and other values. Ultimately, the owner evaluated all the information when making the final decisions. Several design iterations were completed in this process.

At the time the building owner approached the authors with this project, a preliminary concept for the hardware store and warehouse/lumberyard building had been developed based on the Phase I and II building. This meant that the energy analysis was brought into the design process later than is optimal, but the owner and architect were willing to work on design alternatives to improve energy performance. This building design has a rectangular warehouse/lumberyard section along a north-south axis and a rectangular retail/office section along an east-west axis. The building included steel stud construction, high clerestory windows in the retail/office area, hydronic radiant floor heating in the retail/office area, gas-fired radiant heaters in the warehouse, and a transpired solar collector on the south wall of the warehouse. A simulation model based on the preliminary conceptual drawings was created and called the Original Model.

An annual energy simulation was completed with weather file A, which represents the "average" weather year based on long-term weather data. The energy loads in the Original Model building are dominated by the heating and lighting loads. The heating energy use is lower than that of the Design Baseline Model because of improved insulation levels, less outside air intake in the retail/office area, and increased heat gain from the lights. The lighting energy has increased because the Original Model assumes a LPD of 1.5 W/ft^2 (16 W/m^2) in the warehouse and the Design Baseline Model is limited to 0.42 W/ft^2 (4.5 W/m^2) by the 10 CFR 435 energy code. These lighting levels are high for this space because it is a retail lumberyard that requires more lighting than a warehouse that is devoted strictly to storage.

In the Design Baseline Model, the two largest loads are heating and lighting. One goal of this project was to be able to light the store with 100% daylighting under bright sky conditions, which are common for this location. To achieve this, the first change was to include dimmable luminaires and daylighting controls. Three dormer windows were added to the north side of the retail area and ridgeline skylights were added to the warehouse because there was not enough light in the retail area and the warehouse. In addition, the wall insulation values in the design were changed to work with the exterior finish systems. All these changes are summarized as Design Variation #1:

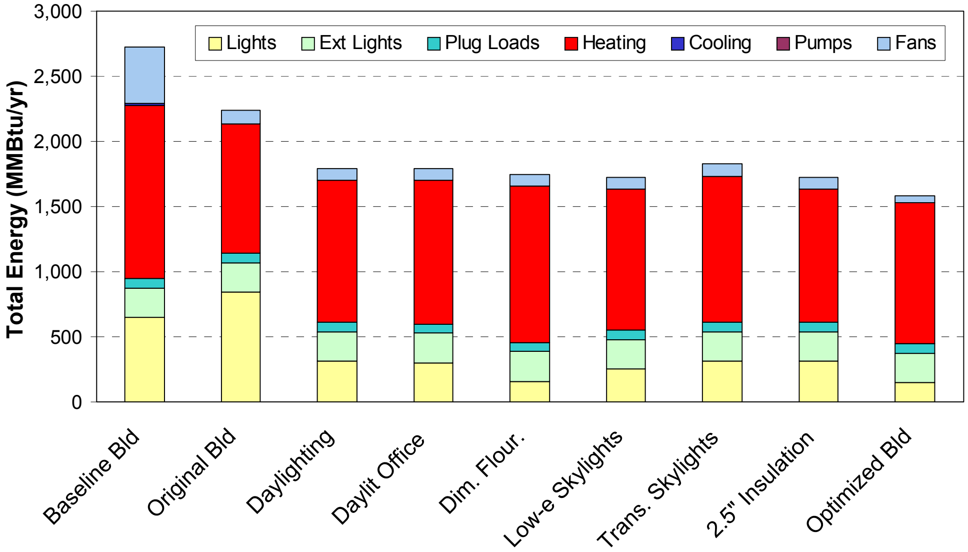
Additional variations were explored to investigate other energy efficiency opportunities, which are listed in Table 2. The remaining variations included the changes made in Design Variation #1. The design changes focused on increasing the natural lighting in the spaces, investigating the use of natural ventilation, and reducing envelope loads. Variations 2 and 3 were mini-studies that consisted of numerous runs with different HVAC systems and simulation periods to optimize the overhang length and natural ventilation. The energy totals cannot be directly compared to the other variations; however, the building design changes can be carried over to the final design.

The predicted total energy consumption of all the simulations is listed in Table 2 and shown graphically with end uses in Figure 1. The most effective reduction in total energy comes from the Optimized Model, which shows a 42% energy saving compared to the Design Baseline Model.

Table 2. Total Energy Consumption for Design Variations

Variation	Model Description	Total Energy MMBtu/yr *(GJ/yr)*	Energy Use Intensity kBtu/ft2·yr *(MJ/m2·yr)*	Improvement over Design Baseline Model
	Design Baseline	2,722 *(2,872)*	73.5 *(835)*	
	Original	2,241 *(2,364)*	60.6 *(688)*	18%
1	Daylighting	1,791 *(1,890)*	48.4 *(550)*	34%
2	Optimal clerestory overhangs	not calculated		
3	Natural ventilation	not calculated		
4	Daylighting in First Floor Office Space	1,789 *(1,887)*	48.4 *(550)*	34%
5	Dimmable Fluorescent Lamps	1,747 *(1,843)*	47.2 *(536)*	36%
6	Low-E Warehouse Skylights	1,722 *(1,817)*	46.6 *(529)*	37%
7	Insulated Translucent Warehouse Skylights	1,826 *(1,926)*	49.4 *(561)*	33%
8	Added 2.5-in. Wall Insulation	1,721 *(1,816)*	46.5 *(528)*	37%
9	Optimized (variations 1-6, 8)	1,586 *(1,673)*	42.9 *(487)*	42%

Figure 1. Total Energy Consumption for the Models Listed in Table 2



The Optimized Model uses 77% less energy for lighting than the Design Baseline Model and 82% less lighting energy than the Original Model. The annual energy costs were calculated with expected utility rate structures for natural gas and electricity service. The Optimized Model produced a 41% energy cost saving compared to the code compliant Design Baseline Model, with annual cost for the Design Baseline at $29,960 and the Optimized Model's at $17,652.

Several recommendations from the energy design process were made to improve the energy efficiency and operability of the building. Some, like the thermal and lighting parameters, resulted directly from the energy simulations. Other recommendations could not be simulated in DOE-2 and were based on engineering judgment and experience. Economics or other design changes prevented some recommendations from being included in the building.

CONSTRUCTION AND COMMISSIONING

Construction on the Phase III building of the BigHorn Center began on June 9, 1999 and was completed on April 15, 2000. The total project cost, excluding the land, was $5.2 million ($116/ft^2 or $1,250/m^2) and included the main building, storage sheds for lumber, and parking lots. The energy-efficient features and PV system added approximately 10% to the total cost.

There was no definite separation between the design and construction phases of the BigHorn Center. The building and systems wre modified throughout the construction process, which is common for small buildings. The major advantage of this process is the ability to improve the design as the building comes together with new ideas or new technologies. There are two main potential disadvantages. First, the changes are often not documented properly, which can lead to incomplete building plans and disagreements between the owner and contractors about what was decided. Second, the impact of the changes on building performance is often not fully analyzed.

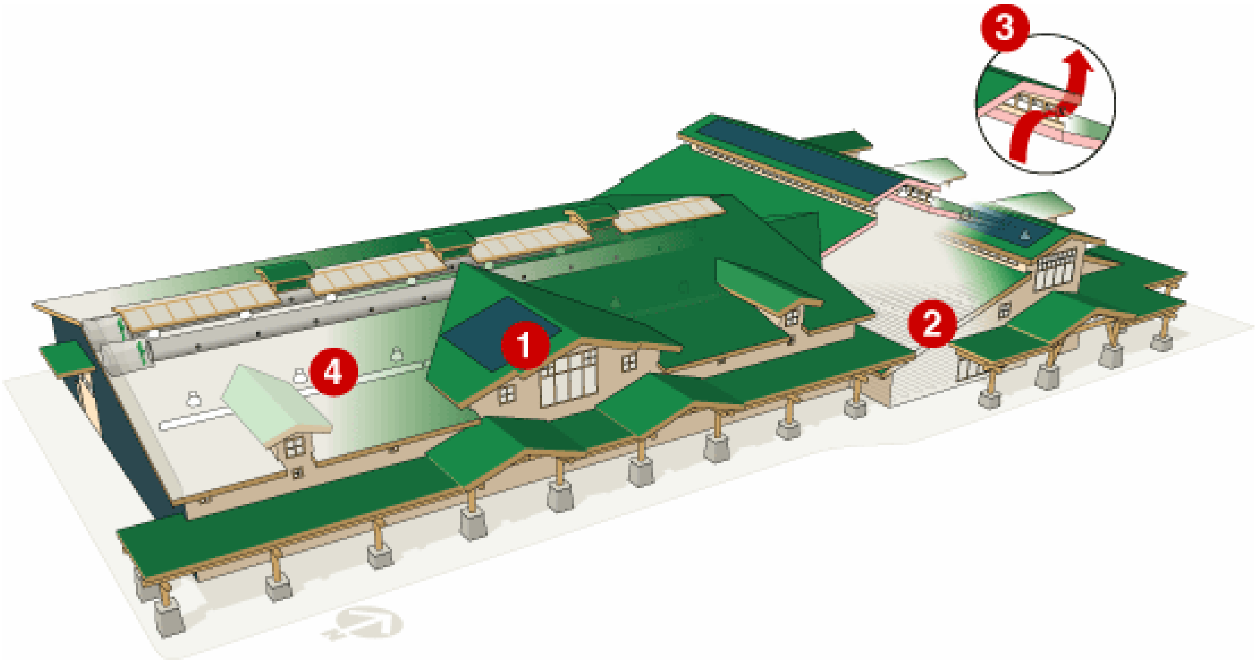
The BigHorn Center was commissioned by the contractors. This process worked well because the owner had a good working relationship with the contractors; however, some problems resulted from disagreements over decisions made during the construction that were not fully documented.

BIGHORN CENTER DESCRIPTION

The BigHorn Center features numerous energy-saving innovations. The building envelope is well insulated to reduce the heating load, which is the primary energy load because of the cold winters and cool summers. The extensive use of natural light, combined with energy-efficient electrical lighting design, provides good illumination and excellent energy savings. The reduced lighting loads, management of solar gains, and cool climate allow natural ventilation to meet the cooling loads. A hydronic radiant floor system, gas-fired radiant heaters, and a transpired solar collector deliver heat. An 8.9-kW roof-integrated PV system offsets electrical energy consumption. In addition, on-site wetland areas were expanded and used to develop the stormwater management plan. The environmental design is in keeping with the developer's commitment to green buildings.

An illustration of the BigHorn Home Improvement Center with some of the energy efficiency features is shown in Figure 2. The 18,396 ft^2 (1,709 m^2) retail/office space is on the right of the figure with a long east-west axis, and the 23,970 ft^2 (2,227 m^2) warehouse/lumber yard is on the left side of the figure with a long north-south axis. The retail space and warehouse are single-story open interior floor plans. Most of the office space is on a second floor mezzanine. More information on this building is listed in the DOE High-Performance Building Database (DOE 2005).

Figure 2. **Illustration of the layout and some of the energy features of the BigHorn Home Improvement Center (1) PV panels, (2) radiant floor heating, (3) natural ventilation, and (4) daylighting**



EVALUATION PROCEDURES

The energy performance of the BigHorn Center was evaluated by continuous detailed end-use monitoring, utility bill analysis, walk-through inspections of the building, spot measurements, and computer simulations. This section describes the monitoring plan and equipment, results, and comparison to simulated baseline predictions. Guidance for monitoring and reporting the energy performance of commercial buildings can be found in the *Procedure for Measuring and Reporting Commercial Building Energy Performance* (Barley et al. 2005).

Performance Monitoring Plan

The overall goal of the energy monitoring analysis was to measure and evaluate the building energy use patterns. This goal was broken down into the following objectives for the energy-monitoring plan:

1. Evaluate the whole-building energy performance and compare this with the design expectations.
2. Analyze the monthly electrical demand and cost profiles.
3. Evaluate the lighting system performance, including the effects of daylighting.
4. Evaluate the PV system performance.
5. Compare the building energy performance to a code-compliant baseline.
6. Generate a list of lessons learned to apply to other buildings.

To satisfy these objectives, a data-monitoring plan was developed and the following measurements were taken:

1. Surveys of electrical equipment in the building, including spot measurements of power or current
2. Monthly building utility bills for natural gas and electricity
3. Total electrical energy at 15-minute increments
4. Electrical energy use of major end uses at 15-minute increments
5. Electrical energy delivered to the building by the PV system in 15-minute increments
6. Temperature and flow of the radiant floor water loop
7. Solar radiation incident on the PV system and temperature of the PV cells.

A data acquisition system (DAS) was designed to monitor all the data points. The monitoring equipment for the electrical end use measurements consisted of current transformers (CTs) and watt-hour transducers. Five additional measurements were recorded through the data logger. The sensors for the PV cell temperature and the PV solar radiation were mounted on one of the PV panels above the clerestory and were taken to verify the performance of the PV system. The temperature and flow of the hot water for the radiant floor heating system were measured to estimate the amount of heat that goes into the floor.

The expected accuracy of the sensors used in the monitoring system is determined from product specifications. Individual electricity measurements are ±0.5% based on manufacturer's data. Some of the values are summations or subtractions of individual measurements, but the errors are assumed to be independent and do not increase the level of uncertainty. Based on the expected uncertainty of the energy use measurements and the long-term reliability of the DAS, we expected the uncertainty of the annual performance metrics based on measured energy use to be ±1%.

MEASURED PERFORMANCE AND EVALUATION

The net and total annual energy use for the facility are shown in Table 3 for site and source energy. *Site* refers to the energy consumed at the location, which is equivalent to the energy measured by the utility meters. The *source* energy refers to the energy used to generate and deliver the energy to the building. The conversion factors for energy measured at the site to source energy are 1.084 for natural gas and 3.167 for electricity (EIA 2003). *Facility* refers to the energy consumed in the building and the exterior lights, and *Building* refers to the energy consumed in the building, including the roof ice melt but not the exterior lights. The building and facility energy use intensities (EUIs) are listed at the bottom of Table 3 for site and source energy.

Total electrical energy consumption increased by 16% from the first year to the second, and gas consumption decreased by 24%. The reasons for these changes are discussed below. Overall, site energy consumption decreased by 14%, but energy costs increased slightly because of higher gas and electricity costs. Higher electricity costs are due to increased consumption, higher monthly peak demands, and higher rate charges.

A monthly view of the data is presented in Figure 3, which shows the daily average source energy consumption by major end use from February 2001 to August 2003. The energy produced by the PV system is also shown as a line graph. The PV energy production was adjusted to reflect the amount of source energy that was offset by producing and using the PV energy onsite.

The total energy consumption in Figure 3 shows a strong seasonal correlation. The increase in the winter is caused by the high heating loads, higher lighting loads caused by the reduced number of daylight hours, and the snow and ice melt systems. The heating energy consumption is a combination of the gas use taken from the utility bills plus pump energy for the hydronic heating system and fan energy for the transpired solar collector. The heating load approaches zero in summer months and has shown a general decrease over the monitoring period. Table 3 shows a 24% decrease in the gas energy use from the 2001–2002 winter to the 2002–2003 winter. This decrease is mostly due to the introduction of a dry fire-protection system in the warehouse in March 2002. Before this change, the warehouse was kept warmer than 40°F (4.4°C) to ensure that all pipes remained above freezing. A second reason for the reduced gas use was the reduced use of the sidewalk snowmelt system, which was not effective and was phased out during the 2001–2002 winter. Finally, the 2002–2003 winter was slightly warmer than the 2001–2002 winter, with 5% fewer HDDs.

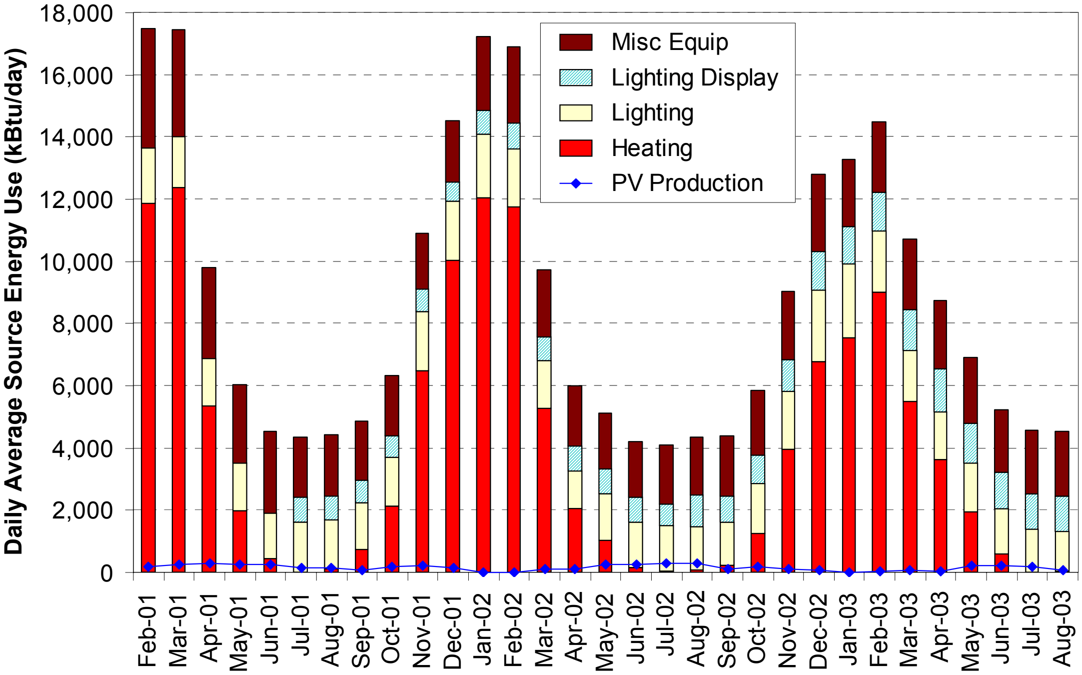
The lighting loads in Figure 3 consist of all the interior ambient lights and exterior lights. The lighting display is monitored separately, and the limited accent lighting loads are monitored with the miscellaneous loads. There is a slight increase in the total lighting load from the first year to the second year. Table 3 shows that the retail/office area lighting energy decreased by 16.5 MMBtu because the daylighting controls were fine tuned, and a higher number of the light bulbs burned out after the first year of operation. The warehouse lighting energy increased by 16 MMBtu and the exterior lighting energy increased by 11.5 MMBtu. These increases are mainly due to the changes in the cleaning process that left more lights on for longer periods. The lighting display load increased by more than 50% from the first monitoring year to the second as more lighting fixtures were added to the display.

The miscellaneous loads include items noted in Table 3. The display lighting load was included in the miscellaneous loads from February 2001 to June 2001. The miscellaneous loads increased during the winter by approximately 20%, which is mainly due to the roof ice melt and the two electric space heaters. There has been a slight increase in the miscellaneous loads during the monitoring period because more plug loads and accent lighting were added.

Table 3. Measured Annual Energy Totals by End Use

End Use	Site Energy		Source Energy	
	9/1/2001–8/31/2002	**9/1/2002–8/31/2003**	**9/1/2001–8/31/2002**	**9/1/2002–8/31/2003**
	(MMBtu) ***(GJ)***	**(MMBtu)** ***(GJ)***	**(MMBtu)** ***(GJ)***	**(MMBtu)** ***(GJ)***
Heating (gas)	1,410 *(1,488)*	1,075 *(1,134)*	1,528 *(1,613)*	1,166 *(1,230)*
Pumps	19.9 *(21.0)*	20.1 *(21.2)*	63.0 *(66.5)*	63.6 *(67.1)*
Solar Wall Fan	1.2 *(1.3)*	0.8 *(0.8)*	3.7 *(3.9)*	2.6 *(2.7)*
Retail Lights	150.6 *(158.9)*	134.1 *(141.5)*	477.0 *(503)*	424.7 *(448.1)*
Warehouse Lights	12.6 *(13.3)*	28.6 *(30.2)*	39.8 *(42.0)*	90.6 *(95.6)*
Lighting Display	88.7 *(93.6)*	134.2 *(141.6)*	267.5 *(282.2)*	424.8 *(448.2)*
Forklift	10.9 *(11.5)*	9.9 *(10.4)*	34.6 *(36.5)*	31.4 *(33.1)*
Miscellaneous Loads	218.6 *(230.6)*	238.1 *(251.2)*	692.3 *(730.3)*	754.1 *(795.6)*
Exterior Lights	22.8 *(24.1)*	33.3 *(35.1)*	72.2 *(76.2)*	105.4 *(111.2)*
Total Electric Energy	525 *(554)*	599 *(632)*	1,663 *(1,754)*	1,896 *(2,000)*
Total Building Energy Use	1,912 *(2,018)*	1,641 *(1,731)*	3,119 *(3,291)*	2,956 *(3,119)*
Total Facility Energy Use	1,935 *(2,042)*	1,674 *(1,766)*	3,192 *(3,367)*	3,062 *(3,230)*
PV Energy Production	19 *(20)*	13 *(14)*	60 *(63)*	41 *(43)*
Total Building EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	45 *(512)*	39 *(439)*	74 *(836)*	70 *(793)*
Total Facility EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	46 *(519)*	40 *(449)*	75 *(855)*	72 *(821)*
Net Building EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	45 *(508)*	38 *(436)*	72 *(820)*	69 *(781)*
Net Facility EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	45 *(513)*	39 *(445)*	74 *(839)*	71 *(810)*

Figure 3. Daily average source energy consumption by end use for the BigHorn Center (monitoring of the lighting display began in July 2001)



Energy Cost Analysis

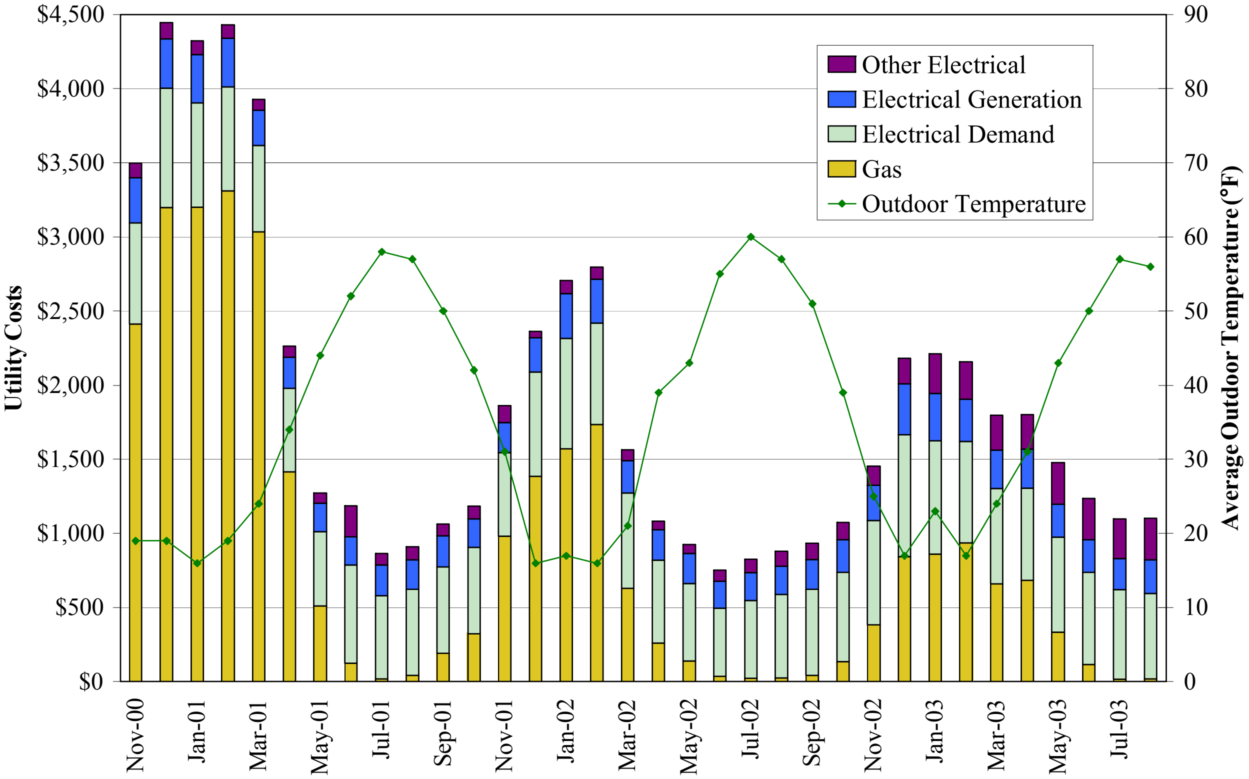
The utility company for gas and electric service is Xcel Energy. Its rate structures are summarized in Table 4. The charges for electricity consist of a fixed charge, an energy rate charge, a demand charge, two to four energy rate charge adjustments, a franchise fee, and sales tax. All the charges remained fixed during the monitoring period except for the energy rate charge adjustments, which varied from month to month. Energy rate adjustments doubled the total electrical energy rate charge from the beginning to the end of the monitoring period; however, the electrical demand charge did not change. The energy rate adjustment charges are included to account for such things as changes in primary fuel costs and air quality improvement costs.

Table 4. Summary of Utility Charges

Category	Actual Costs throughout Monitoring	Costs Used in As-Built Simulations
Natural Gas		
Total Rate Charge ($/therm) *($/GJ)*	$0.34546−$0.85546 *($3.27−$8.11)*	$0.59 *($5.59)*
Metering and Billing	$15.35− $17.29	$15.35
Franchise Fee (% of subtotal)	3.0%	
Sales Tax (% of total)	7.65%	
Electricity		
Service and Facility Charge	$15.30	$15.30
Total Rate Charge ($/kWh)	$0.01455−$0.03004	$0.01645
Demand Charge ($/kW)	$12.55	$12.55
Franchise Fee (% of subtotal)	3.0%	
Sales Tax (% of total)	7.65%	

The monthly energy costs from the utility bills from November 2000 to August 2003 are shown in Figure 4. This graph shows the breakout of the energy charges and the average monthly outdoor temperature. The gas costs were very high during the first winter because consumption and prices were high. The cost of electricity was dominated by the demand charge, which was more than half the electrical utility bill. The "Other Electrical" category includes the fixed monthly charge, energy rate adjustments, fees, and taxes. The increase in this value over the last nine months was due to increases in the energy rate adjustments.

Figure 4. BigHorn Center monthly utility costs



An analysis of the electricity costs was undertaken to determine relative costs, understand the impacts of the demand charges, and determine potential cost saving measures. The electrical demand charges and associated taxes constitute a significant part (59%−80%) of the monthly electricity bills. The demand charge, including taxes, is $13.92/kW based on the maximum 15-minute integrated kilowatt demand used during the billing month.

The impact of demand charges on electricity costs was examined by estimating the electrical energy cost by end use from the 15-minute data. The demand charges were divided among the end uses by determining their fraction of the total load at the time of the monthly peak demand. Highly variable loads can have high energy costs if the peak use period coincides with the building peak demand for the month. An examination of the peak demand days revealed that the peak demand typically occurs under one of four scenarios:

1. During normal business hours in the winter after the sun sets and most of the interior and some exterior lights automatically come on
2. During normal business hours when dark clouds cover the sun and more interior lights come on
3. After store hours when the cleaning crew turns on most of the interior and exterior lights
4. The electric forklift is plugged in for charging when the power draw is already high, which sometimes occurs at the same time as one of the first two scenarios.

In the first two scenarios, little can be done to reduce the demand because the lights are required for normal business operation. Fortunately, these have the smallest peak demand. The third scenario is preventable with some training of the cleaning crew to avoid turning on all the lights at the same time; however, this requires retraining with each new crew. The fourth scenario is preventable by charging the forklift at night. However, this requires a timer on the charging station circuit or someone to come in late at night after the exterior lights are turned off.

The electrical power profiles for typical peak demand days during the summer and winter are shown in Figure 5 and Figure 6. These figures show the average power drawn every 15 minutes. The heavy black line is the purchased electrical power. When this line is below the top of the graph, the PV system provided some of the building electrical load. In Figure 5, the PV system provided some power during the day; however, the PV system was operating on only one of three inverters on this day. In Figure 6, the PV system was not operational.

Figure 5. Electrical power profile on the peak demand day in July 2003

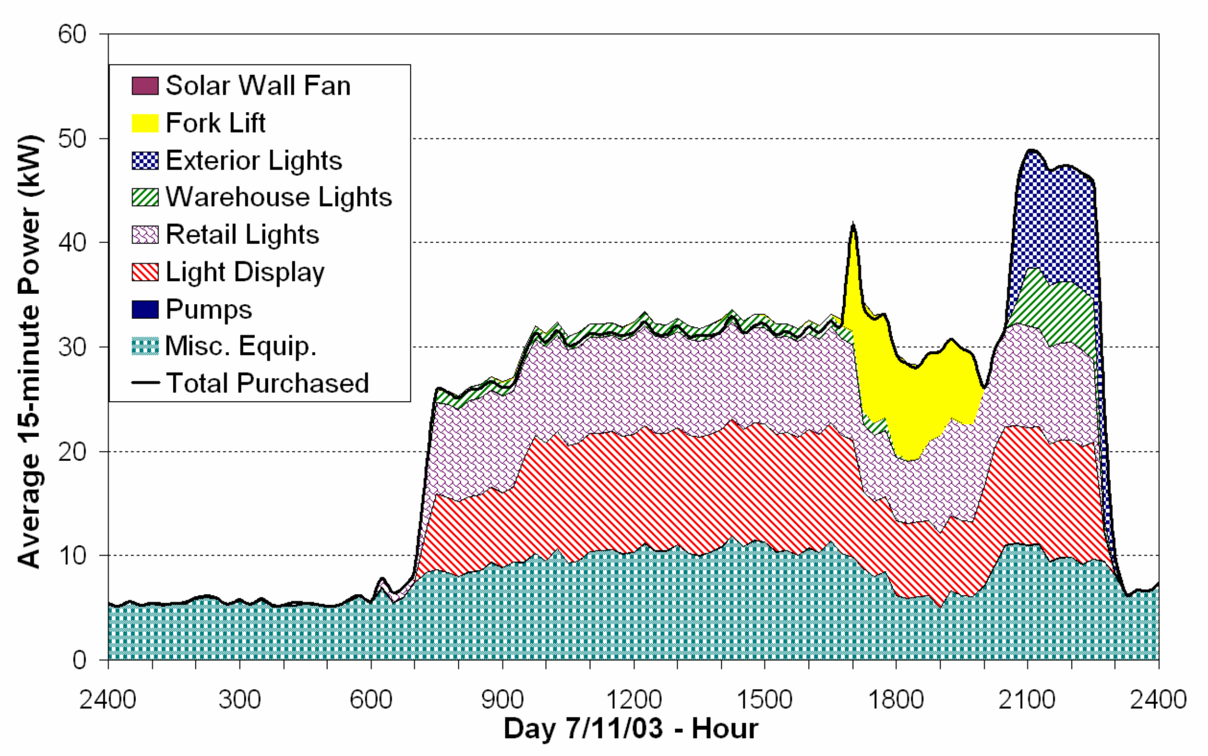
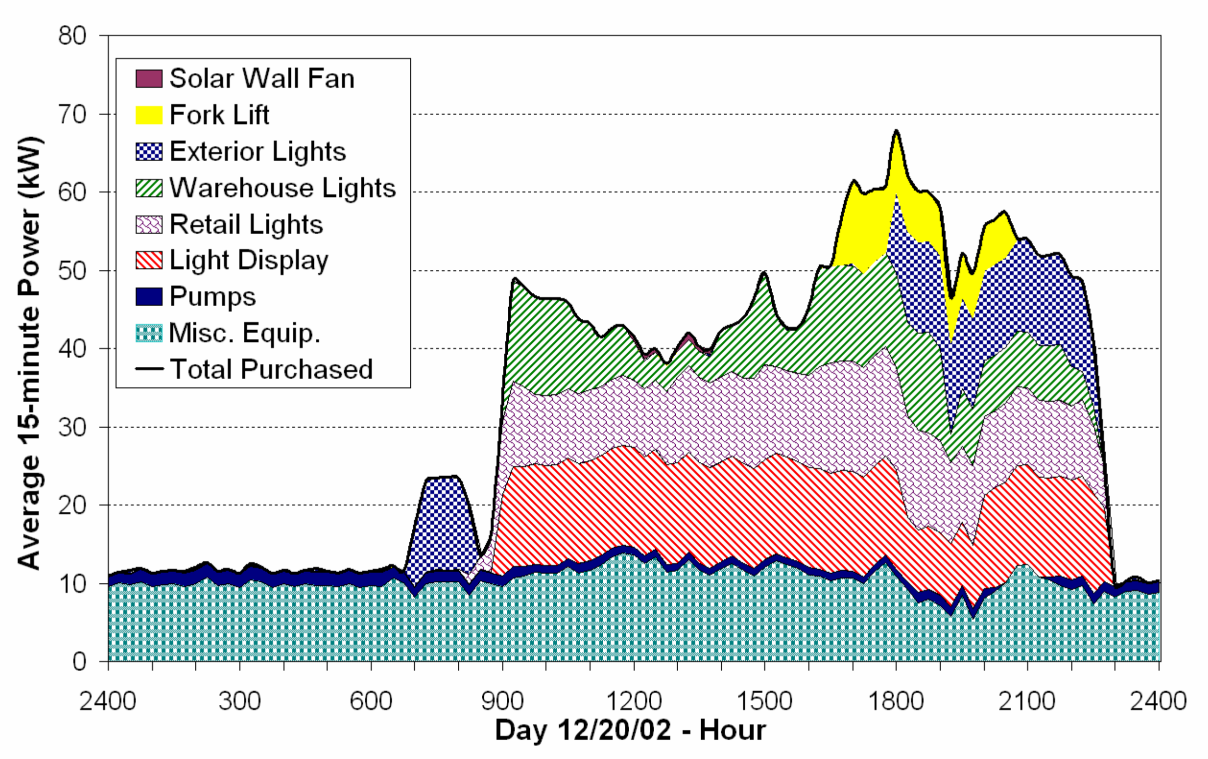


Figure 6. Electrical power profile on the peak demand day in December 2002



The peak demand in Figure 5 occurred after the store was closed. The cleaning crew came in and turned most of the lights on, including the entire lighting display. Earlier in the day, the forklift was plugged in for charging right before closing time, which raised the power draw by nearly 10 kW but still allowed it to remain below peak. The peak demand in Figure 6 occurred when the exterior lights came on at the end of the day while the interior lights were still on and the forklift was charging.

Figure 5 also shows the effect of the daylighting controls on the warehouse lighting load, which was lower in the middle of the day when more daylight was available. The retail lights show a small bump in the morning and an increase in the early evening as it became darker outside.

One way to compare the costs of operating loads is to look at the effective energy charge, which is the total energy cost divided by the total energy use. This comparison was made annually for each load. The miscellaneous loads, pumps, and retail lights have low effective energy charges; the forklift, exterior lights, and warehouse lights have very high effective energy charges. For comparison, the base electrical energy charge, including taxes, varied each month from a low of $0.01613/kWh to a high of $0.0333/kWh during the two-year monitoring period.

The electric forklift had the highest effective energy charge. It cost more than $0.48/kWh from September 1, 2001 to August 31, 2002 and almost $0.26/kWh from September 1, 2002 to August 31, 2003. This cost is high because charging the forklift contributed to the monthly peak demand in 10 of 12 months for the first monitoring period and 7 of 12 months in the second monitoring period. If the forklift had been charged at night and had not incurred demand charges, the annual energy costs would have been $57 and $76 for the 2 monitoring periods. One method of estimating the savings is to subtract these energy costs from the actual costs for the forklift. This method results in a total saving of $2,170.31 for the two-year period. However, this is not the correct method of calculating the saving, because the new monthly peak demand would not simply be the measured demand minus the forklift power. The new monthly peak demand would shift to the next lowest peak demand with a different mixture of loads. Because charging the forklift does not affect other loads in the building, all the data can be reexamined without the forklift load and the new peak demands determined. We performed this analysis and demonstrated an estimated saving of $1,600 for the two-year period by charging the forklift during off-peak hours.

The third scenario that caused the peak demand was due to the number of lights turned on by the cleaning crew. If only half the display lights and half the retail lights had been turned on during cleaning, an additional $360 would have been saved.

Whole-Building Energy Simulation Analysis

Whole-building energy simulations formed a significant part of the design process for this building. They were also instrumental in evaluating the energy performance of the building after construction. We completed energy simulations of the as-built building to better understand the energy performance and compare it to the design predictions. The simulations of the as-built building were conducted with the same simulation program and version as used in the design process (DOE-2.1E - W54).

Development of As-Built Simulation Models

Two simulation models of the as-built building were created (see Table 1 for a summary of the main simulation models used in this project):

- An As-Built Baseline Model was developed that reflects the size and functionality of the as-built building, but it was created to just match the thermal efficiency requirements of ASHRAE Standard 90.1-2001 (ASHRAE 2001). This model was created according to the guidelines of Addendum e to ASHRAE 90.1-2001.
- An As-Built Model was created to accurately reflect the building and was calibrated against the measured building energy data with measured weather data.

The thermal and system parameters for the two models are listed in Table 5.

Table 5. Thermal Parameters of the As-Built Baseline and As-Built Models

Component	As-Built Baseline	As-Built
Wall R-Value (ft^2·°F·hr/Btu) *(m^2·K/W)*	16.0 *(2.8)*	23 *(4.0)* (lower) 16 *(2.8)* (upper)
Window U-Value (Btu/ft^2·°F·hr) *(W/m^2·K)*	0.51 *(2.9)*	0.30 / 0.24* *(1.7 / 1.4)*
Window Solar Heat Gain Coefficient	0.21	0.75 / 0.44
Floor Perimeter Insulation (ft^2·°F·hr/Btu) *(m^2·K/W)*	13.0 *(2.3)*	13.0 *(2.3)*
Floor Center Insulation for the Retail/Office Space (ft^2·°F·hr/Btu) *(m^2·K/W)*	0.0	10.0 *(1.8)*
Roof R-Value (ft^2·°F·hr/Btu) *(m^2·K/W)*	23.0 *(4.0)*	38.0 *(6.7)*
Retail/Office Infiltration – occ/unocc (ACH)	0.5 / 0.3	0.5 / 0.3
Warehouse Infiltration – occ/unocc (ACH)	5.25 / 1.0	5.25 / 1.0
Retail/office LPD (W/ft^2) *(W/m^2)*	1.62 *(0.15)*	1.13 *(0.10)*
Lighting Display (kW)	12.0	12.0
Warehouse LPD (W/ft^2) *(W/m^2)*	1.2 *(0.11)*	0.638 *(0.06)*
Retail/office Plug Load Power (kW)	9.0	9.0
Warehouse Plug Load Power (kW)	15.0	15.0
Daylighting Controls	No	Yes
Retail HVAC System **	PSZ w/ Econ	FPH
Mezzanine ***	-	RESYS
Warehouse HVAC System **	PSZ w/ Econ	UVT

* Window properties in the As-Built Model are listed for the view windows/clerestory and dormer windows

** PSZ = Packaged Single Zone system, FPH = Floor Panel Heating system, UVT = Unit Ventilator

*** RESYS = Residential System (split air conditioning/heating system with a natural ventilation option) modeled in the mezzanine to simulate natural ventilation

To improve the validity of the simulation results, we carefully examined the two models to verify the input details against the construction and operation of the as-built building. The first step in this verification process was to perform a walkthrough of the building to ensure the plans reflected actual conditions. The plug loads, lighting display, and exterior lights were scheduled to match the measured energy consumption data as closely as possible for the calibration period. The LPDs of the interior lighting systems were set to match the peak-measured values. The operating schedules were set to match the measured energy data as closely as possible. The store operation is consistent from day to day; therefore, matching the simulation schedule to the store schedule is relatively easy. The cleaning schedule is not the same every week; therefore, an average schedule was created that best matched the annual totals for the interior and exterior lights.

The heating and ventilating systems in the As-Built Model were designed to match the real building as closely as possible. The boiler capacities and efficiencies for the retail/office heating system were matched to the existing system. The Panel Loss Ratio in the Floor Panel Heating system is the ratio of the panel heat losses to the panel heat output and was assumed to be 0.3 for the retail space, 0.25 for the office space, and 0.5 for the break room. The warehouse heating system was approximated as a Unit Ventilator system. The heat input to the unit ventilator in the warehouse was modeled as electricity and then converted to gas consumption and assumes a burner efficiency of 90%. This approach was taken to separate the gas consumption in the warehouse from the gas consumption in the retail area. The maximum infiltration for the retail/office area was set to 0.5 air changes per hour (ACH) and the maximum for the warehouse was set to 4.0 ACH to simulate one overhead door open.

Next, the As-Built Model was calibrated against the measured energy consumption with a TMY2 weather file for Eagle, Colorado, modified to match weather conditions from September 2002 to August 2003 (weather file B). The modifications were made with monthly temperature data from the utility bills and hourly solar radiation data from a weather station at a similar altitude as Silverthorne but on the other side of the continental divide.

First, the electric loads were calibrated against the measured electricity data. The three largest electrical loads are the ambient lighting, lighting display, and miscellaneous equipment. The schedules were adjusted to closely match the monthly totals. The annual totals from the simulation for these loads were 1.3% lower, 0.3% higher, and 2.1% lower than the measured loads. The total electricity consumption of the As-Built Model was 1.8% lower than measured total energy consumption.

Next, the gas consumption was calibrated with the monthly totals from the utility bills. This was difficult because only the monthly total natural gas for the building is known, and the split between the warehouse and the retail/office area is not known. In addition, the operating conditions and thermostat schedules change occasionally depending on the needs and desires of the building occupants. The warehouse is operated as a drive-in loading space, and at least one overhead door is always open during store operating hours. The radiant gas heaters are operated to keep the space warmer than 37°F (3°C). This operation is difficult to model because the air exchange with the outdoors is unknown. However, the low temperature set point in the warehouse makes it possible to find months when the heating load in the warehouse is small. The largest unknown in the model of the retail/office space heating system is the Panel Loss Ratio; therefore, this value was altered to best match the measured data. The Panel Loss Ratios that best matched the monthly data were 0.05 for the retail and office space and 0.1 for the break room. Next, the maximum infiltration for the warehouse was changed to find the best match for every month of the year. The best fit of the data was found with the maximum warehouse infiltration set to 5.25 ACH. Because of the high flow rates from open doors, measuring the ACH was not feasible. The annual total gas use from the As-Built Model was 4.8% lower than the total from the utility bills. A look at the month-by-month comparison shows a good match for most months. Excluding January, the simulated results are only 0.03% lower than the utility bills. January had some operational differences that were unknown and we were unable to account for them in the model.

Performance from Simulation Models

After the two simulation models were calibrated, they were run with a weather file based on the long-term average weather conditions to show the performance and savings for an average weather year. The annual site energy consumption by end use for the two building models is shown in Figure 7 and Table 6. The net site energy saving was 36% and the net source energy saving was 54%, which includes the measured energy production from the PV system for September 2002 to August 2003. The energy cost saving was 53%, which does not include the PV system because this cannot be modeled in DOE-2. The energy cost must be included in the simulation to properly account for the effect of the PV system on the demand. The simulation predicted that the average monthly peak electrical demand would be reduced by 59% from 124 kW for the As-Built Baseline Model to 50 kW for the As-Built Model. The reduction in annual peak demand is mainly due to the elimination of the HVAC fans and the reduction in the lighting power. The energy cost data were calculated with the utility rate structure as of August 2003, which is summarized in Table 4.

The source energy savings are much greater than the site energy savings because the mix of electrical and gas energy consumption is different in the two building models. The As-Built Baseline Model has much higher energy consumption because of the lights and fans than the As-Built Model, and the As-Built Model has much higher gas consumption. In the As-Built Baseline Model, 68% of the site energy consumption is electricity; in the As-Built Model, the electricity consumption is only 34% of the total.

Figure 7. Simulated annual site energy consumption for the As-Built Baseline Model and As-Built Model with an average year weather file

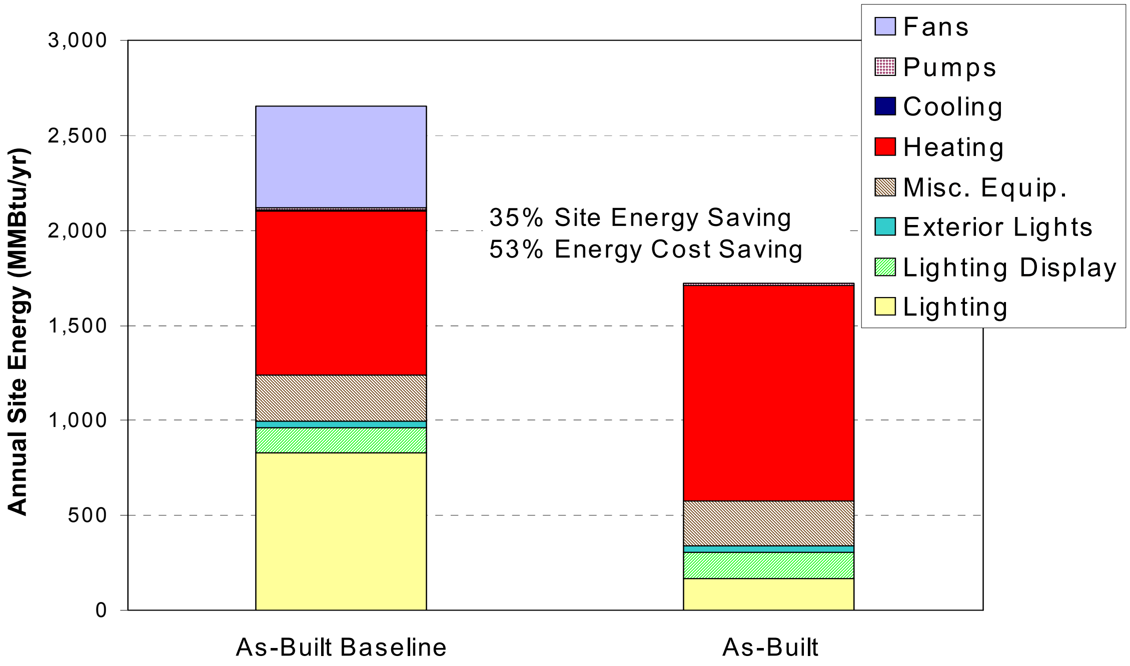


Table 6. Annual Facility Energy Use from the As-Built Simulations (end use numbers are for site energy use)

Performance Metric	As-Built Baseline	As-Built	% Saving
Lighting – MMBtu *(GJ)*	830 *(876)*	168 *(177)*	80%
Lighting Display – MMBtu *(GJ)*	135 *(142)*	135 *(142)*	0%
Exterior Lights – MMBtu *(GJ)*	35 *(37)*	35 *(37)*	0%
Miscellaneous Equipment – MMBtu *(GJ)*	241 *(254)*	241 *(254)*	0%
Heating – MMBtu *(GJ)*	861 *(908)*	1,130 *(1,192)*	-31%
Cooling – MMBtu *(GJ)*	9 *(9)*	0 *(0)*	100%
Pumps – MMBtu *(GJ)*	11 *(12)*	15 *(16)*	-41%
Fans – MMBtu *(GJ)*	532 *(541)*	0 *(0)*	100%
HVAC Total – MMBtu *(GJ)*	1,413 *(1,491)*	1,145 *(1,208)*	19%
Average Monthly Peak Demand (kW)	124	50	59%
Total Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	62.6 *(711)*	40.7 *(462)*	35%
Net Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	62.6 *(711)*	40.3 *(458)*	36%
Total Source EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	155.9 *(1,770)*	73.3 *(832)*	53%
Net Source EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	155.9 *(1,770)*	72.1 *(819)*	54%
Total Energy Cost Intensity – \$/ft^2·yr *(\$/m^2·yr)*	\$1.08 *(\$11.63)*	\$0.51 *(\$5.49)*	53%
Retail Only: Total Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	79.7 *(905)*	60.2 *(684)*	24%
Warehouse Only: Total Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	48.0 *(545)*	24.2 *(275)*	50%

The energy use patterns for the retail/office and warehouse spaces are very different, and the simulation models allow us to look at the spaces separately. The energy supplied by the PV system was divided between the two spaces based on their percentage of the facility electrical energy total.

The retail/office space shows an annual site energy saving of 24% and a source energy saving of 44%. The energy saving comes from a reduction in the lights and from the elimination of the fans and cooling load. The heating energy in the As-Built Model is more than double the value for the As-Built Baseline Model. The increased heating load is mainly due to lower heat gains from the lights and fans. The source energy saving in the retail/office space is much larger than the site energy saving because gas is used more efficiently than electric lights and fans to heat the building.

The warehouse has a 50% site energy saving and a 79% source energy saving. The energy saving comes mainly from the reduction in the lighting loads and the elimination of the fans. The warehouse heating energy in the As-Built Model is approximately the same as the As-Built Baseline Model. This result may seem counterintuitive to the results from the retail/office space. There are two main reasons for the difference: (1) because of the low heating set point, the required heating load is very small and much of the heat gain from the additional lights and fans in the baseline building warms the space above the heating set point; and (2) the transpired solar collector adds a small amount of useful heat to the space through the warm air delivered to the space and by conducting heat from the hot air space through the wall into the warehouse.

Another potentially large energy saving can be attributed to the addition of the carbon monoxide (CO) sensor controls on the roof-mounted exhaust fans. The original building design called for continuous operation of these fans during occupied periods; however, the CO sensors were installed and these fans have come on only once.

Lighting and Daylighting Evaluation Results

We evaluated the lighting systems at BigHorn to determine the energy savings and the illuminance quality. The *Procedure to Measure Indoor Lighting Energy Performance* provides performance metrics for evaluating lighting design, including daylighting (Deru et al. 2005b). In addition, illuminance measurements were taken in the retail area using a modification of the International Energy Agency protocol established under Daylight in Buildings Task 21 (Atif et al. 1997). The goals of the monitoring plan were to:

1. Measure the energy consumption by the lighting systems.
2. Determine the energy savings that result from the lighting design without daylighting controls.
3. Determine the amount of electric lighting offset by daylighting and the energy saved in lighting.
4. Analyze the operation of the lighting design and optimize its performance.
5. Quantitatively assess the quality of the lighting and daylighting designs.
6. Document the successes and weakness of the lighting design.

The lighting systems represent a significant fraction of the energy use in the BigHorn Center and an even greater percentage of the energy costs. For the September 2002 to August 2003 period, the lighting systems accounted for 29% of the electrical energy use, 36% of the electrical energy cost, and 26% of the total energy cost. These numbers do not include the lighting display energy use, which is treated as a plug load in this analysis.

In general, the natural lighting in the winter is higher because the lower sun angle allows better daylight penetration through the clerestory windows. The winter daylight levels provide most of the lighting needs during the day. There are some glare problems in the space at certain times of the day. The morning sun through the large east window produces high illuminance levels, which can cause glare problems in the center of the store. There are also short periods of direct sun through the clerestory windows on the north side during the winter. This direct beam can also cause minor glare problems for customers when they look at products.

The measured LPDs provide another view of the energy use patterns in the building. The normal operation of the retail area uses less than half the installed capacity and measured peak is 16% less than the installed capacity. The warehouse uses less than 10% of the installed capacity most of the time. The measured peak in both spaces is lower than the installed capacity because not all of the lights are turned on at once and there are always a few burned out light bulbs. Burned out bulbs have been a significant problem in the retail area, where an estimated 10% of the bulbs can be out of service at any given time.

The Lighting Design Energy Saving results from the design of the lighting design only with no occupancy or daylighting controls. They compare the maximum LPD allowed by code to the installed LPD. For this case, ASHRAE Standard 90.1-2001 was used to determine the maximum allowable LPDs. Table 7 presents the LPDs and savings for the retail/office area and warehouse. The retail/office area LPD for ASHRAE 90.1 was calculated as the area weighted average of the LPDs of each space in the retail and office areas. The installed LPD includes two sets of luminaires added to the retail area after construction, but it does not include the area or the lights in the lighting display area.

Table 7. Lighting Design Energy Savings

Space	ASHRAE 90.1 W/ft^2 *(W/m^2)*	Installed W/ft^2 *(W/m^2)*	Saving
Retail/Office Area	1.63 *(17.5)*	1.25 *(13.5)*	23%
Warehouse	1.20 *(12.9)*	0.79 *(8.5)*	34%
Whole Building	1.39 *(15.0)*	1.00 *(10.8)*	28%

The Lighting Energy Savings represents the actual energy savings and includes the savings that result from the occupancy controls and the daylighting controls. It can be calculated by two methods. The first method compares the measured lighting energy use to what would be expected by using the allowable LPDs according to the energy code and the operating schedule. This approach has the advantage that it uses measured data, but the disadvantage is that the accuracy of the expected energy use is based on an approximation of the annual operating schedule. The second method of calculating the energy savings is from the calibrated whole-building energy simulations of the As-Built Baseline Model and the As-Built Model. This approach has the advantage of using the same operating schedule, but the simulation may not represent the as-built conditions exactly. The measured energy use is from September 1, 2003 to August 31, 2003. The savings predicted by both methods are similar, because the simulations were closely aligned with the energy code and the as-built building. Using the measured energy data, the Lighting Energy Saving for the retail area was 69%, the Lighting Energy Saving for the warehouse was 93%, and the whole-building Lighting Energy Saving was 81%.

Photovoltaic System Evaluation Results

The 8.9-kW PV system is divided into three arrays, each of which has a dedicated inverter connected to each of the three phases of the building electrical distribution system. The system was evaluated to determine the energy it produced, its effect on the building purchased electrical energy, and its performance. The *Procedure for Measuring and Reporting the Performance of Photovoltaic Systems in Buildings* (Pless et al. 2005) provides guidance on evaluating the performance of PV systems in the built environment. Additional measurements were taken for a more detailed evaluation of the system performance. The goals of the monitoring plan were to:

1. Measure the delivered AC energy production by the PV system.
2. Determine the percentage of the building electrical energy consumption offset by the PV system.
3. Determine building electrical demand offset by the PV system and the energy cost savings.
4. Determine the performance of the PV system compared to the expected performance.

A number of problems have caused the performance of the PV system to be sporadic. The seasonal variation in the output of the PV system is highly variable. The winter production is generally poor because of the shorter days, the lower incidence angle of the solar radiation, occasional snow cover on the PV arrays, and several problems with system operation. The highest percentage of the monthly facility electrical load met was 7.3% in July 2002, and the lowest was 0.0% in January 2002 and 2003.

The energy cost saving from the PV system operation is very small. This is mainly due to the utility rate structure and the operation of the building. During the two monitoring years, our measurements show that the PV system reduced the monthly peak demand in only two of the months and only for a total of 3 kW. Most of the energy from the PV system is produced when the building's incremental energy cost is \$0.02–\$0.03/kWh. The building peak demands usually occur in the late afternoons and early evenings when the PV system is at low production or off. The PV system was not fully functional during the monitoring period, and the output of the system would have been about 2–3 times the measured value if the system had operated correctly. If the system were fully operational, the energy cost savings would probably be 3–4 times more, assuming slightly more peak demand would be offset by the PV system.

From the initial operation of the PV system, energy production was lower than expected. The poor performance was believed to be caused by issues with the inverters and several problems with the circuitry connecting the PV system to the building electrical bus. Most of the problems stem from the fact that the inverters were not designed to operate in a grid-tied system; therefore, they required additional circuitry and did not have maximum power point tracking ability. These problems caused the system to have a lower than optimal output and caused the system to go off line frequently, which required manual restarts.

Space Conditioning System Evaluation Results

The space conditioning systems are not typical of commercial buildings because there is no cooling system, no ventilation system, and the heating systems are radiant. The cooling loads are met by natural ventilation, and the ventilation requirements is easily satisfied by infiltration when the windows are closed. Because there is no cooling system and no need for ventilation air, there was no need for a duct system in the retail/office area. Eliminating the ductwork freed up the interior space for improved daylighting and provided a cleaner looking interior. The heating system for the warehouse and retail/office areas is the largest energy end use. It consumes 40% of the annual building source energy; in the winter, it can exceed 60% of the monthly source energy.

Even though there are zero CDDs base 65°F (18°C), there is still a cooling load on days when the afternoon outdoor temperature exceeds 80°F (27°C). The CDD calculation is based on the daily average temperature (not the hourly temperature), so a large diurnal temperature swing can be misleading. Energy simulations of the Design Baseline Model showed that the building needed mechanical cooling for 160 hours over the year. The remaining cooling load was met by economizer operation. The Optimized Model has lower internal gains from the lights, which allowed all the cooling loads to be met by natural ventilation.

Natural ventilation is initiated by the energy management system (EMS), which opens the north-facing clerestory windows based on the internal and external temperatures. In addition, doors are manually opened in the front, back, and side connections to the warehouse. For most days, this system works well; however, there are some exceptions. On the few very warm days per year (5–10 days near 90°F [32°C]), the mezzanine temperature approaches 80°F (27°C), and portable fans are used to improve occupant comfort. An opposite problem in this mountain location is that the outside air can cool off quickly, which can produce drafts of cold air on the mezzanine occupants sitting below the clerestory windows. The thermostat, which is at the same level as the window openings and controls the windows, does not immediately sense this cold air. In this case, the windows must be closed by overriding the EMS control scheme.

The designers decided on the hydronic radiant floor system for the retail/office area because of (1) the reduced noise from the elimination of the fans, (2) the improved comfort from the warm floor, and (3) the ability to have multiple zones within one large open space for better heating control. The main disadvantage of this type of system is that it has a slow response time and nighttime setbacks are often not used. The hot water is provided by four natural gas boilers with a 442 kBtu/hr (130 kW) output and an overall rated efficiency of 85%. This system was designed to provide hot water for the retail/office area and the sidewalk snowmelt system. Using boilers with an efficiency of 92% would save approximately $250 per year for heating the retail/office area, which is only a little more than 1% of the total annual utility costs.

The primary heating system for the warehouse comprises gas-fired radiant heaters. The warehouse is used as a drive-through lumberyard with at least one overhead door open during business hours. Because of this, the space has minimal space conditioning. The temperature is maintained just above freezing in the winter and there is no need for cooling in the summer. Some heat is supplied to the space by the transpired solar collector when there is adequate solar gain on the collector. This system provides warm air through fabric ducts mounted high in the space. Transpired solar collectors are most effective in spaces that need large amounts of ventilation. However, the BigHorn warehouse does not need ventilation because an overhead door is usually open. The low temperature warm air delivered by the transpired solar collector does not effectively heat this space when the door is open. For the September 2002–August 2003 monitoring year, the transpired solar collector fans ran only about one-third of the days in the heating season for two to three hours in the middle of the day.

CONCLUSIONS

The authors worked with the owners of the BigHorn Center to improve the design of their facility by using a whole-building approach that uses energy performance simulation to look at the way the building's site, walls, floors, electrical, and mechanical systems work together most efficiently. The operation of the building systems was verified to ensure that they were operating as designed; however, occupant behavior and operating conditions could not always be anticipated. Careful monitoring of operating performance led to fine-tuning system operations to improve the performance. Maintaining a high level of performance has required a consistent effort by the operating staff, who have been alerted to specific issues with the lighting and heating systems.

The estimated performance of the BigHorn Home Improvement Center from calibrated simulations is shown in Table 8. The detailed monitoring and analysis have shown that the BigHorn Center uses 36% less site energy, 54% less source energy, and has 53% lower energy costs than typical, minimally code-compliant retail buildings of similar size. The source energy savings are much better than the site energy savings because the energy efficiency features in the as-built building had a large impact on the electrical load and increased the gas consumption compared to the baseline building. The lighting design and the extensive use of daylighting reduced the lighting energy requirements by 80%, which contributes significantly to the reduced energy loads in the building. Approximately half the lighting energy savings can be attributed to lower LPDs and half to daylighting controls. Reducing the lighting and control of solar gains has lowered the internal gains enough to meet the cooling load with natural ventilation. The 8.9-kW PV system provides 2.5% of the electricity needed to operate the building. Improvements to the PV system and building operation should improve the performance to almost 8%.

Table 8. Cost, Site, and Source Energy Savings Summary

	Cost		Net Site Energy		Net Source Energy	
	**$\$/ft^2 \cdot yr$** *($\$/m^2 \cdot yr$)*	**Percent Savings**	**$kBtu/ft^2 \cdot yr$** *($MJ/m^2 \cdot yr$)*	**Percent Savings**	**$kBtu/ft^2 \cdot yr$** *($MJ/m^2 \cdot yr$)*	**Percent Savings**
Baseline	**$1.08 *($11.63)***	**53%**	**63 *(720)***	**36%**	**156 *(1,770)***	**54%**
As-Built	**$0.51 *($5.49)***		**40 *(450)***		**72 *(820)***	

Lessons Learned

Involvement in this project has provided real-world examples of how advanced building technologies work together. Lessons learned have already been applied to other research projects and will continue to be valuable for future projects. The lessons learned can be divided in to four categories: 1) design, construction, and commissioning; 2) technical; 3) building operation; and 4) energy monitoring and analysis.

Design, Construction, and Commissioning

1. Setting specific performance goals that the whole design team believes in is a critical first step toward producing a building that operates efficiently.
2. Energy simulations played an important part in helping us understand the forces that drive energy performance and allowed us to investigate many design alternatives. Energy simulations had the greatest impact on the daylighting design.
3. DOE-2 is limited in the flexibility of HVAC systems that can be modeled. DOE-2 cannot include cooling or natural ventilation in the same model with a radiant floor heating system.
4. The effectiveness of the radiant systems versus forced air systems is difficult to compare in DOE-2. The panel heat loss factor is a crude proxy for heat transfer from the floor. There is no model for the gas-fired radiant heaters in the warehouse; therefore, the system was approximated with electric unit heaters. Finally, the systems cannot be controlled based on comfort conditions.
5. The electrical panels should be modular to group like loads. The electrical panels at BigHorn are not organized well, which makes the building difficult to operate and monitor energy performance end use.
6. There should be close communication between the energy engineer, mechanical engineer, and electrical engineer throughout the design and implementation of the building control systems.
7. Building construction should be monitored for issues that could affect energy use. This includes ensuring the proper materials and equipment are used and that they are installed correctly.
8. Systems that affect occupant comfort should be monitored during construction. An uncomfortable environment can lead to higher energy consumption if the occupants change their working environment to maintain comfort. Examples include lighting quality and thermal comfort.
9. The performance of daylighting design is often not as good as anticipated. The operable windows had less glass area than assumed in the simulations, dark overhangs reduced the light reflected through the clerestories, and the impact of the window screens was not taken into account. In addition, the tall rows of merchandise create dark areas in the aisles.
10. The translucent roof panels in the warehouse provided excellent daylighting.
11. The quality of the lighting from the pendant compact fluorescent light (CFL) fixtures is poor in the mezzanine, where they are relatively close to the working surface. Linear T-8 fluorescent fixtures would have been better for lighting quality, control, and maintenance.
12. Operable high windows should have been added to the private offices on the mezzanine. These windows would allow more light from the clerestory and allow ventilation air to circulate by natural convection.

13. The design of the hydronic systems (radiant floor and snowmelt) should be considered carefully for head loss and heat transfer issues. The snowmelt system was disabled because of a poor design, which resulted in low flows and ineffective snow melting capabilities.
14. Changes to the design during construction should be documented carefully, and responsibility for implementing the changes should be noted.
15. The roof and roof drains should be designed to avoid ice buildup, which can damage the roof and prevent proper drainage of the melting snow and ice. Poor roof design can lead to higher energy use because electric roof ice melt is required. Control of roof ice-melt systems is difficult and is often left on continuously, which results in excessive energy use.
16. Commissioning should follow a formal process with complete documentation. The documentation will provide records for the culpability of the performance and will provide valuable information for the building operation and maintenance.
17. Commissioning can be completed by an independent commissioning agent or by the contractor and subcontractors. An independent agent provides an objective review of the building and systems and acts as an owner's representative, but this comes at an added cost. The contractor and subcontractors are very familiar with their work, but they usually do not follow a formal process and they may not provide an objective review of the work.
18. Passive barometric dampers are installed in the warehouse that are supposed to open when the ceiling exhaust fans turn on; however, they also open when the wind is blowing directly on the dampers allowing cold air to enter directly into the warehouse.

Technical

1. Light sensor locations must be carefully planned to measure the intended light levels and avoid extraneous light sources. The exterior light sensor had a full view of the exterior lights, which caused the lights to cycle on and off until the sensor was shielded from these lights.
2. Lighting systems should be controlled by the EMS with easily accessible manual overrides to turn lights on after hours. The manual overrides should have timers or the EMS should sweep the systems to ensure that the lights do not stay on excessively. The human-computer interface and easily accessible manual overrides are critical for success.
3. Grid-tied PV systems and inverters should be carefully designed as an integrated system.
4. An automatic monitoring system for PV system operation should be installed. There is no way to know whether a grid-tied PV system is operating correctly without manually checking the inverter output on its display terminal.
5. The transpired solar collector is not effective in this building. Transpired solar collectors can provide large amounts of preheated ventilation air. However, the warehouse always has at least one large overhead door open during business hours, there is no need to provide ventilation air.
6. Some PV panels showed signs of deteriorating after three years. The plastic laminate separated from the PV material in small areas spread over the PV panels.

Building Operation

1. The CFL pendant fixtures are not the best options for this application. Strip fluorescent fixtures are more energy efficient, easier to control, and cheaper to maintain. The CFLs installed have a real operating life of approximately 4,000 hours—much less than the 10,000 hours advertised.
2. The timing of recharging the electric forklift can make a large difference in the operating cost. The forklift should be charged at night to avoid coinciding with the monthly peak demand.
3. Lights used during cleaning should be turned on only in the parts of the store the cleaners are working. The monthly peak electrical demand is often incurred during cleaning and after store operation hours.
4. The automated natural ventilation system works well most of the time. However, the system required extra effort in the beginning because the automated windows did not operate properly. In addition, control has been difficult under some circumstances. The natural ventilation window control should include outside temperature so the windows can be closed before the weather becomes too cold and produces cold drafts.
5. If the outdoor temperature remains higher than 80°F (27°C) for extended periods, the natural ventilation does not provide adequate cooling. Predictive controls could allow the building to precool on days that are going to be hot.
6. The PV system contributes very little to reducing building peak electrical demands. The peak electric load is typically in the late afternoon to early evening; the PV peak output is in the middle of the day.

7. The building energy performance benefited from post occupancy fine-tuning of the system operations. Achieving and maintaining high performance requires a constant effort, which is absent in most buildings.
8. The ceiling fans in the retail area should operate at lower speed to avoid drafts in the mezzanine and thermostatically controlled for better control. During natural ventilation operation, the fans above the retail area should turn off or be reversible to aid the upward airflow. The fans over the mezzanine should remain blowing down at all times to help comfort.
9. The CO sensors on the warehouse exhaust fans have been successful for demand-controlled ventilation. The exhaust fans were originally designed to run continuously during occupied periods, but they have operated only once with the CO sensor control.
10. Computers are often left on overnight, which adds significantly to the building nighttime load. Leaving all the computers and monitors in the building on, but in standby mode, is about 2 kW or about one-third of the nighttime load in the summer.

Energy Monitoring and Analysis

1. The EMS should be investigated to ensure that it is suitable for data logging and reporting. The data logging capabilities of the BigHorn Center EMS were not compatible with the requirements of a rigorous, long-term monitoring project.
2. Space temperatures should be measured and recorded on a system that is separate from the EMS for detailed energy monitoring projects.
3. Weather information is important for high-performance building projects that are often more weather dependent. Preferably, weather data should be measured on site, but a nearby reliable weather station with the required data can also be used.
4. The monitoring plan should be carefully laid out early, beginning with a list of specific questions. The most suitable performance metrics are then chosen, which leads to the data and analysis techniques required.
5. Creating energy cost goals during design, and verifying the costs are difficult because energy prices change. Utility prices varied by 40% during the 3-year monitoring period.

Recommendations

Several actions could further improve and maintain the energy performance of the building. Our top recommendations are presented here. Most of these issues have been discussed previously, but they are presented here with more specific information.

1. Charge the electric forklift during off-peak hours. The BigHorn Center pays \$0.02–\$0.03/kWh for electricity, which makes operating the electric forklift inexpensive if it does not incur demand charges. During the 2 years of monitoring, demand charges have increased the effective energy charge for the forklift to \$0.26–\$0.48/kWh. By charging the forklift at night, the annual energy costs for the forklift are expected to be less than \$100. This recommendation does not save energy, but reduces costs by shifting the energy consumption to off-peak periods.
2. Work with the cleaning crew to control the number of lights turned on during cleaning. If only half the retail and half the lighting display are turned on at a time, this will probably save \$150–\$200 annually.
3. Continue to monitor the energy performance of the building each month. This should include comparing monthly total energy by end use to past and expected performance.
4. Consider the energy demand and use implications of adding loads to the building. Over the monitoring period, there was a trend of adding lights and appliances to the building, all of which increase energy consumption and possibly peak demand.
5. Replace the PV system inverters with ones that are designed to be grid-tied to significantly improve system reliability and performance.
6. Install power control devices on the vending machines. These products have been shown to save nearly 50% of the energy and typically have a payback period of 2−3 years

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This is one of the nation's first commercial building projects to integrate extensive high-performance design into a retail space. The extensive use of natural light, combined with energy-efficient electrical lighting design, provides good illumination and excellent energy savings. The reduced lighting loads, management of solar gains, and cool climate allow natural ventilation to meet the cooling loads. A hydronic radiant floor system, gas-fired radiant heaters, and a transpired solar collector deliver heat. An 8.9-kW roof-integrated photovoltaic (PV) system offsets a portion of the electricity.

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