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Technical Report

Analysis of the Design and Energy Performance of the Pennsylvania Department of Environmental Protection Cambria Office Building

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Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Introduction

The Commonwealth of Pennsylvania established the Governor's Green Government Council (GGGC 1998) to encourage environmental sustainability through its policymaking and in its government agencies. One of those agencies is the Pennsylvania Department of Environmental Protection (DEP), which has established itself as a leader in this endeavor by building and operating several high-performance, green buildings. One of DEP's green buildings is its Cambria office building in Ebensburg, Pennsylvania, which was completed in the fall of 2000.

DEP used an integrated design process for its Cambria building to meet its goal of producing a high-performing, environmentally sound building. The building features efficient wall and roof insulation, high-performance windows, ground-source heat pumps, an underfloor air distribution system, energy recovery ventilators, daylighting, motion sensors on restroom lights, and an 18.2-kW photovoltaic (PV) system for on-site electricity production. In addition to the energy efficiency measures, DEP chose paints and adhesives with low-level volatile organic compounds and finish materials based on their origination, recycled content, and their potential for being recycled in the future. The effort was successful in achieving a LEED (Leadership in Energy and Environmental Design) 2.0 Gold Certification for the building from the U.S. Green Building Council.

DEP then asked the National Renewable Energy Laboratory (NREL) to evaluate the energy performance of the Cambria building to determine if it had met design goals. The focus of this report is the analysis of an integrated design process used to construct the facility and the postoccupancy energy performance. NREL collected energy use and other performance data and compared those data with a standard baseline computer model compliant with the minimum levels of Standard 90.1-2001 from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2001). NREL used the metered data and analysis to formulate recommendations to further improve building performance.

Research Goals and Approach

This report 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. In this project, NREL compared the design process to a 10-step low-energy design process that we had previously developed and continue to refine (Torcellini et al. 1999). This process covers predesign through postoccupancy, relies heavily on building energy simulation, and includes other important qualitative and quantitative features such as design charrettes with all members of the design team and the establishment of energy goals through the use of computer modeling. It would not have been possible for NREL to conduct this research without close collaboration with real building design and construction projects. It is not practical to use classical controlled repeatable experimental techniques for objects as large and complex as commercial buildings and for design and construction processes that of necessity involve so many different players over an extended period.

NREL established the following goals for working with the Cambria 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.

DEP installed a building energy monitoring system for the major end uses during construction. A second monitoring system for indoor air quality that measures temperature, relative humidity, and carbon dioxide levels was also added by DEP. NREL installed additional instrumentation to monitor the energy production of the PV systems and the weather conditions. Information from these systems and from the utility bills was used to analyze the building energy performance over three years. Based on initial results, NREL made changes to the building's operation and control sequences to improve the energy performance. Performance metrics for site energy, source energy, and energy cost savings were determined with the energy consumption data.

Results

The Cambria building is an example of a high-performance building produced at a reasonable cost of $93/ft^2 ($1,000/m^2). The building (without the PV systems) shows an estimated 40% energy saving and a 43% energy cost saving. These savings are for the total building energy use and were determined with whole-building energy simulations that were calibrated with measured data. The As-Built Baseline Model was compliant with ASHRAE 90.1-2001. The annual energy consumption for the As-Built Baseline Model and As-Built Model is shown in Figure ES-1. Most of the energy savings are from a reduction in the heating and lighting energy. Table ES-1 shows the annual energy performance for site energy, source energy, and energy cost.

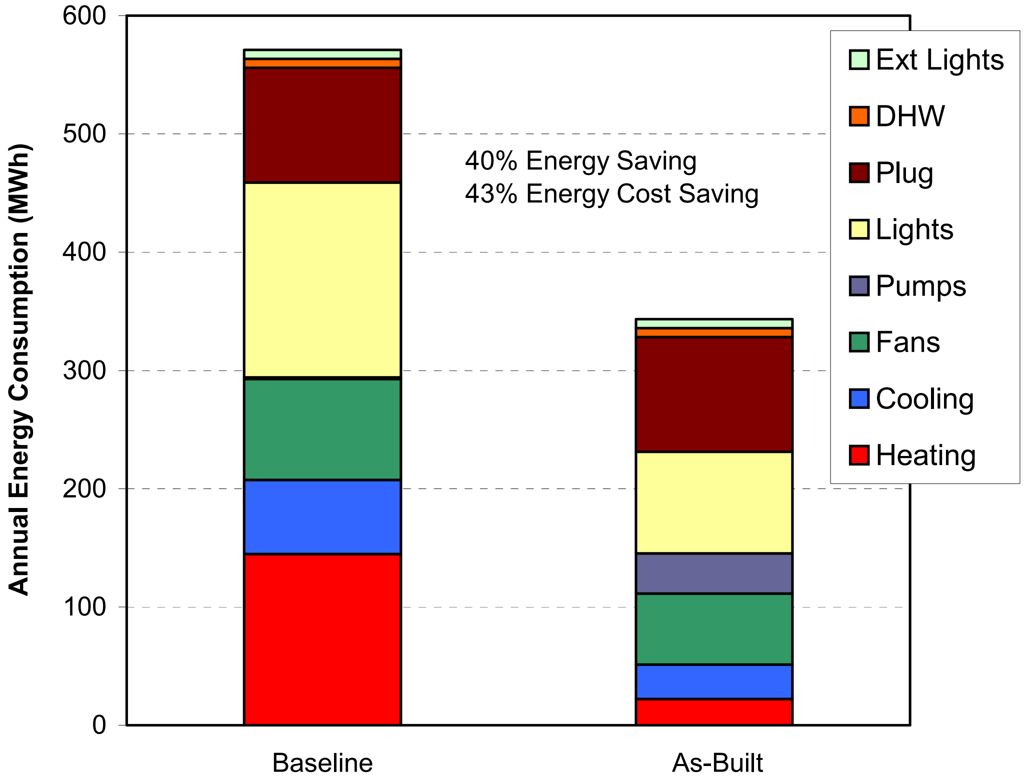


Figure ES-1 Annual site energy consumption for the As-Built Baseline Model and As-Built Model

Table ES-1 Energy and Energy Cost Performance Metrics

	Cost		Total Site Energy		Total Source Energy	
	\$/ft^2·yr *(\$/m^2·yr)*	**Percent Savings**	**kBtu/ft^2·yr** *(MJ/m^2·yr)*	**Percent Savings**	**kBtu/ft^2·yr** *(MJ/m^2·yr)*	**Percent Savings**
Baseline	\$1.80 *(\$19.38)*	43%	57 *(642)*	40%	180 *(1,800)*	40%
As-Built	\$1.02 *(\$10.89)*		34 *(386)*		108 *(1,226)*	

1 Introduction

As a result of a new state policy instituted by the Governor of Pennsylvania to encourage green building practices, the Pennsylvania Department of Environmental Protection (DEP) set a goal to create new buildings that advance the concept of high-performance green buildings. The first building under this initiative was completed in the spring of 1998 and is DEP's regional headquarters building in Harrisburg. The second building is the Cambria building in Ebensburg, which was completed in the fall of 2000. Most of the building's 34,500 ft^2 (3,205 m^2) is used for office space. The main objectives for this building were to provide a comfortable and productive work environment and minimize its environmental impacts.

For the Cambria building, DEP integrated high-performance building features into its design process from the beginning to meet its goal of producing a high-performance, environmentally sound building. Among the high-performance design features chosen for this building were efficient wall and roof insulation, high-performance windows, ground-source heat pumps, an underfloor air distribution system (UFAD), energy recovery ventilators (ERVs), daylighting, motion sensors on restroom lights, and an 18.2-kW photovoltaic (PV) system for on-site electricity production. (Figure 1-1 shows the main entrance of the building and the building's PV system.) DEP extended the sustainable design concepts used for the Cambria building to the building's interior by choosing paints and adhesives with low-level volatile organic compounds (VOCs) and finish materials based on their origination, recycled content, and their potential for being recycled in the future. The Cambria design team performed a life-cycle analysis to estimate the costs and environmental impacts of the building construction and operation. The effort was successful in achieving a LEED (Leadership in Energy and Environmental Design) 2.0 Gold Certification for the building from the U.S. Green Building Council (USGBC 2004).

In the spring of 2001, the National Renewable Energy Laboratory (NREL) was invited to evaluate the energy performance of the Cambria building. NREL evaluated both the integrated design process used to construct the building and the building's postoccupancy energy performance. The results of that analysis are the focus of this report, which 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. This process covers predesign through postoccupancy, relies heavily on building energy simulation, and includes other important qualitative and quantitative features such as design charrettes with all members of the design team, and the establishment of energy goals through the use of computer modeling. It would not have


NREL PIX #10138

Figure 1-1 South-facing view of the Pennsylvania DEP Cambria building

been possible for NREL to conduct this research without close collaboration with real building design and construction projects. It is not practical to use classical controlled repeatable experimental techniques for objects as large and complex as commercial buildings, and for design and construction processes that of necessity involve so many different players over an extended period.

1.1 Building Evaluation Scope

NREL's participation with the Cambria building was established with the following goals:

- Monitor and analyze the performance of the building and its subsystems for a period of at least two years
- Implement improvements to the building operation based on the monitoring and analysis
- Document lessons learned and determine which of the energy-efficient features could be applied to other office buildings
- Develop and test standardized monitoring protocols developed by NREL as part of the Performance Metrics Research Project.

NREL measured energy use compared to a simulated ASHRAE 90.1-2001 baseline building. Energy and water use were normalized by area and occupancy. A comparison was also made between this building and the Energy Information Administration's (EIA) Commercial Buildings' Energy Consumption Survey (CBECS).

In collaboration with 7group and the staff at Cambria, NREL evaluated the design process and monitored, evaluated, and documented the building's energy performance. The evaluation period was July 2001 through June 2003.

Many of the individual high-performance building components incorporated into the design were also studied in detail. The evaluation presented in this report focuses on the whole building performance; however, additional analysis was done for the PV, mechanical, and daylighting systems.

2 Background

2.1 Energy Use in Commercial Buildings in the United States

The operation of commercial buildings accounts for approximately 18% of the total primary energy consumption in the United States. The total for all buildings is more than one-third of the primary energy consumption and more than 70% of the electricity consumption. The operation of buildings in the United States results in 38% of U.S. and 9% of global carbon dioxide (CO_2) emissions. Electricity consumption in the commercial building sector doubled between 1980 and 2002; it is expected to increase another 50% by 2025 (DOE 2004). Reducing site energy consumption in commercial buildings through energy-efficient and renewable building technologies would significantly reduce primary energy consumption in the United States. Site energy is also a concern for the building owner or those responsible for paying the utility bills.

Typical site energy consumption by end use for office buildings is shown in Figure 2-1 (DOE 2004). The average building site energy use intensity (EUI) is 97.2 kBtu/ft^2·yr. These numbers are based on 1995 data collected by EIA. Most of the space heating, water heating, and cooking use natural gas; the rest of the energy consumption is electricity. The primary energy consumed to generate and distribute the electricity is approximately three times the energy used on site. Lighting is the largest primary energy end use; therefore, reduction in lighting loads should be a primary objective in office buildings.

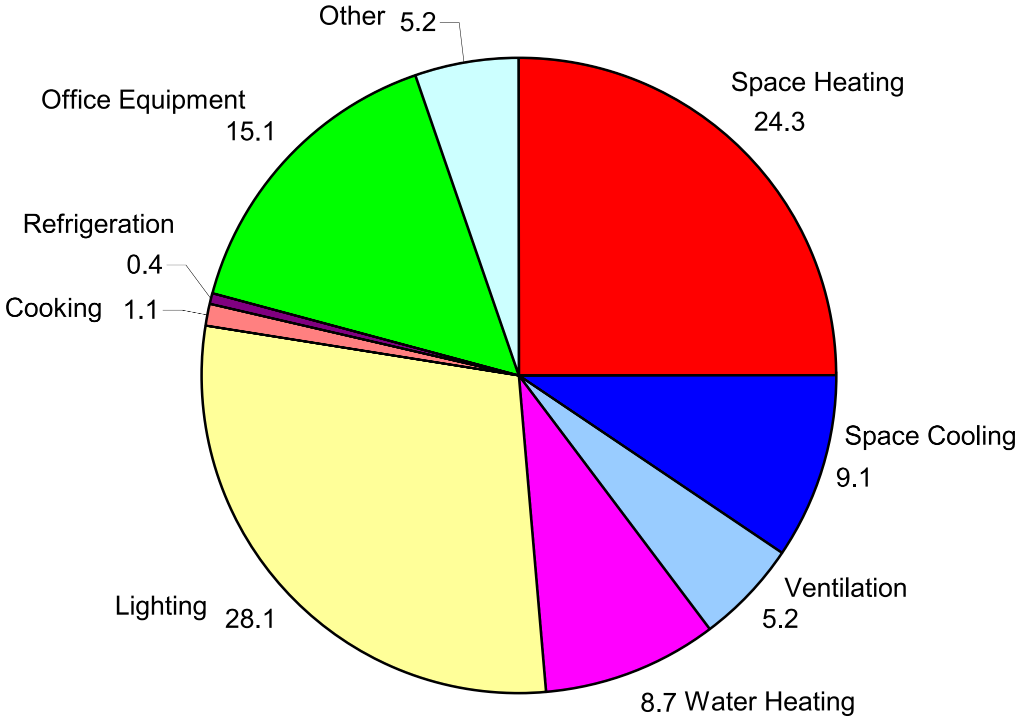


Figure 2-1 Typical site EUIs by end use for office buildings (kBtu/ft^2·yr) (DOE 2004)

2.2 NREL Research Objectives

NREL conducts buildings research for the U.S. Department of Energy's (DOE) High Performance Buildings initiative. NREL evaluates commercial buildings from a whole-building perspective to understand the impact of integrated design issues on energy use and costs in commercial buildings. By documenting analysis methodologies and results on new commercial design, NREL is providing direct assistance to industry. NREL's research objectives are to:

- Develop processes for high-performance building design, construction, and operation
- Provide the tools needed to replicate the processes
- Research new technologies for high-performance buildings
- Develop standardized metrics and procedures for measuring building energy performance
- Measure and document building performance in high-profile examples.

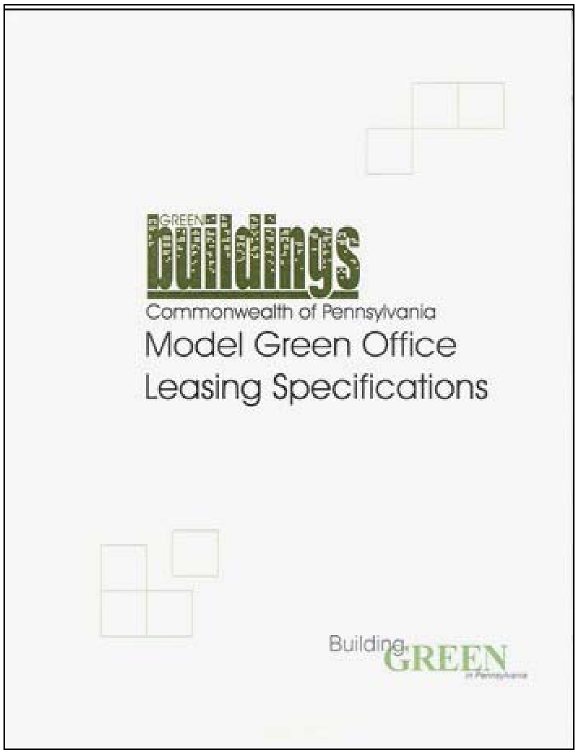
2.3 Pennsylvania DEP Green Building Efforts

Pennsylvania DEP took its first steps in creating and operating high-performance green buildings with the construction of the South Central Regional Office Building (SCROB) located in Harrisburg, Pennsylvania. The goals for this building included the identification and incorporation of sustainable building practices and energy efficiency into a cost-effective facility located on a semiurban brownfield site. DEP staff used the lessons learned from this first project to rewrite their agency building specifications to include and enhance their sustainable building practices, energy efficiency, and integrated design practices. The primary objectives were to use green technology to:

- Significantly reduce energy consumption and operational costs.
- Maximize the use of sustainable materials.
- Improve the health, motivation, and productivity of the work force with improved air quality and the use of natural light.

In July 1997, using the new building specifications that resulted from SCROB lessons learned as a guide, DEP requested that the Department of General Services obtain proposals for the Cambria project as an office facility that would be leased to the Commonwealth of Pennsylvania. The Cambria building was the next step in what later evolved into the Commonwealth's Building Green in Pennsylvania Program. In September 1998, the final execution of the lease for the Cambria building was awarded to a developer that had proposed the lowest annual lease, and the design was initiated.

As the Cambria project progressed, a series of additional goals were identified and negotiated into the project proposal. These goals later become the initial performance standards criteria for the *Model Green Office Leasing Specifications* published in May 1999 (Figure 2-5) (GGGC 1999).



GREEN buildings

Commonwealth of Pennsylvania

Model Green Office Leasing Specifications

Building GREEN in Pennsylvania

Figure 2-2 Cover page of the *Model Green Office Leasing Specifications* (1999)

3 Design Process

Because an integrated design approach was used successfully for the first green building project in Harrisburg, DEP used the same design approach for the Cambria building. An integrated design approach encourages all of the participants (owner, architect, engineers, contractors, etc.) to work together and find optimal solutions early in the design process to meet energy goals. This process targets downsizing or eliminating systems components, minimizing redundancies, improving performance, and reducing energy consumption. Including the contractors in the integrated design process improves their buy-in because contractors are able to understand design decisions. Contractor buy-in provides a smoother transition from design to construction and helps to control costs.

The Cambria building is owned by a third party and leased to DEP. DEP developed, as part of the requirements of the building, green specifications that were incorporated into the design. The owner had an incentive to incorporate the features in a manner that was consistent with a positive cash flow based on the lease cost. This arrangement forced a truly integrated design process to meet green standards. It also required that the costs be minimized to make the project financially viable to the third party.

In addition to the integrated design process, the project followed a design-build scenario in which the design and construction phases of a project are performed under a single contract. A design-build concept provides a single point of contact and streamlines the design process, which can save time and money. In a design-build process, the need for value engineering is eliminated because the project costs are estimated throughout the design. Therefore, economic values are considered with the systems optimizations. For example, much of the design focused on identifying optimized system solutions that lowered first costs and operating costs. By continually searching for these opportunities, many of which are identified in this report, the project design team was able to incorporate significant green building features into the design and deliver a building at conventional construction costs. One potential drawback of using the design-build approach is that some of the design occurs during construction with little consideration about systems integration and sometimes no documentation.

The project developer assembled the design and construction teams subject to DEP approval. The following companies participated in the project design and construction:

- Contractor/Developer: Miller Brothers Construction
- Owner: MBC Properties
- Architect: Kulp Boecker Architects, P.C.
- Mechanical Engineer: Phoenix GeoThermal Services
- Mechanical Contractor: Climate Comfort Heating & Air Conditioning, Inc.
- Civil Engineer: WJP Engineers
- Energy Modeling/Consulting: Energy Opportunities, Inc.

3.1 Project Performance Objectives

Energy consumption, cost, and environmental impact were primary concerns of the Cambria project. Many of the project goals were related to energy issues and initially included the following:

1. A maximum site energy budget of 40 kBtu/ft^2/yr (450 MJ/m^2/yr), not including plug loads and PV system contributions.
2. A lighting budget not to exceed 0.9 W/ft^2 (9.7 W/m^2) for ambient lighting.
3. The indoor surface temperature of glazing shall not be less than 62°F (17°C) when the outdoor temperature is 20°F (–6.7°C).

4. The indoor surface temperature of opaque wall surfaces shall not be less than 70°F (21°C) when the outdoor temperature is 20°F (–6.7°C).

Additional project goals were established as the design progressed:

1. Heating, ventilating, and air conditioning (HVAC) chiller size shall not exceed 600 ft^2/ton (15.8 m^2/kW).
2. The ventilation system must provide fresh air to maintain indoor air at less than 700 ppm CO_2 during hours of occupancy.
3. Cooling season indoor relative humidity (RH) shall not exceed 45% at established design conditions.
4. Heating season humidity shall be no less than 25% at established design conditions.

In addition to these specific performance-based goals, the team committed to achieving a LEED Gold rating, and established additional performance targets required for earning LEED credits related to site issues, water use, energy efficiency, materials, and indoor environmental quality (IAQ). As the project team worked its way through the LEED certification process, such targeted goals defined minimum performance thresholds for limiting site wetlands disturbance; using alternative transportation; implementing effective stormwater management; reducing heat island effects; limiting potable water consumption; maximizing energy efficiency; utilizing high percentages of recycled, local, and renewable materials; monitoring indoor air quality; increasing ventilation effectiveness, minimizing the use of off-gassing materials and VOCs; augmenting controllability; maintaining thermal comfort ranges; incorporating daylighting strategies; and providing occupants with access to views. These targeted LEED performance goals informed all design decisions.

3.2 Energy Design Process

With the project goals well defined by the Commonwealth's Model Lease Office Specifications, the early phases of design focused on building orientation, form, and required functions. As a result, the design concept originally conceived by the developer was modified significantly. The original plan envisioned a relatively square box with a flat roof and an orientation that responded to the road along the property's edge in order to maximize curb appeal. The resulting building would have been poorly oriented with limited ability to capture solar energy and daylight. This concept came from an initial assumption that such a configuration would minimize construction costs.

The original location of the building on the site was changed to optimize solar orientation and preserve wetlands on the property. Further design modifications to the building and the parking lots enabled the project to protect all of the pre-existing wetlands while meeting the programmatic requirements. The adjusted site plan also minimized the building along the street line, preserving a natural setting along the street.

3.3 Thermal Envelope

The contractor suggested to the design team the use of insulated concrete forms (ICFs) for the majority of the exterior wall construction. They had used ICFs on a previous project and found them to save labor and time compared to other wall construction systems. Following evaluation by the architect, owner, and energy consultant, ICFs were incorporated into the design from the foundation up to the sill height of the second-floor windows. Steel frame walls were used above this point. For the purposes of ensuring similar thermal performance with this wall system to the ICFs, a 1-in. (2.5-cm) layer of rigid board insulation was added to the exterior of the steel studs to mitigate thermal bridging through the studs and cellulose was used in the stud cavities.

The design team target for the thermal performance of the roof was a minimum of R-30 $hr \cdot ft^2 \cdot °F/Btu$ (5.3 $m^2 \cdot K/W$). Additional considerations included improving the daylighting and providing good acoustical performance. The roofing system originally envisioned comprised a steel deck supported by steel bar joists, with rigid insulation sandwiched between the deck and a standing-seam metal roof. The final design consisted of a series of products: wood/steel trusses, reflective roof decking composed of 100% postconsumer recycled waste paper along with a nail base, and recycled steel shingles. This roof assembly, which exceeded the performance criteria, provided additional environmental benefits, and offered better acoustical properties.

The building fenestration design consisted of a combination of punched opening windows and storefront windows (primarily in the core near the front entrance). In order to comply with the project's performance requirement of an interior glazing surface temperature of 62°F (17°C) when the outdoor temperature is 20°F (−6.7°C), two options were considered. The first option was to use radiative or convective perimeter heating. This approach had an initial cost estimate of $25,000. The second option, recommended by the design team as an integrated design solution, was to use triple-glazed windows and attempt to eliminate the perimeter heating system. An analysis completed by the design team, which included the use of Window 4.1 (Arasteh et al. 1994), demonstrated that low-e, triple-glazed windows would exceed the performance requirement, allow for the elimination of perimeter heating, contribute to energy savings via reduced heat gain and loss loads, and in turn, allow for HVAC system downsizing. The owner initially balked at the extra cost of these windows (about $15,000), but further analysis demonstrated that the use of these windows was the least expensive way to meet the project's performance requirement. Overall, building performance was improved and first costs were reduced, a key integrated design solution.

3.4 Lighting and Daylighting

Because reduced energy use for electric lighting was identified as a critical issue to be addressed during the early stages of design, the building configuration was elongated along an east-west axis to gain better solar access and optimize daylight penetration into the building. The rooflines were sloped in order to allow the use of north- and south-facing clerestory windows on the second floor for daylighting, which also provided an angled surface for mounting PV panels. Light shelves were added on the south side of the first floor to help direct some daylight deeper into the office space. These daylighting features are illustrated in Figure 3-1. To improve the success of the daylighting, the second floor plan was designed to place the large open office spaces adjacent to exterior walls and locate enclosed offices in the center of the building rather than at the perimeter. As a result, these private offices do not block access to daylight, and the vast majority of occupants are afforded access to this daylight and views. In addition, a major programming effort was undertaken to ensure that most of the occupants were located in these large open office spaces on the second floor because of their access to daylighting. The first floor was designed to accommodate meeting spaces, storage, support functions, and workspace for field staff who spend the majority of their time away from the office.

As is common in a design-build scenario, an independent lighting designer was not included on the design team. Lighting design was a combined effort by the architect, electrical contractor, energy consultant, and a product sales representative. DEP decided on the use of a lighting system that provided 30 fc (foot candles) of ambient light with undercabinet task lighting at workstations for supplemental light. Daylighting was an important part of the design and resulted in the use of clerestory windows, overhangs, light shelves, and a dimming system.

The initial lighting design called for a lighting power density (LPD) of 0.82 W/ft^2 (8.8 W/m^2). Subsequent refinement of the lighting system resulted in a final design LPD of 0.75 W/ft^2 (8 W/m^2), not including task lighting. The LPD of the task lighting in the office areas is approximately 0.5 W/ft^2 (5.4 W/m^2).

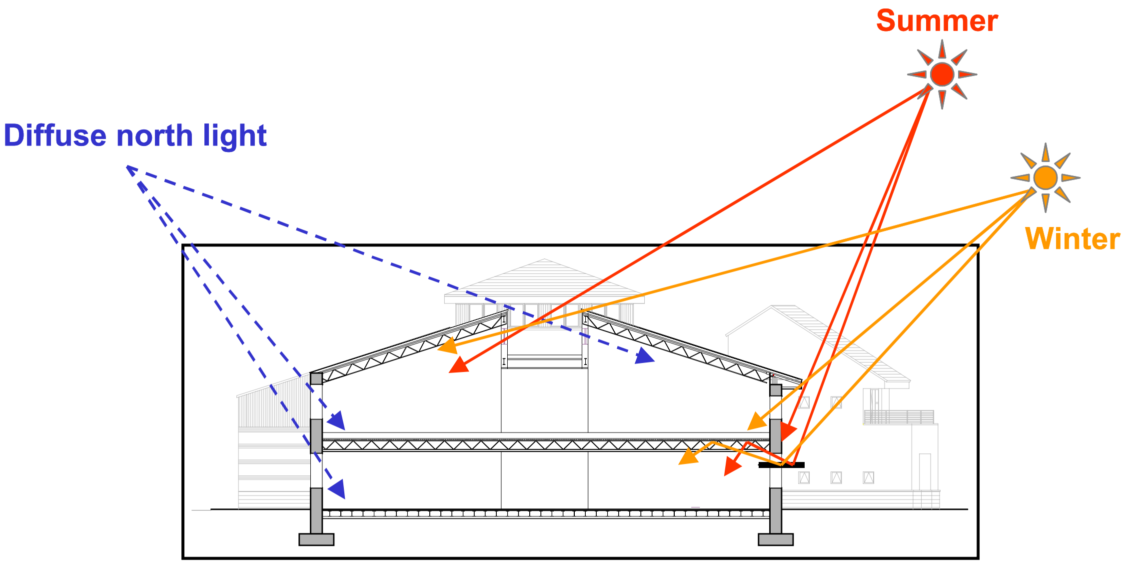


Figure 3-1 Daylighting design features of the Cambria building

The exterior lighting design was also modified. The original parking lot lighting design contained 14 cut-off fixtures with 400-W standard metal halide lamps mounted on nine poles. Additional analysis resulted in a final design of five cut-off fixtures with 400-W pulse start metal halide lamps each mounted on its own pole. The final design met the illumination recommendations of the Illuminating Engineering Society of North America (IESNA 2000) while reducing the first cost by more than $3,600 and reducing the energy costs by more than $1,800 per year compared to the original design.

3.5 Heating, Ventilation, and Air Conditioning

Initial HVAC selection for the Cambria building focused on the use of the gas boiler/absorption air-conditioner system used at SCROB. It was determined that the Cambria building and its loads were too small for this type of equipment. Recommendations by the contractor centered on packaged rooftop units. However, it became clear early in the design process that the HVAC system proposed by the contractor would not be able to meet all of the performance criteria, and an investigation ensued to analyze alternatives. An analysis of the mechanical systems was completed that compared a packaged rooftop system with ground-source heat pumps with ERVs. A DOE-2 energy model was used as input for a life-cycle costing analysis, which included first cost, maintenance cost, energy cost, and depreciation over a 25-year time frame. The ground-source heat pump system was shown to save more than $500,000 over the 25-year period.

Following this report, another analysis was conducted comparing seven different HVAC options including packaged rooftop units, conventional boiler/chiller systems, various gas-fired chiller options, and ground-source heat pumps. The report included a professional cost estimate of each system, annual maintenance costs, and estimated energy costs using the DOE-2 energy model constructed for the first study. The results showed the ground-source heat pumps had the lowest operating cost and lowest annual maintenance costs. The chiller based systems were shown to have significantly higher maintenance costs based on data from the 1995 ASHRAE *HVAC Applications Handbook* (ASHRAE 1995). Maintenance problems with the HVAC system at SCROB were a key factor in selecting a system with low maintenance.

Based on the analyses described above, ground-source heat pumps were selected as the system with the lowest operating costs that fit the maintenance capabilities of the developer and lessee. However, the first costs of this system were the highest of those considered. The decision was still made to pursue the ground-source heat pump system and investigate changes in the building design, which would allow the system first costs to be offset.

Subsequent consultations and discussions between DEP, the mechanical contractor, the project architect and the building owner resulted in the retention of a mechanical engineer to design a ground-source heat pump system with ERVs. The use of an experienced ground-source heat pump system designer combined with two integrated design solutions (described below), contributed to keeping the cost of the system within an affordable range.

One of the project goals inherent in the Model Lease Office Specs was an HVAC system area-capacity ratio of greater than 600 ft^2/ton (15.8 m^2/kW). Typical office building HVAC design in this climate ranges from 250 to 400 ft^2/ton (6.6 to 10.6 m^2/kW). To achieve this goal, the design team had to work together to optimize all the building systems in order to achieve significant load reductions. Collaboration with the mechanical designer is of vital importance in the development of the loads calculations to ensure that they accurately reflect the loads and the capabilities of the HVAC system. The result of the combined team effort produced an important integrated design solution, which produced an HVAC system area-capacity ratio of 663 ft^2/ton (17.5 m^2/kW). The key ingredients to the design solution were the building orientation, augmented thermal envelope, lower LPD, and thermal energy recovery, which combined to reduce the cooling loads by approximately 50%. The overall result was smaller HVAC equipment and fewer ground-source heat pump wells, reducing the total project cost by an estimated $60,000.

DEP specified a raised access flooring system for a UFAD system and modular electrical, telephone, and data distribution for the Cambria building. The system was specified because of the improved IAQ, reduced churn cost for reconfiguring workspaces, greater flexibility, ease of cabling access, and improved energy efficiency. DEP renegotiated the lease agreement with the building owner to compensate for the increased first costs of the raised floor system.

An additional integrated design solution was discovered during a design meeting on the mechanical systems. Team members in attendance included the architect, mechanical engineer, mechanical contractor, energy modeler, developer, and lessee. The architect had initially predetermined that the location of the mechanical equipment would be in a penthouse. The meeting began with a discussion about how to coordinate the installation of the piping, ductwork, etc. from the penthouse out into the building. The architect realized the inefficiencies and asked where the mechanical space would optimally be located to reduce installation cost and simplify the system design. After a long pause, the mechanical engineer (who indicated that he had never been asked that question) suggested that the optimum solution would be to divide the central mechanical space into two rooms located on the first floor, one in each wing of the building. The ductwork for the UFAD system could then feed directly into the first floor. To serve the second floor, the ductwork would only have to go up about 6 ft (1.8 m) to connect to the raised floor. The only ducts from the roof would be the much smaller ventilation air ducts.

The developer raised the issue that this design change would eliminate prime leasable space that would have to be added elsewhere. To accommodate this request, the architect added 1.5 ft and 2 ft (0.46 m and 0.61 m) to the west and east ends of the building. The savings to the project resulting from the elimination of the mechanical penthouse and the reduced duct and pipe runs (including the increased cost of adding space to the building) were estimated at $40,000. In addition, HVAC system performance was enhanced due to the minimal turns in the duct system, and maintenance personnel have easier access to the mechanical equipment.

3.6 Design Phase Energy Modeling

Hourly energy simulations with DOE-2 were used at various stages in the project. Energy simulations formed a significant part of the HVAC analysis, which resulted in the selection of the ground-source heat pump system. This analysis used a simplified building model for the purposes of comparing the HVAC systems. A more detailed model was created and used to validate and measure the results of design decisions (i.e., the detailed model was not used as a design tool) and was called the Design Building Model. Figure 3-2 shows a rendering of the detailed building model used in DOE-2. The simulations used the ASHRAE WYEC (Weather Year for Energy Calculation) weather data file for Pittsburgh, Pennsylvania, the closest site to Ebensburg, Pennsylvania. WYEC data were used because the simulation appeared unstable when using the preferred TMY2 weather files. An error was later discovered in the DOE-2 default values that caused the instabilities, which is explained in Section 6.3.

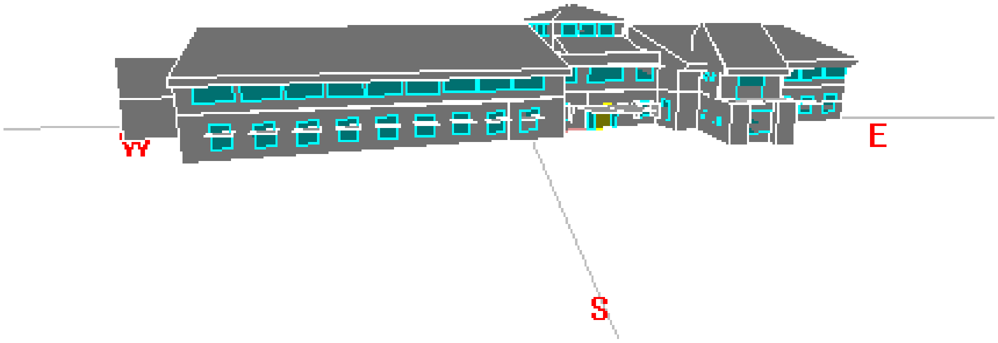


Figure 3-2 Rendering of the Cambria office building used for energy simulation

The Design Building Model was compared to a budget or Design Baseline Building Model that was compliant with ASHRAE 90.1-1989. These initial results showed that the Design Building Model had an energy cost reduction of more than 55% compared to the Design Baseline Building Model. The Design Baseline Building Model was refined in March and April 2000 to comply with the requirements of ASHRAE 90.1-1999. The results remained the same, showing a 55% cost reduction.

The final Design Building Model submitted for LEED certification included the utility rate structure and the purchasing of green power. The adjusted results demonstrated a 50% cost reduction. With the inclusion of the estimated revenue from the PV system, the overall energy cost reduction was projected to be 66%, as shown in Table 3-1. Figure 3-3 shows a breakdown of the energy consumption by end use. The lighting showed the most significant energy cost saving at 61% and the total HVAC energy cost saving was 49%.

Table 3-1 Estimated Energy and Cost Savings

Fuel	Design Use (kBtu)	Design Cost ($/ft^2)	Baseline Use (kBtu)	Baseline Cost ($/ft^2)	% Savings	
					Energy	Cost
Total building energy use	851	0.77	1,597	1.54	47%	50%
PV energy production	82	0.25	0	0		
Net building energy use	768	0.52	1,597	1.54	52%	66%

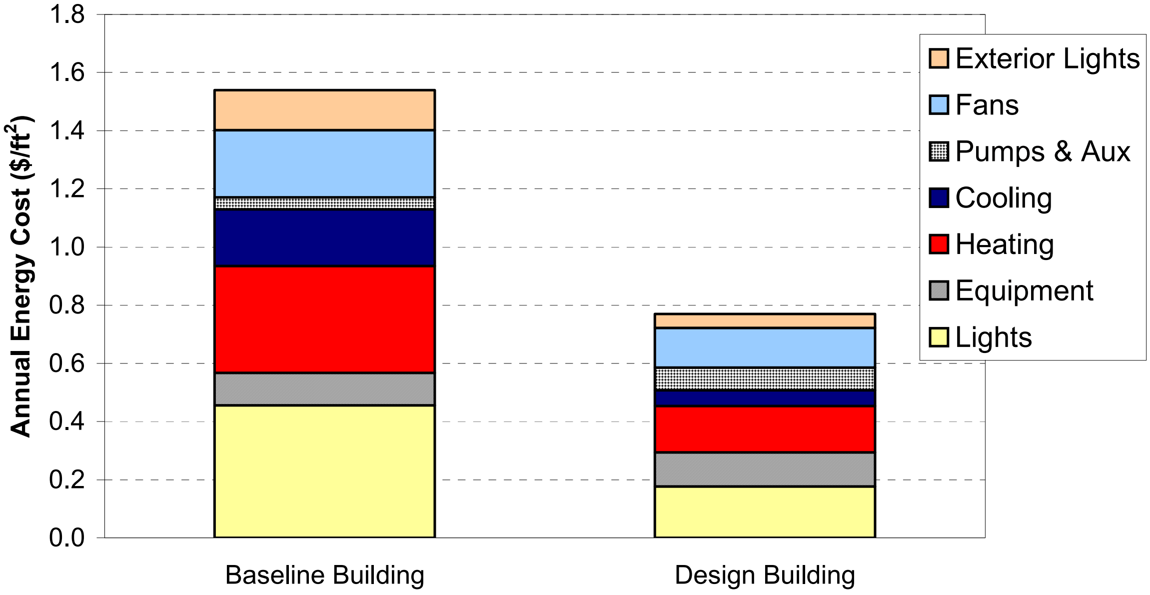


Figure 3-3 Comparison of the energy cost performance of the Design Building Model to the Design Baseline Building Model

3.7 Photovoltaic System

During the summer of 1999, DEP began to express serious interest in a renewable energy system for the building. Early analysis quickly centered on a PV system. The architect initially envisioned a small PV array to be placed on the roof of the second-floor conference room element.

Energy Opportunities, Inc., conducted a preliminary analysis in September 1999 on the design implications and optimum system size of a PV array. At the same time, an analysis of options for purchasing green power was conducted. The goal of these analyses was to determine the feasibility and potential cost implications of adding a PV system to the building. The study looked at many options and showed reasonable economic returns depending on three assumptions. First, the emergency generator would have to be eliminated and replaced by a PV system with battery backup. Second, federal tax savings were identified that would reduce the system first costs. Finally, a green power provider (Green Mountain Energy) was identified that was willing to pay a premium price for the all the electricity produced by the system. This study showed DEP that a system in the range of 15 kW was potentially feasible and additional analysis was conducted.

A firm price estimate and design for the PV system was obtained from the installer. As the design progressed, the battery component of the system was eliminated because of maintenance concerns, which meant that the emergency generator had to be included in the building design. The installer identified PV panels available through a DOE-sponsored buy-down program that significantly reduced the cost estimate for the system. An agreement was negotiated with Green Mountain Energy to sell all the power generated by the PV system to Green Mountain Energy at a premium price and purchase green power to meet all the electricity loads for the building at a lower rate. The green power purchased for the building energy consumption is from a mixture of wind and solar production and is slightly more expensive than the rates charged by the local utility. After a lengthy review process, a two-year contract was executed with Green Mountain Energy effective February 26, 2002.

The final analysis showed a total installed system cost of $50,000 after the buy-down and tax benefits. Annual energy savings would amount to $1,400 and revenue from the sale of the power generated by the system would amount to $7,200. Total savings of $8,600 were projected to result in a simple payback of 5.8 years.

The final design consisted of a 17.2-kW PV system mounted on the roof with a 15-kW three-phase inverter tied directly to the building’s main distribution panel. An additional 1-kW PV system is mounted on two single-axis tracking devices near the main entrance of the building. This system has a single-phase inverter and is tied into the east heating power panel. The larger system is the only one that is monitored as part of the agreement with Green Mountain Energy.

4 Construction and Commissioning

As is typically the case with a design-build project, the construction of the project began before design was complete. The project construction was completed in phases and coincided with the development of the design to a certain extent.

During construction, the design team continued to develop energy-efficient features and integrate them into the project. Some of these decisions would have been better served had they been addressed more comprehensively in the design stage. One of the weaknesses of the design-build process is that the "design-as-you-go" concept does not always result in a thorough design.

Commissioning was undertaken during the latter stages of construction. 7group was hired to perform commissioning as required by LEED. The commissioning agent participated in major systems start-ups and was on site to conduct prefunctional tests on the HVAC system.

The commissioning process was able to identify several issues during the final stages of construction, including:

- Identifying improper location of the temperature sensors. (They were moved from the return air stream to wall mounting within the space.)
- Discovering a possible issue with the enclosure of the transformer for the PV system.
- Identifying that the PV system was experiencing functional problems.
- Finding faulty piping installation in the west mechanical room, which failed during system testing.
- Discovering a potential sprinkler pipe freezing issue in the stairwell and recommending a solution.
- Identifying the cause of ERV failure first noted when DEP reviewed the IAQ monitoring results and CO_2 levels were very high.
- Discovering that the 1 in. (2.5 cm) of rigid insulation was not installed over all areas of the steel stud portions of the building's exterior walls. (The insulation was added and the siding re-installed.)

The overall effectiveness of the commissioning process on this project was limited by several factors. Commissioning did not begin until late in construction. The project was not fully documented, which is common in a design-build scenario. Mechanical drawings and specifications were limited to single-line duct and pipe drawings. Electrical drawings did not exist. The commissioning agent ended up serving as a third party referee at times and as system designer on occasion.

Following occupancy, a couple of minor issues arose with regard to HVAC and lighting. A heat pump was added to the main telecommunications room to address a higher than anticipated cooling load. Three areas were identified which required additional illumination:

- The file room lighting system was supplemented with three continuous rows of surface mount, two-tube fluorescent fixtures controlled by a timer switch, and the existing three-tube parabolic fluorescent fixtures were moved to the corridors on either side of the files.
- An additional row of indirect fixtures (removed from the file room) was installed in a second-floor conference room.
- Additional compact fluorescent task lighting was purchased for the tables in the supervisor offices and the draft tables in a few of the cubicles.

5 Cambria Building Description

The Cambria building is a two-story, 34,500-ft^2 (3,205-m^2) structure oriented on a long east-west axis, as shown in Figures 5-1 and 5-2. The building contains office space for approximately 100 people, a large file storage area, two small laboratory areas, conference rooms, a break room, and general storage areas.

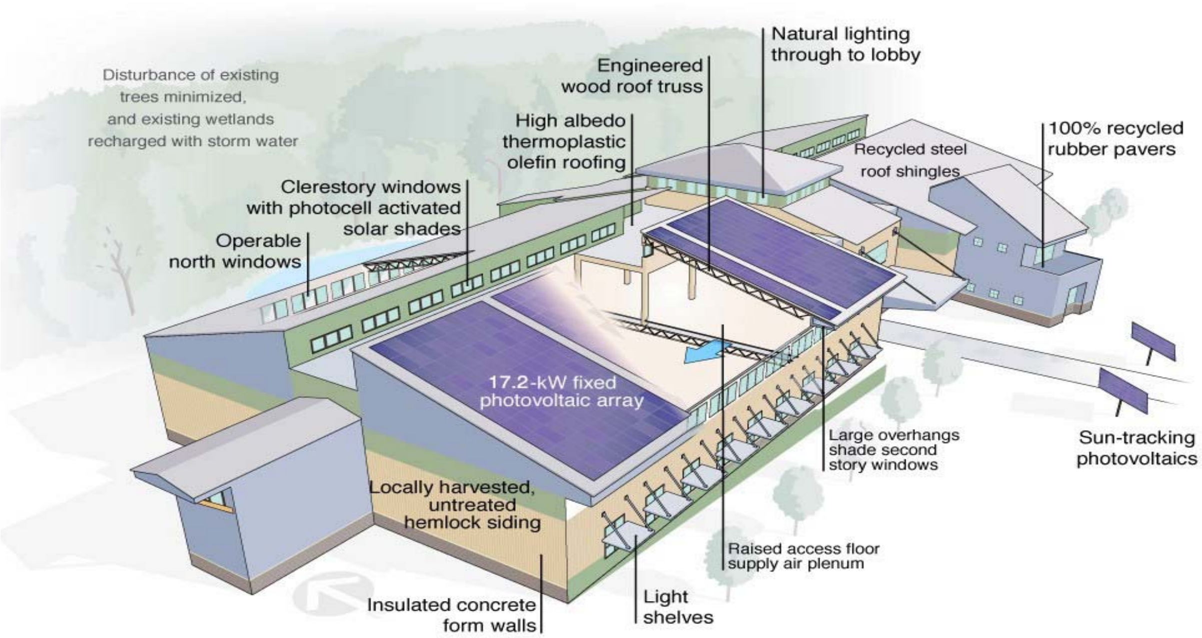
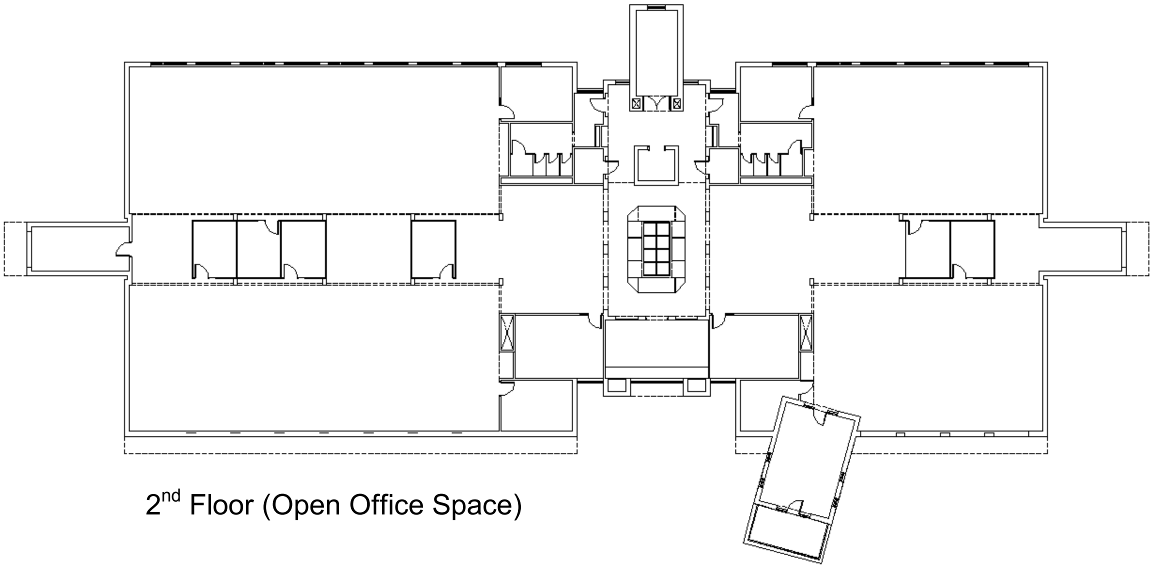
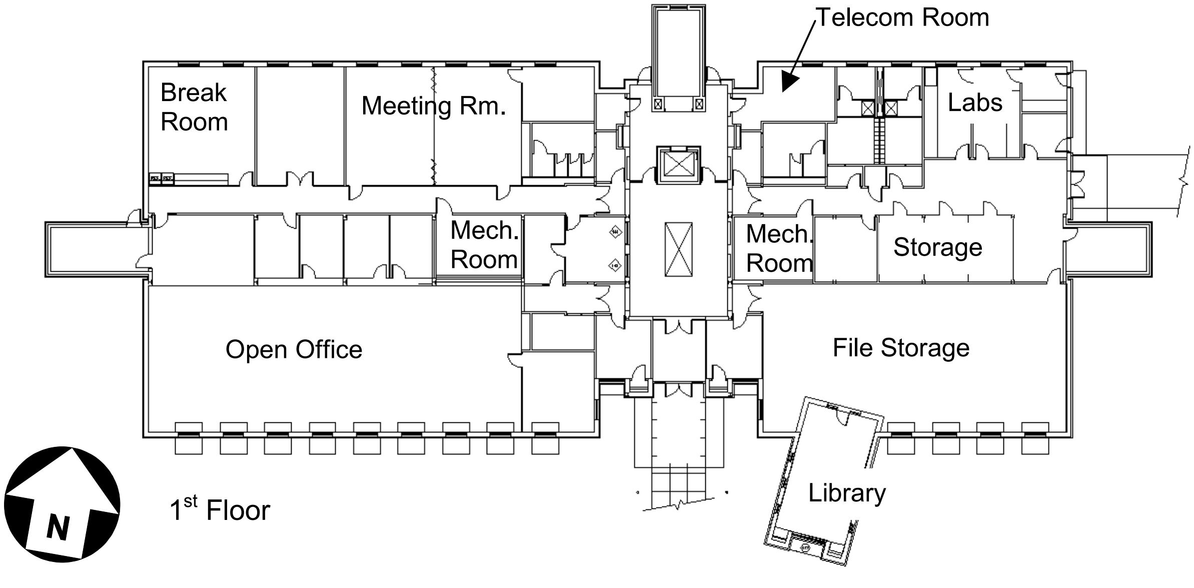


Figure 5-1 Illustration of the high-performance features of the Cambria building



2nd Floor (Open Office Space)



1st Floor

Figure 5-2 Floor plans of the Cambria building

5.1 Building Envelope

The building rests on a slab-on-grade with 2 in. (5 cm) of horizontal perimeter insulation extending in 4 ft (1.2 m) from the exterior wall. The walls are primarily constructed of ICFs with an insulating value of R-27 hr·ft^2·°F/Btu (4.8 m^2·K/W). Remaining walls are 6-in. (15-cm) steel frame with spray cellulose insulation in the cavity and 1-in. (2.5-cm) rigid insulation on the exterior. The roof consists of decking and insulation with a total insulating value of R-33 hr·ft^2·°F/Btu (5.8 m^2·K/W). Windows are triple-pane with aluminum frame for the entryways and triple-pane, wood frame for all other windows. Window insulating values are U-0.24 Btu/hr·ft^2·°F (1.4 W/m^2·K) and U-0.26 Btu/hr·ft^2·°F (1.5 W/m^2·K), respectively.

5.2 Lighting and Daylighting

The luminaires in the open office areas are indirect fixtures with 32-W T-8 fluorescent lamps with an installed capacity of 0.75 W/ft^2 (8.1 W/m^2). The LPD of the task lighting in the office areas is approximately 0.5 W/ft^2 (5.4 W/m^2). The luminaires in the second-floor offices have dimmable ballasts controlled by lighting sensors in each of the office areas. Undercabinet task lighting in each cubicle is controlled by a motion sensor connected to a power strip. Compact fluorescent lamps are used in other areas of the building such as the restrooms and lobby. Occupancy sensors are installed on the restroom lighting. Timing circuits in the breaker boxes control the building ambient and exterior lighting systems with override switches near the main entrance.

Daylighting features were incorporated into the design beginning with the building orientation on an east-west axis (see Figure 5-1). Virtually all fenestration faces either north or south. The second floor is primarily open office plan and houses the majority of building occupants. The daylighting design incorporates clerestory windows facing north and south along the center of the building. The south-facing clerestory windows are equipped with motorized sunscreens controlled by a photosensor to block direct-beam radiation. Overhangs shade the second floor windows on the south elevation. Light shelves are installed on the south-facing, first-floor windows. The interior finishes were selected to improve the light reflection and provide contrast. The first-floor ceiling tiles have a light reflectance of 89%, the second floor has high vaulted white ceilings with an open truss construction, the bottom 2.5 ft (0.8 m) of the walls are a light, natural wood color, the top portion of the walls are painted off-white (light reflectance of 75%), and the cubicle dividers are off-white. The carpet and the desktops are black. The *IESNA Lighting Handbook* recommends the following light reflectances for surfaces in offices: ceilings, 80% or more; floors, 20%–40%; walls, 50%–70%; partitions, 40%–70%; and furniture, 25%–45% (IESNA 2000).

The use of the task-ambient lighting scheme, light-colored surfaces, and lighting design resulted in a reduced first cost for the lighting system of approximately $20,000 compared to the original design. The lighting system saving does not include the additional first cost saving related to downsizing the HVAC system because of reduced heat gain from the lights.

Immediately after the building was occupied, the lighting in the file storage area was noted to be inadequate. The files are stored in tall rows of moveable shelves that block much of the light, making it difficult to read the files. Thirty light fixtures were added in this space in order to provide adequate lighting. The light fixtures used two T-8 lamps.

5.3 Mechanical Systems

Ground-source heat pumps with ERVs are the primary heating and cooling sources. All of the heat pumps, except number 16, are located in two mechanical rooms serving the east and west wings of the building. Table 5-1 lists the heat pump capacities and areas served. Heat pump 16 was installed in the telecommunications room after the first year of operation because heat pump 13 did not provide adequate cooling to this space. Heat pump 13 provides cooling to the entire northeast quadrant of the building, which is used mostly for storage and laboratory space. The telecommunications room has very different space conditioning requirements than the other areas, and the temperature sensor for controlling the heat pump is located in the storage area. Total rated cooling capacity for the building is 53.7 tons (189 kW), which is 640 ft^2/ton (2.6 m^2/kW).

Electric resistance heaters provide auxiliary heating for the heat pumps. Nine units have integral single-stage heaters and heat pumps 5 and 6 have duct-mounted, two-stage heaters. Electrical power was never wired to the duct-mounted heaters.

A schematic of the waterside loop for the HVAC systems is shown in Figure 5-3. Each heat pump has a dedicated series of one to three ¼-hp (190-W) pumps for groundwater circulation, which run continuously. The pumps are connected to common supply and return headers in each mechanical room.

Table 5-1 Cambria Office Heat Pump Schedule

	Heat Pump	Area Served	Cooling Capacity kBtu/hr *(kW)*	Auxiliary Heater kBtu/hr *(kW)*	Flow CFM *(l/s)*	Circulation Pumps
West Side	1	1st-floor lunch and storage	26 *(7.6)*	25.6 *(7.5)*	800 *(378)*	1
	2	1st-floor meeting room	60 *(17.6)*	51.2 *(15)*	2,000 *(944)*	*2*
	3	1st-floor south offices	42 *(12.3)*	25.6 *(7.5)*	1,400 *(661)*	*2*
	4	1st-floor reception, copy room, and conference room	22 *(6.4)*	25.6 *(7.5)*	800 *(378)*	1
	5	2nd-floor north	96 *(28.1)*	*	3,200 *(1,510)*	3
	6	2nd-floor south	72 *(21.1)*	*	2,400 *(1,133)*	2
East Side	11	1st- and 2nd-floor lobby	54 *(15.8)*	51.2 *(15)*	1,800 *(849)*	2
	12	Central files and library	54 *(15.8)*	51.2 *(15)*	1,800 *(849)*	2
	13	1st-floor labs, storage, and telecom room	70 *(20.5)*	51.2 *(15)*	2,400 *(1,133)*	2
	14	2nd-floor south	48 *(14.1)*	25.6 *(7.5)*	1,600 *(755)*	2
	15	2nd-floor north	70 *(20.5)*	51.2 *(15)*	2,400 *(1,133)*	2
	16 **	Telecom room	30 *(8.8)*	24 *(7.0)*	1,000 *(472)*	1
	Total		**644 *(189)***	**382 *(113)***	**21,600 *(10,193)***	**22**

*Heat pumps 5 and 6 have duct-mounted auxiliary heaters of unknown size with no power supplied to them.

**Heat pump 16 was added after the first year of operation to provide cooling directly to the Telecom room.

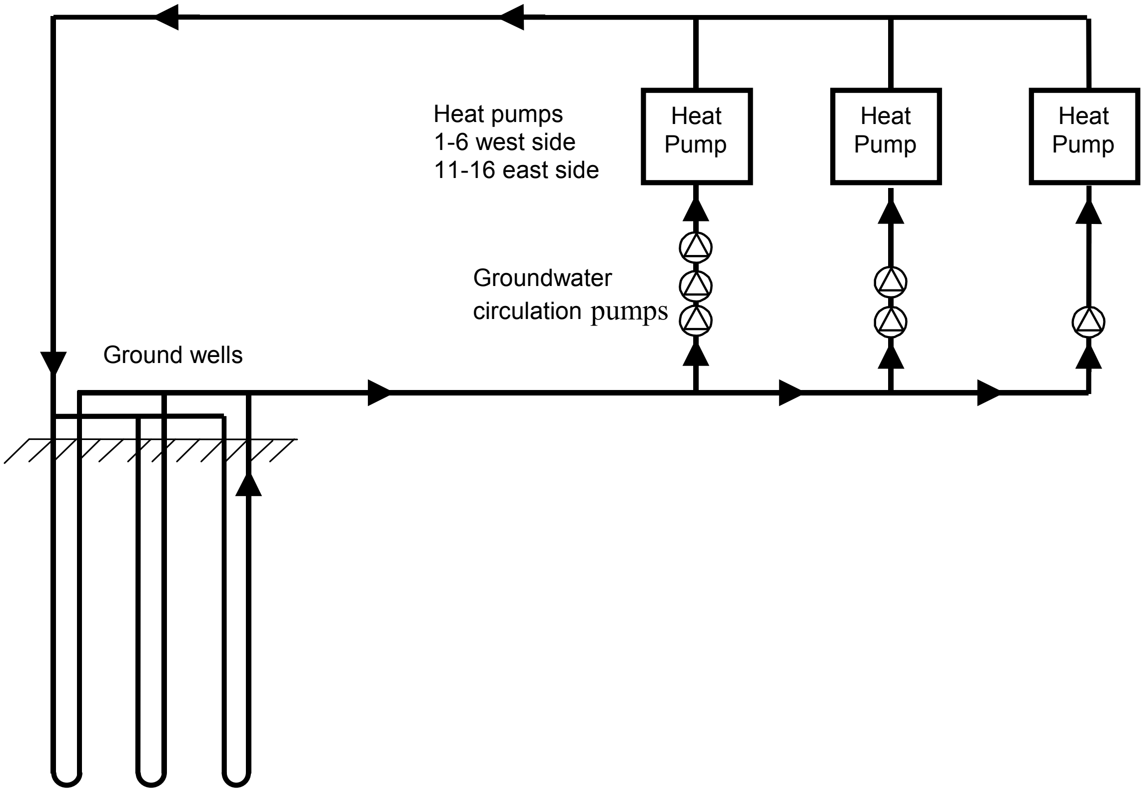


Figure 5-3 HVAC waterside schematic

A schematic of the airside loop for the HVAC systems is shown in Figure 5-4. Two ERVs, one for each wing, supply ventilation and exhaust air and are located on the roof. Each uses a fixed-plate, enthalpic heat-exchange core for both latent and sensible thermal energy recovery. They use constant volume supply and exhaust fans. The west ERV fans draw 8.5 kW and supply 3,000 cfm (1,400 l/s) of outside air, and the east ERV fans draw 4.5 kW and supply 1,500 cfm (700 l/s) of outside air. The outside air is preconditioned by the ERVs, then supplied to the mechanical rooms, which act as supply air plenums for the heat pumps. The constant volume fans in the heat pumps draw return air from central return air ducts for each floor and mix this with the preconditioned outside air in the mechanical rooms. Heat pump 16 is located in the telecommunications room, and therefore cannot use outside air from the ERVs.

The ERVs have simple on-off controllers located in the ERVs. Daily schedules can be input to the controllers. The design intent was to run the ERVs during operating hours and turn them off during nights and weekends. The heat pumps are separately controlled by dedicated programmable thermostats. The thermostats are located in the mechanical rooms and connected to temperature sensors located in the zones served by each heat pump. The design intent was to maintain constant temperature set points, and run the heat pump fans continuously during the day and as needed during nights and weekends to maintain temperature set points. There were no temperature setbacks or setups because it was thought that it would be difficult for the systems to recover and that there would be little or no energy savings.

The majority of the building uses a UFAD system with swirl diffusers mounted in the raised floor. The swirl diffusers are located in the common areas and in each office area, and they can be manually adjusted by the occupant to control the amount of air entering his or her workspace. Return air registers are located high in the spaces. The system uses a displacement ventilation principle by supplying fresh air near the occupants and removing the older stale air high in the space. Figure 5-5 shows the components of the raised floor system including a view of the manually operated swirl diffuser.

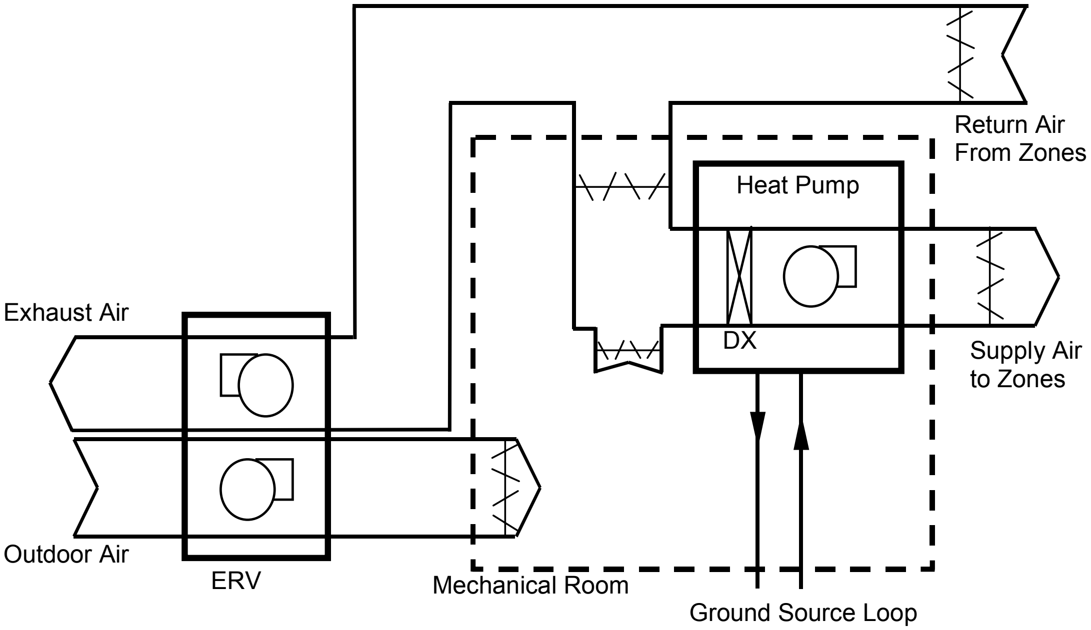


Figure 5-4 HVAC airside schematic

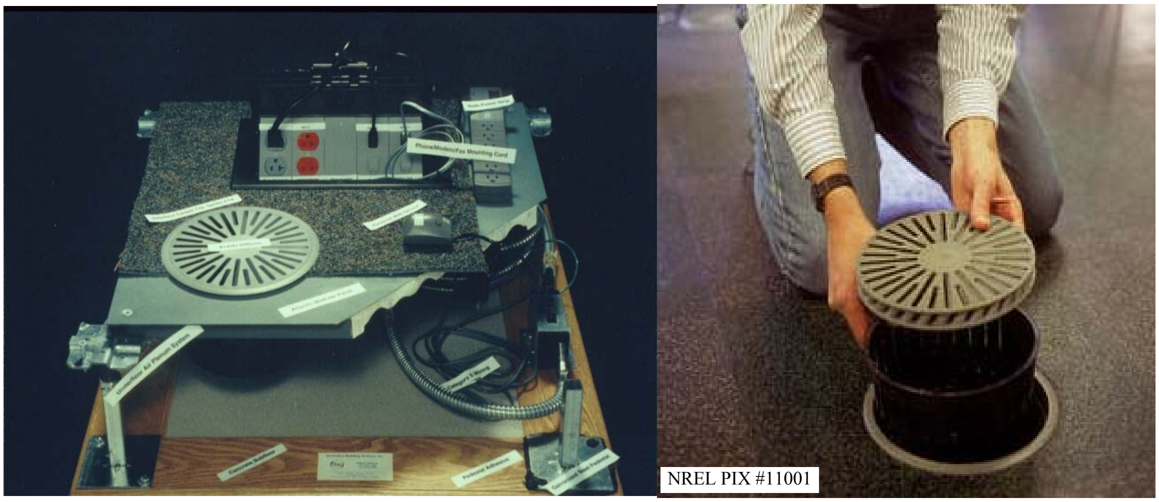

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Figure 5-5 Components of the raised floor system

5.4 Photovoltaic System

There are two PV systems on the building. A 17.2-kW system is mounted on the roof with a 15-kW, three-phase commercial grid-tied inverter; there is a 1-kW system mounted on two single-axis trackers in front of the building (Figures 1-1 and 5-1). Both systems use 43-W, amorphous-silicon PV panels to produce electricity. The large system feeds into the main distribution panel through a utility-grade power meter. The output of the inverter for the large system requires an isolation transformer to connect to the power grid. The transformer reduces the output of the system by approximately 3% when the system is operating, and it draws approximately 370 W of power when the PV system is not producing power. The small PV system has a single-phase, 1-kW inverter and feeds into the heating panel on the east side of the building. The energy output of only the large PV system is metered for the purposes of generating revenue.

6 Whole-Building Energy Evaluation

NREL evaluated the energy performance of the Cambria building with continuous end-use monitoring, analysis of utility bills, walk-through inspections of the building, spot measurements, and computer simulations. This section describes the monitoring plan and equipment, results, and comparison used to model baseline predictions. Guidance for monitoring and reporting the energy performance of commercial buildings can be found in *Procedure for Measuring and Reporting Commercial Building Energy Performance* (NREL 2005a).

6.1 Performance Monitoring Plan

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

1. Determine the energy use in the building systems.
2. Verify that the design performance objectives are being met.
3. Improve the performance of the building energy systems where possible.
4. Track systems to ensure long-term performance of the building.
5. Evaluate the lighting system performance including the effects of daylighting.
6. Evaluate the PV system performance.
7. Compare the building energy performance to an energy code-compliant building and to the typical building stock for this region.
8. Meet requirements of the LEED Green Building Rating System™ Version 2.0 Energy Credit 5 – Measurement and Verification, the intent of which is to “provide for the ongoing accountability and optimization of building energy and water consumption performance over time.”

In order to satisfy these objectives 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 electricity
3. Total electrical power at 15-minute increments
4. Electrical power of major end uses at 15-minute increments
5. Electrical energy delivered to the building by the PV system in 15-minute increments
6. Weather data including dry-bulb temperature, RH, horizontal and PV plane solar radiation, and PV system cell temperature.

There are four energy-monitoring systems in the Cambria building. The building’s net electrical energy use is measured by the utility power meter. Another utility grade meter monitors the energy production of the large PV system. A SquareD PowerLogic® monitoring system monitors the energy use in each of the 10 major electrical panels. Finally, a Campbell Scientific CR10X data logger is used to monitor the space temperatures, RH and CO_2 levels, the weather station, and both PV systems.

The PowerLogic electrical monitoring system was part of the building design and was installed by the building contractor. The system consists of 10 Enercept power meters and a personal computer that polls the meters and records the data every 15 minutes. Table 6-1 shows the electrical panels and the loads monitored by this system. The personal computer has remote control software and is connected to a phone line to allow remote access for data retrieval. The system began storing monitored data near the end of June 2001.

Table 6-1 Electrical Panels on the Electrical Monitoring System

Electrical Panel	Loads
1st E heat panel	heat pumps, fans, circulation pumps, water heater
1st E light panel	lights
1st E rec panel	telephones, water cooler, freezer, receptacles
1st W heat panel	heat pumps, fans, circulation pumps
1st W light panel	lights
1st W rec panel	receptacles, break room loads
2nd light panel	lights, water cooler, sprinkler compressor
2nd rec panel	receptacles
Elevator	elevator
EMR panel	egress lights, exit signs, fire panel

The electrical monitoring system and the associated computer has proven to be difficult to use and not very reliable. The meters have no memory and can only relay instantaneous readings; therefore, only the instantaneous power is known at 15-minute increments and not the energy consumed. If the personal computer fails, there is a loss of data until the computer is manually rebooted. The downtime of the personal computer has resulted in a loss of more than 30% of the data for the two-year monitoring period. Some months have no missing data; two months have no data. In addition, the data are stored in weeklong increments in database files. These files are large and fill up the hard drive space quickly, and they make data retrieval difficult because only one week at a time can be accessed. The computer assigned to this system was old, and its small hard drive filled up near the end of June 2003. The computer was not maintained or replaced; therefore, no archived data were available from this system starting in July 2003.

The Campbell Scientific data logger was installed by a DEP contractor to monitor the space conditions in each of the four quadrants on the second floor and the southwest quadrant and main conference room on the first floor. These measurements consist of the temperature, RH, and CO_2. Originally, the data logger was programmed to record data every 10 minutes. NREL installed additional instrumentation to monitor the PV systems and the weather and connected them to this data logger. The data logger was reprogrammed to record the totals or averages of each variable every 15 minutes and record the total PV power every minute. A personal computer is dedicated to poll the data logger every two hours to collect the new data. The data logger has enough memory to go for approximately one month without overwriting the 15-minute data. An external memory module is also attached to the data logger that can store nearly two years of 15-minute data. A description of the data points and monitoring frequency on the data logger are shown in Table 6-2.

Table 6-2 Monitoring Points and Frequency on the Campbell Scientific Data Logger

Data Point	Frequency
Space temperature (6 points, time averaged)	15 min
Space RH (6 points, time averaged)	15 min
Space CO_2 (6 points, time averaged)	15 min
Space CO_2 (6 points, maximum)	15 min
Outdoor temperature	15 min
Outdoor RH	15 min
Global horizontal solar radiation	15 min
Global PV-plane solar radiation	15 min
PV cell temperature	15 min
Main PV system AC voltage (3 phases)	15 min
Main PV system power production	15 min and 1 min
Main PV system power consumption	15 min and 1 min
Small PV system power production	15 min and 1 min

Several performance metrics are used to examine the energy performance of the building. The *Procedure for Measuring and Reporting Commercial Building Energy Performance* (NREL 2005a) describes these metrics and the methods of determining them in detail. This section uses these performance metrics to analyze the energy performance at various levels. The first level of analysis is on an annual basis from the utility bills. Monthly energy consumption by end use is used to examine the energy distribution and the seasonal variations. Average daily profiles are used to analyze the daily energy use patterns. Whole-building energy simulations are used to determine the performance compared to an energy code-compliant building for typical weather. The simulations are used to examine the effects of changing the energy systems in the building. Finally, the building is rated using the ENERGY STAR® Portfolio Manager.

6.2 Measured Energy Performance

6.2.1 Annual Energy Performance

Analyzing utility bills was the only method available for determining total energy use before July 2001. Table 6-3 summarizes energy use and peak demand for the Cambria building from 2001 to 2003 using the utility bills and PV monitoring. Net site energy use gives credit for electricity generated on site by the PV system; total site energy use is the total electricity consumed. The heating degree-days (HDDs) and cooling degree-days (CDDs) are also included for comparison of the weather years.

Table 6-3 Annual Energy Use from Utility Bills

Performance Metric	2001	2002	2003
Net site electrical energy – MMBtu/yr *(GJ/yr)*	1,446 *(1,526)*	1,242 *(1,310)*	1,243 *(1,311)*
Total site electrical energy – MMBtu/yr *(GJ/yr)*	1,496 *(1,578)*	1,269 *(1,339)*	1,262 *(1,331)*
Net PV energy production – MMBtu/yr *(GJ/yr)*	50 *(53)*	27 *(28)*	19 *(20)*
Percent total energy from PV system	3.3%	2.2%	1.5%
Average monthly peak demand (kW)	80	82	83
Maximum peak demand (kW)	(Feb) 90	(Dec) 99	(Jan) 95
Average load factor	59%	50%	50%
Net site purchased energy cost	$28,120	$29,919	$35,197
HDDs (55°F [13°C])	6,117	5,886	6,554
CDDs (55°F [13°C])	2,469	2,885	2,501

Source energy is a measure of the energy required to supply the energy in the form it is used at the site. Appropriate source energy conversion factors for the Cambria building are difficult to determine because electricity is provided through an energy contract from a supplier that specializes in distributing electricity generated by renewable sources. The contract leads to a real increase in energy costs, but in theory, should reduce the source energy use attributed to operating the Cambria building. If we assume that only transmission losses apply and a source energy conversion factor of 90% is applicable, the annual net source energy use was 1,607 MMBtu/yr (1,695 GJ/yr) for 2001 and 1,379 MMBtu/yr (1,455 GJ) for 2002. However, if we assume that a national average source energy conversion factor of 31.6% applies, the annual net source energy use was 4,580 MMBtu/yr (4,832 GJ) for 2001 and 3,935 MMBtu/yr (4,150 GJ) for 2002 and 2003. The details of how the conversion factor was calculated are included in Appendix D.

The EUI, which is the annual energy use per square foot, provides a succinct method of representing energy performance. Table 6-4 lists results for EUI and energy cost intensity based on a building area of 34,500 ft^2 (3205 m^2).

Table 6-4 Energy Use Intensity Results from Utility Bills

Performance Metric	2001	2002	2003
Net Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	42 *(477)*	36 *(409)*	36 *(409)*
Total Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	43 *(488)*	37 *(420)*	37 *(420)*
90% Net Source EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	47 *(534)*	40 *(454)*	40 *(454)*
31.6% Net Source EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	133 *(1,510)*	114 *(1,295)*	114 *(1,295)*
Net Site Energy Cost Intensity – $/$ft^2$·yr *($/m^2·yr)*	0.82 *(8.83)*	0.87 *(9.36)*	1.02 *(10.98)*

6.2.2 Monthly Energy Performance by End Use

The monthly daily average energy consumption by end use was calculated from the 15-minute instantaneous power readings from the electrical monitoring system assuming an average power for the previous 15-minute period. There are two potential errors with this method. The first is that almost one-third of the data were missing due to failures in the monitoring system, and the second is the assumption that the average power over a 15-minute period may not be represented well by one instantaneous reading. Fortunately, the power levels in this building are relatively constant during the occupied and unoccupied periods, and averaging the values over the period of a month should produce reasonable results. NREL checked this method of predicting the monthly daily average energy totals by comparing the total building energy consumption from the electrical monitoring system to the utility bills plus the energy produced from the PV systems. This comparison is shown in Figure 6-1. The average difference is −1.7% and the largest monthly difference is −7.3%. Therefore, it is reasonable to use the values from the PowerLogic system to estimate the monthly daily average energy consumption of the major end uses for comparison purposes. Note that the data are completely missing for November and December 2002.

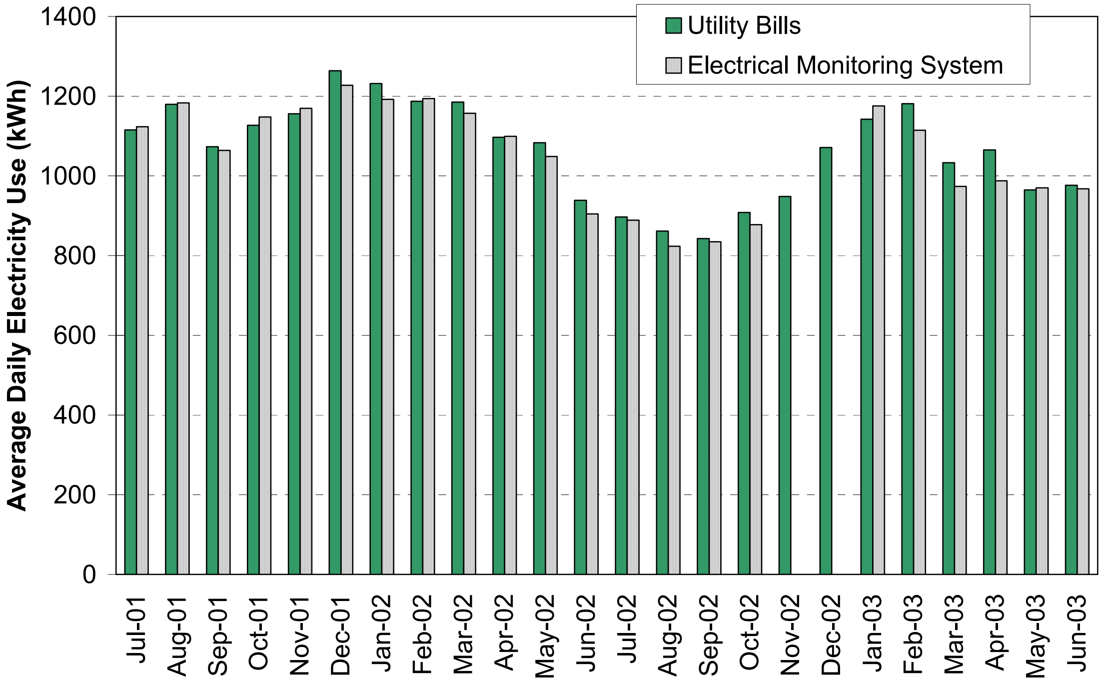

Figure 6-1 Comparison of the monthly daily average total energy consumption

The weather conditions are important drivers of the energy use in buildings. The monthly HDD (base 55°F [13°C]) and CDD (base 55°F [13°C]) are shown in Figures 6-2 and 6-3. The data for January 2001 to June 2001 is adjusted from a Federal Aviation Administration weather station at the Blair County Airport in Altoona, Pennsylvania (Appendix C). Starting in July 2001, weather data were measured at the building site. Notice that the summer of 2002 was much warmer than the summers of 2001 and 2003, with 1,850ºF·days (1,028ºC·days) CDD from May to September 2002 versus 1,446ºF·days (803ºC·days) CDD for 2001, and 1,455ºF·days (808ºC·days) CDD for 2003. In addition, the winter of 2002–2003 was colder than the winter of 2001–2002, with 3,256ºF·days (1,809ºC·days) HDD for December to March 2002–2003 versus 2,445ºF·days (1,358ºC·days) HDD for December to March 2001–2002.

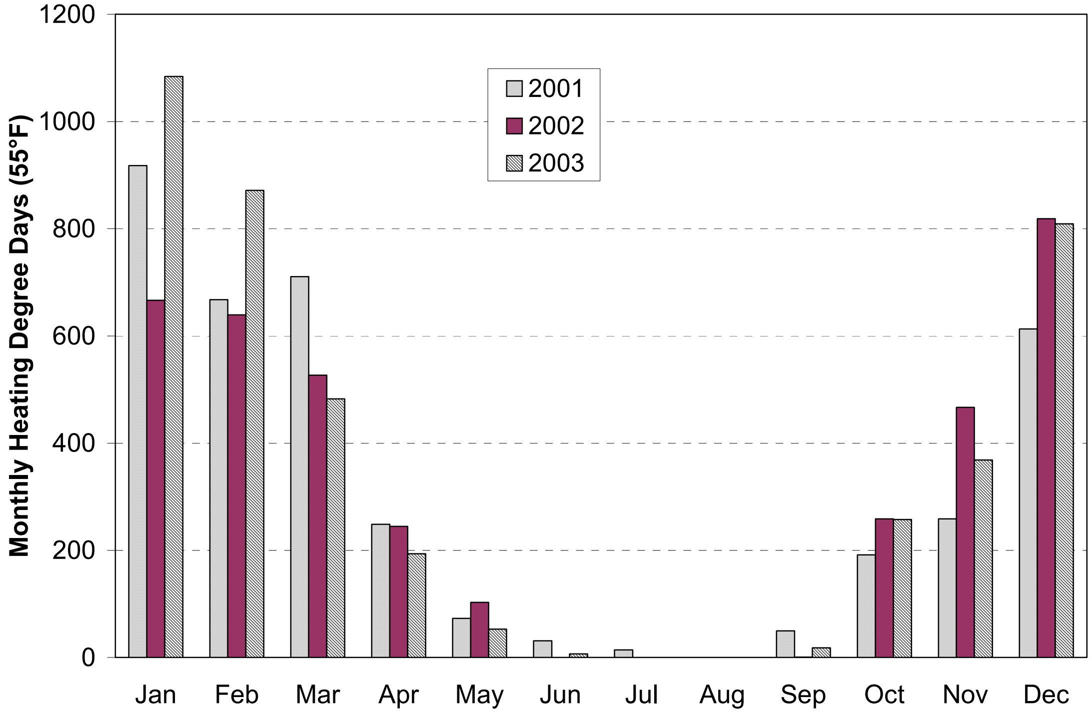

Figure 6-2 Monthly HDDs (base 55°F [13°C])

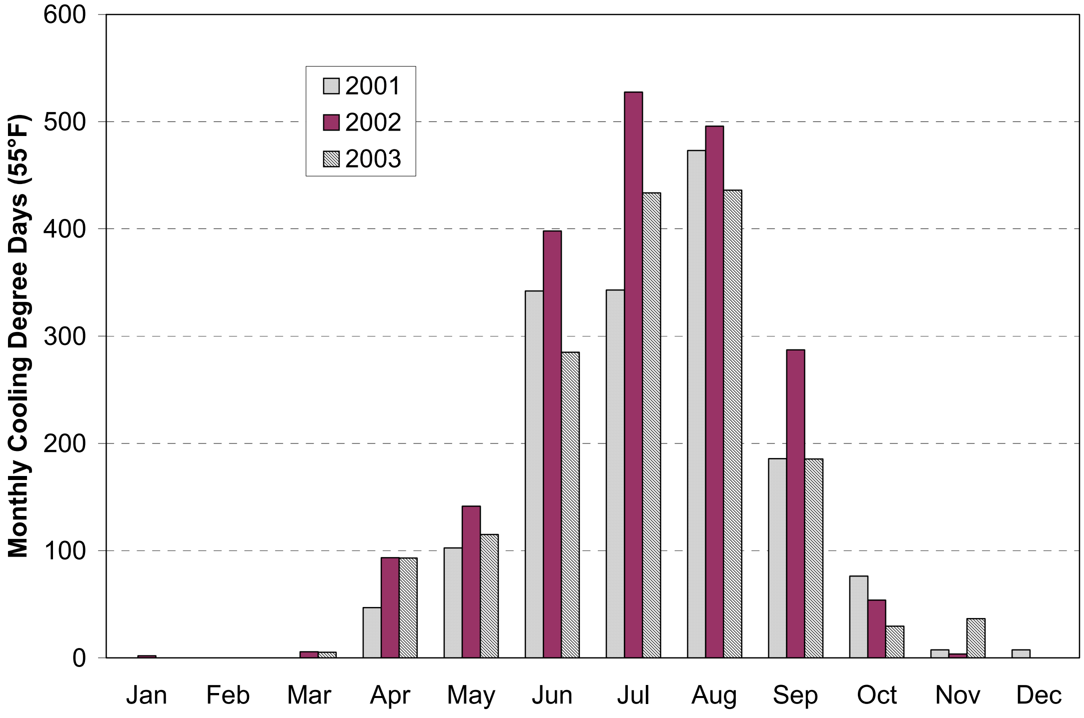

Figure 6-3 Monthly CDDs (base 55°F [13°C])

The breakdown of energy consumption by end use is shown in Figures 6-4 and 6-19, for weekdays and weekends/holidays. These figures show the average daily energy use by month for the HVAC, lighting, and plug loads for July 2001 through June 2003. These graphs also show the energy production by the PV systems. The PV system monitoring began in June 2002 on the Campbell data logger system. In addition, the average monthly outdoor dry-bulb temperature is shown on the graphs.

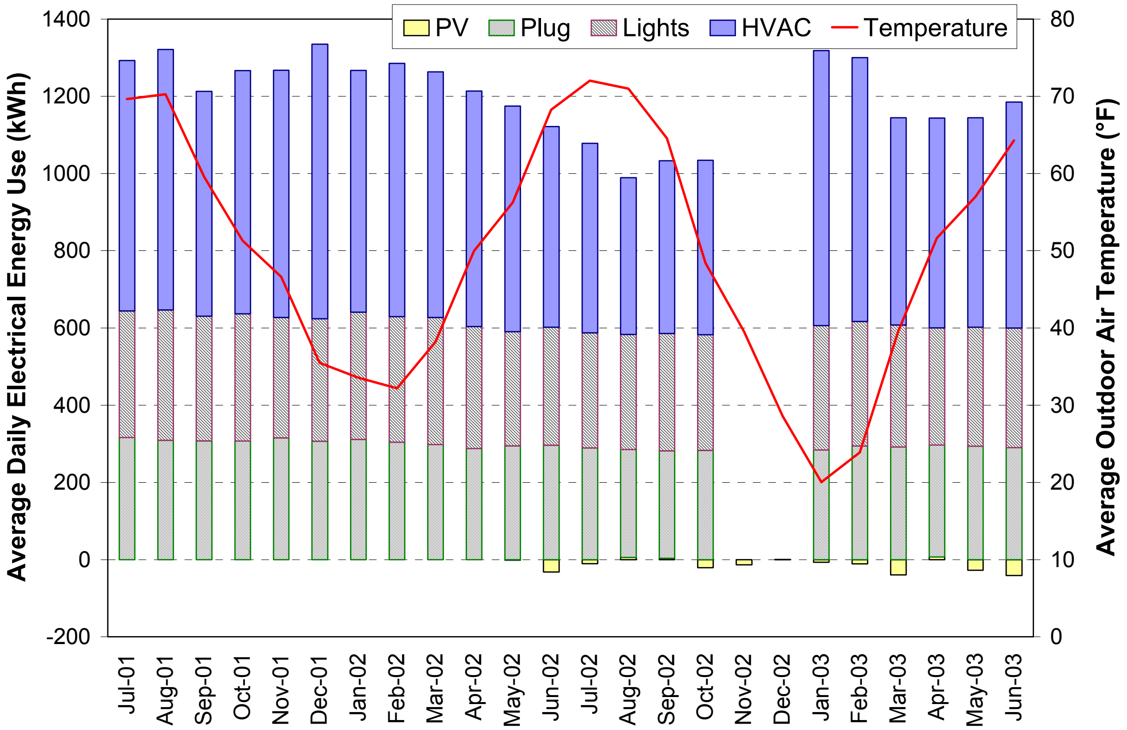

Figure 6-4 Daily average energy use and PV production for weekdays from July 2001 to June 2003 (PV system monitoring began in June 2002)

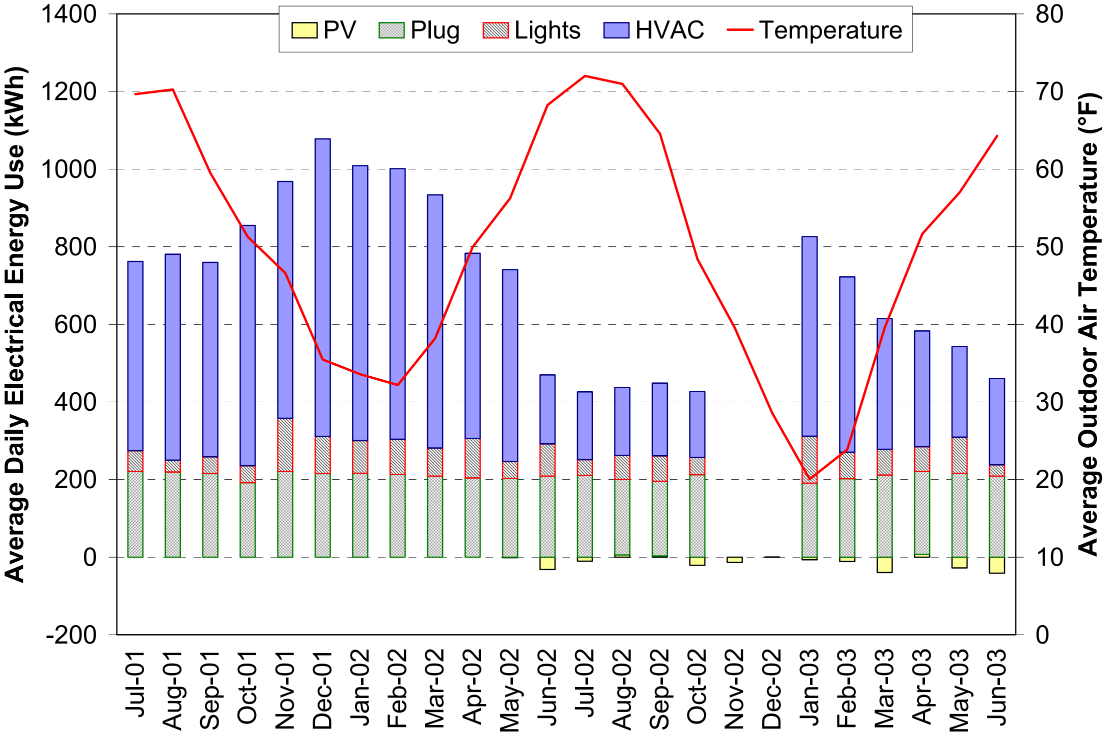

Figure 6-5 Daily average energy use and PV production for weekends/holidays from July 2001 to June 2003 (PV system monitoring began in June 2002)

The energy use for plug loads is similar from month to month, which is expected in an office building with consistent schedules. The lighting loads show a slight increase in the winter, which is mostly due to increased use of exterior and manually controlled interior lights. Overall, the HVAC systems consume approximately 55% of the total energy, the lights 21%, and the plug loads 24%.

The weekday HVAC energy use had smaller than expected variations in weather conditions from July 2001 to May 2002. An investigation of the HVAC controls revealed that the controller on the west ERV was incorrectly set. The schedule to turn the unit off was programmed correctly, but it was not activated, which left the unit running continuously. In addition, the heat pump fans ran continuously and there was no setback on the heat pump thermostats. The effect of these control problems can also been seen in the weekends/holidays HVAC energy use. The HVAC energy use for winter weekends/holidays was actually higher than the weekday energy use. This was due to the high amount of outside air being brought into the building by the west ERV when there were minimal internal gains to help heat the building.

Changes were made to the HVAC controls at the beginning of June 2002. The controller on the west ERV was correctly programmed to turn on at 6:00 a.m., turn off at 5:00 p.m. Eastern Standard Time (EST), Monday through Friday, and stay off on the weekends. The east ERV was set to the same schedule. The thermostats were reprogrammed with cooling set points of 72°F (22°C) and 78°F (26°C) and heating set points of 70°F (21°C) and 66°F (19°C) during occupied and unoccupied periods. The occupied hours were set from 5:00 a.m. to 6:00 p.m. EST. In addition, the clock on HP11 was off by 12 hours; therefore, reprogramming with a setback caused it to come on at night and turn off during the day. The clock was reset to the correct time.

The effects of these changes are most noticeable in the weekend/holiday HVAC energy use in Figure 6-19, which shows a large drop from May to June 2002. The weekend/holiday HVAC energy use for the remainder of the monitoring period remained lower than the previous year's values despite a warmer summer and a colder winter. The lower energy use is also evident in the weekday graph in Figure 6-4.

The average daily HVAC energy use for July 2002 is more than 100 kWh less than the July 2001 value, even with nearly twice as many CDDs in July 2002 as in July 2001.

After the thermostats were adjusted, there were some comfort complaints in isolated parts of the building, which led DEP to remove the heating setbacks and cooling setups on all the thermostats. In one case, the thermostat was set with a higher heating temperature at night than during the day. The main heating problem was in the upstairs restrooms, which have an outside wall but no direct heating source. The restrooms rely on the exhaust fans drawing warm air from the main part of the building. All of the thermostats were reprogrammed in July of 2003 with less aggressive setback and setup schedules. The thermostats were reprogrammed with cooling set points of 72°F (22°C) and 76°F (24°C) and heating set points of 72°F (22°C) and 68°F (68°C), and the occupied hours were set to 4:00 a.m. to 6:00 p.m. EST. A more detailed examination of the HVAC systems is completed in Section 7.1.

The plug loads remain high during the weekend/holiday periods. The plug load power level during unoccupied periods is approximately half of the value during occupied periods. This is due to a large amount of electrical equipment being left on continuously. A more detailed examination of the plug loads is completed in Section 7.3.

The PV systems provided between –0.7% and 4% of the overall monthly energy consumption in the building. The inconsistent system performance is mainly due to the poor performance of the inverter on the large PV system. The negative percentage is due to the energy consumption by the isolation transformer when the system is not producing power. A more detailed analysis of the PV systems is contained in Section 7.4.

6.2.3 Average Daily Profiles

Another way to examine energy use is to plot the average daily load profiles by month. This aggregates the monthly data into one graph and allows a view of the daily and seasonal variations. Daily load profiles were created from the PowerLogic data for weekdays and for weekends/holidays for every month during the data-monitoring period. The seasonal variations in the building daily load profiles from 2001 to 2003 are shown in Figures 6-6 and 6-7. The dates for the graphs were set because July 2001 was the first full month of data collection and changes were made to the HVAC control systems in June 2002 that had a significant impact on the energy consumption. The most noticeable differences between the two figures is that the nighttime loads are higher in Figure 6-6 and the daytime loads for July and January are higher in Figure 6-7. Changes to the HVAC control settings (Section 7.1) lowered the nighttime loads. Some of these changes were reversed by January 2003, resulting in an increase in the nighttime loads. The daytime loads are higher in Figure 6-7 because the weather in July and January was more severe (hotter or colder) than in the months in Figure 6-6. The weather differences are seen in the HDD and CDD as shown in Figures 6-2 and 6-3.

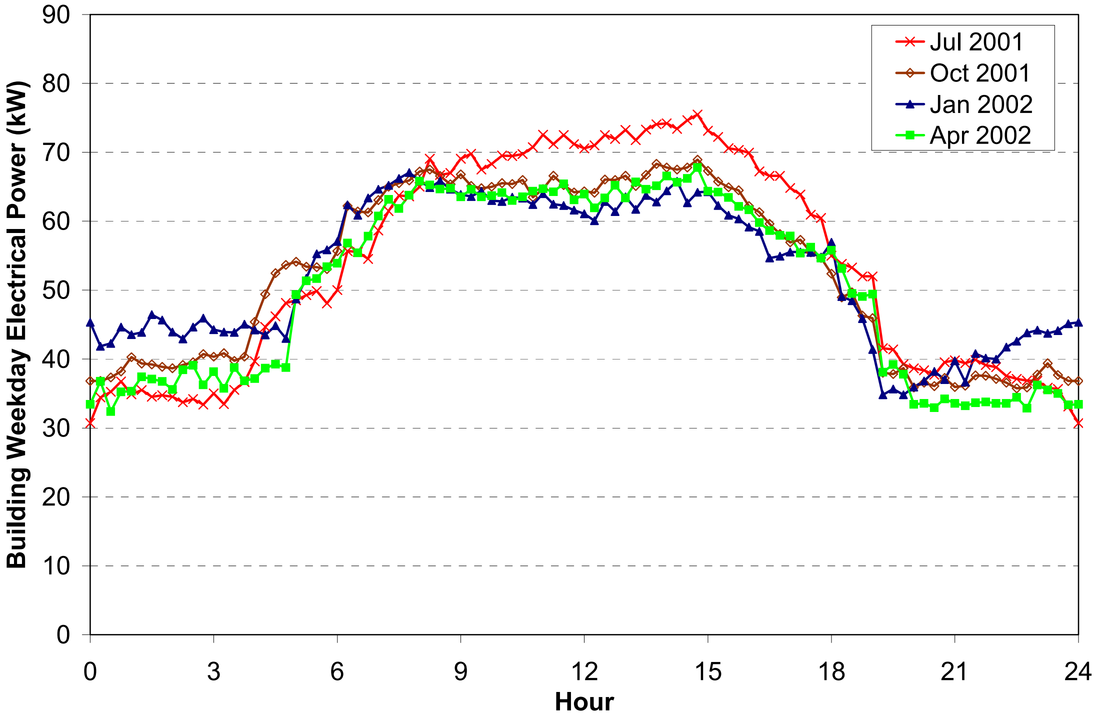

Figure 6-6 Average daily building load profile for weekdays (2001–2002)

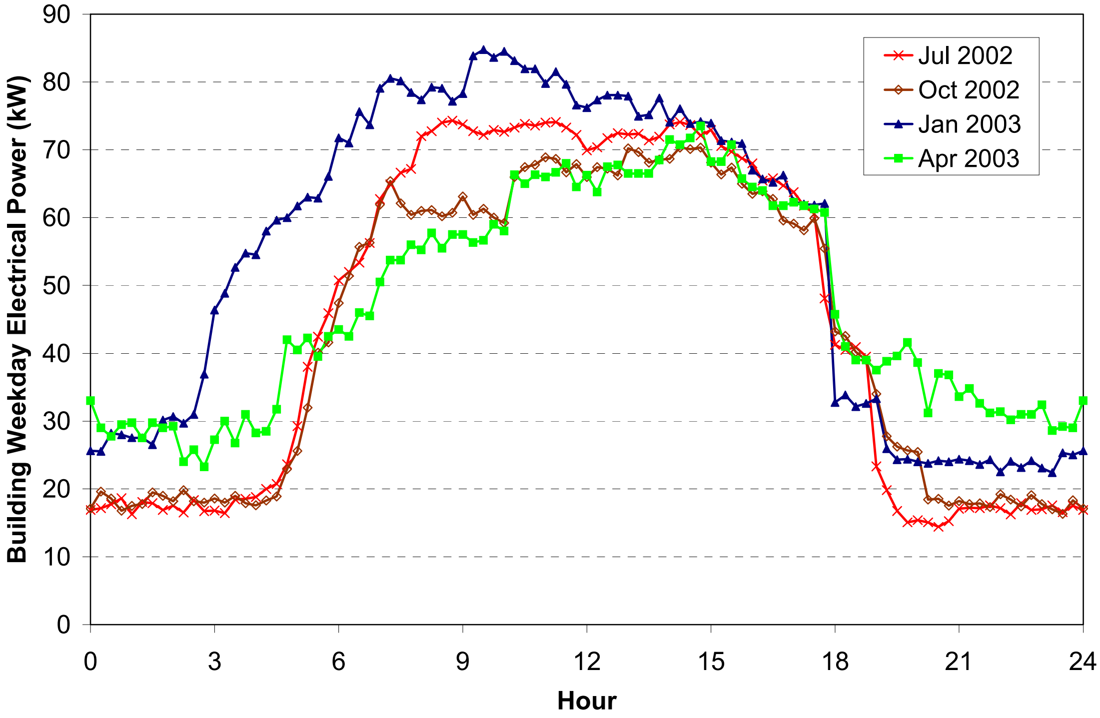

Figure 6-7 Average daily building load profile for weekdays (2002–2003)

6.3 Whole-Building Energy Simulation Analysis

Computer modeling was used to provide a means of comparing the actual performance of the Cambria building to what it would have been were it built to meet the minimum standards of the energy code. The simulation models used in the design phase were updated and calibrated to match the as-built building. A baseline energy model was developed to meet the minimum standards of ASHRAE Standard 90.1-2001 (ASHRAE 2001). An informative addition to the standard, Addendum e, was developed that provides a method of applying the Energy Cost Budget method to rating buildings that perform better than required by the standard (ASHRAE 2002 and 2003). This addendum is included in Standard 90.1-2004 as Appendix G. The Baseline Building Model used a packaged heat pump for heating because natural gas is not available at the building. The models were calibrated using measured weather and energy consumption data for 2002 and used schedules for occupancy and receptacles developed from measurements. Then the calibrated As-built and As-Built Baseline Models were run with a "typical" year weather file from Pittsburgh, which is the closest location with a TMY2 weather file.

The simulation models used in the design phase used ASHRAE's WYEC weather data for Pittsburgh, Pennsylvania. WYEC data were used because the simulation appeared unstable when the preferred TMY2 weather files were used. While using the model to develop the calibrated version, an error was found in the performance curves for the cooling operation of the ground-source heat pumps. One of the points in the performance curve was far out of range. The cooling performance curves were reset to the library values for water-loop heat pumps. Subsequent runs with Pittsburgh TMY2 weather data showed no instabilities, and the TMY2 weather data were used for the remaining simulations.

6.3.1 Model Calibration

The Design Building Model and the Design Baseline Building Model were calibrated to more accurately describe the actual equipment loads and building use, and hence, provide better prediction of actual energy use. The calibrated model is called the As-Built Model. The information for adjusting the As-Built Model came from several sources:

- Ongoing measured electricity use from three sources: 1) the total metered utility electricity use (kWh and monthly peak kW), 2) the total roof-mounted PV array electricity production (monthly kWh), and 3) the PowerLogic system that monitors power in each of 10 major electrical panels (15-minute kW)
- Hand measurements of typical electrical loads connected to the panels
- Observations of occupancy patterns, thermostat settings, time clock settings, and other operating characteristics
- Ongoing measurements of local weather data, including horizontal solar radiation, outside dry-bulb temperature, and outside RH.

The simulation model was calibrated using data from 2002. One problem in the calibration process is selecting a period with good data, few changes in operations, and that represents seasonal variations. The year 2002 was selected because the building had been in use for slightly more than a year and most of the operations were consistent. The period between January and May was selected because there were no changes in the operation of the building. Starting in June 2002, NREL changed the thermostats and reprogrammed the west ERV to turn off at night.

We used weather data measured on site and from nearby weather stations to create a TMY2 style weather file for 2002. The weather file was used to calibrate the As-Built Model against measured building energy performance. The details of how this file was created are contained in Appendix C.

The first step in calibrating the models is to make sure that the model parameters match the as-built building. Several adjustments were made to the models based on the all the available information regarding the building construction and operation.

- Energy consumption of major components, including the circulation pumps for the ground loop, HVAC fans, ERV fans, lights, and plug loads
- Hourly schedules that describe energy use, or occupancy, changes over the course of a weekday and a weekend/holiday day
- Operating set points, such as thermostat settings and supply air temperature.

Component Power Levels

The power levels for major building components as measured and as simulated in the Design Building Model are listed in Table 6-5. In most cases, the model had significantly lower power levels than the actual building. The lower power levels are especially significant for the ERVs, which also had longer run times than anticipated in the model. The power levels for all of these components were adjusted in the As-Built Model to match the measured values.

Table 6-5 Comparison of Measured Power Levels with the Design Building Model (before calibration)

Item	Measured (kW)	Design Building Model (kW)	Model Difference (%)
Pumps-ground loop	4.06	2.60	–36.0
Fans-HVAC	8.60	9.23	7.3
ERVs	13.00	5.22	–59.8
Lights	21.90	18.64	–14.9
Equipment (plug)	17.80	17.80	0.0

Hourly Schedules

The Design Building Model had a maximum occupancy of 120 people with a maximum scheduled diversity of 0.8 or 96 people. Observations reported by DEP staff indicated a maximum typical occupancy of 70 people (maximum scheduled diversity 0.58 based on 120 people). Total weekday occupancy-hours are 743 modeled versus 706 reported. The As-Built Model was adjusted to use the reported weekday profile as shown in Table 6-6. For Saturdays, three occupants are assumed from 8:00 a.m. until 12:00 p.m. For Sundays and holidays, occupancy is assumed to be zero. The domestic hot water schedule was changed to reflect the occupancy schedule.

The Design Building Model had a maximum lighting power of 23.3 kW with a maximum scheduled diversity of 0.80, or 18.6 kW. The measured average maximum was 21.9 kW. Average daily usage in the Design Building Model was 226 kWh, and the measured value is 310 kWh (37.4% more). The As-Built Model weekday lighting schedule shown in Table 6-6 was generated using the measured data for January through October 2002. The lighting load profile varied little from month to month as can be seen in Figure 7-19. The measured lighting energy use for weekends and holidays is not consistent due to the number of holidays that fall on a weekday and the inconsistent use of the building on the weekends. The weekend and holiday lighting schedule for the As-Built Model was set to be nearly constant and was created to match the average daily total measured energy use of 69 kWh.

The Design Building Model had a maximum equipment power of 22.2 kW with a maximum scheduled diversity of 0.8, or 17.8 kW. The measured average maximum was also 17.8 kW. However, the Design

Building Model assumed an average daily consumption of 138 kWh, but the measured value is 292 kWh (112% more). The weekday plug load schedules shown in Table 6-6 were created to match the measured load profiles shown in Figure 7-20. The Design Building Model assumed zero energy consumption for plug loads on the weekends and holidays; however, the measured value is 207 kWh. The As-Built Model schedule was modified to produce a flat profile that matches the measured average daily energy use.

Table 6-6 Calibrated Hourly Schedules for the As-Built Model

Schedule	Max Value	Fraction of Max Value for Hours 1–12											
		1	2	3	4	5	6	7	8	9	10	11	12
Occupancy WD	120	0.0	0.0	0.0	0.0	0.0	0.0	0.04	0.50	0.58	0.58	0.58	0.58
Lights WD	23.3	0.13	0.13	0.13	0.15	0.24	0.72	0.90	0.92	0.94	0.94	0.94	0.94
Lights WEH	23.3	0.13	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.13	0.14	0.15
Plugs WD	22.2	0.40	0.40	0.40	0.40	0.40	0.42	0.53	0.73	0.80	0.80	0.80	0.75
Plugs WEH	22.2	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.38	0.39	0.39	0.39	0.39

Schedule	Max Value	Fraction of Max Value for Hours 13–24											
		13	14	15	16	17	18	19	20	21	22	23	24
Occupancy WD	120	0.42	0.58	0.58	0.58	0.50	0.25	0.08	0.00	0.00	0.00	0.00	0.00
Lights WD	23.3	0.93	0.93	0.94	0.9	0.83	0.66	0.40	0.11	0.12	0.14	0.14	0.13
Lights WEH	23.3	0.14	0.13	0.13	0.13	0.11	0.08	0.08	0.07	0.11	0.14	0.13	0.13
Plugs WD	22.2	0.74	0.78	0.77	0.64	0.51	0.44	0.42	0.41	0.41	0.41	0.41	0.41
Plugs WEH	22.2	0.39	0.39	0.39	0.39	0.39	0.38	0.39	0.39	0.38	0.39	0.39	0.38

Set Points and Other Changes to the Model

A few other changes were made to the model based on observations made by NREL and 7group during site visits:

- Thermostats in the original model were 72°F (22°C) heating, 74°F (23°C) cooling, with no setback or setup. These were changed in the calibrated model to 70°F (21°C) heating, 72°F (22°C) cooling to match the building thermostat set points. The set points during the period used for calibration were constant.
- The original model used a supply air temperature for cooling of 63°F (17°C), as representative of UFAD systems. However, the supply air temperature in the building was measured to be closer to 55°F (13°C).

The next step in the calibration process was to run the simulation and compare the results with the measured data. As stated earlier, the period from January to May 2002 was selected as the calibration period. The plug load and lighting profiles were adjusted to match the measured data from January to May 2002. Using these adjusted profiles, the As-Built Model was compared to the energy use measured by the PowerLogic system. The energy use from the calibrated model was compared to the measured energy use from the PowerLogic system and the utility bills in Figure 6-8 and Table 6-7.

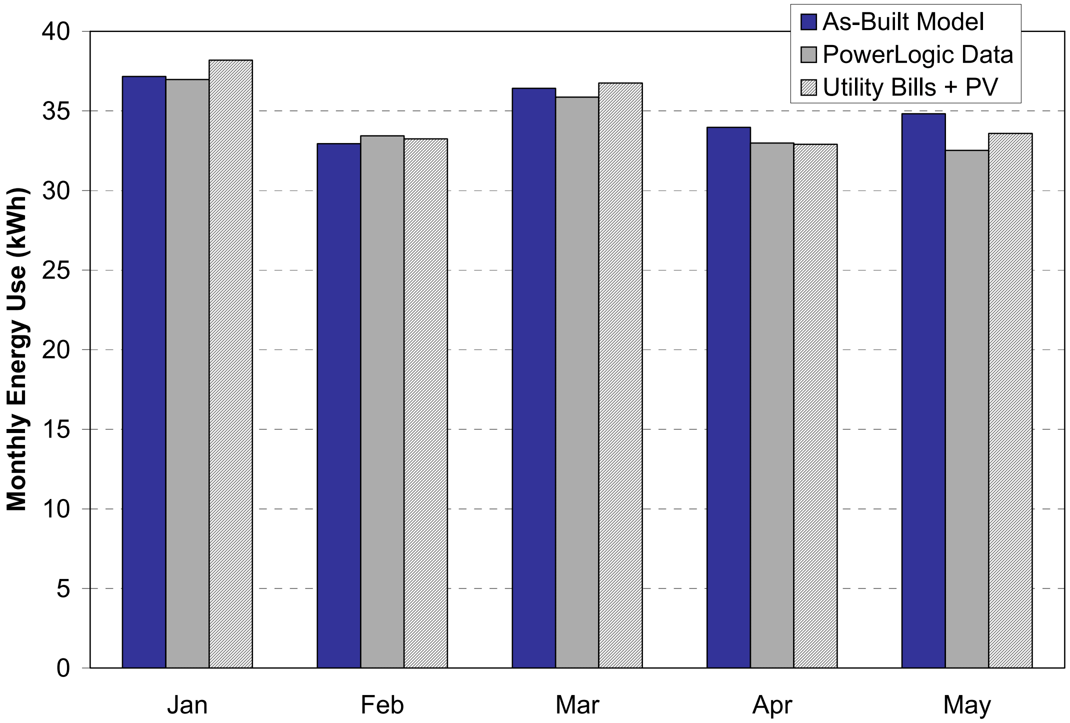

Figure 6-8 Energy use from the calibrated simulation model and measurements for five months in 2002.

Table 6-7 Percentage Difference between the Calibrated Model Energy Use and the Measured Energy Use

Month	Utility Bills[1]	PowerLogic Data			
	Total	Total	HVAC	Lights	Plug
Jan	–2.7%	0.5%	4.1%	–3.6%	–3.8%
Feb	–0.9%	–1.5%	–0.6%	–3.4%	–1.7%
Mar	–0.9%	1.6%	1.9%	0.9%	1.4%
Apr	3.2%	3.0%	6.6%	–4.6%	2.5%
May	3.7%	7.1%	7.7%	12.2%	1.8%
Total	0.4%	2.1%	3.8%	0.1%	0.0%

[1] The utility bill energy use is the sum of the utility bill adjusted to the calendar month plus the separately metered contribution from the roof-mounted PV array.

The utility bills are the best reference for calibration because of the high accuracy of the utility meter and the large number of missing data from the PowerLogic system. There is fair agreement between the As-Built Model and the utility bills, with the As-Built Model only 0.4% higher for the five months and the largest monthly difference is only 3.7% higher. However, there is a tendency to underpredict the energy in the heating months and overpredict the energy in the cooling months. Looking at the comparison of the end-use data from the PowerLogic system, there is no clear answer for the behavior of the model.

The lighting energy in the simulation model follows the same schedule for the entire year, but the lighting energy in the building has variations due to cleaning crew and occupant behaviors. The modeled HVAC energy varies the most from the PowerLogic data. The HVAC system is complex from a heat transfer point of view. The pumps and fans are simple to model because they are constant speed and ran continuously during the calibration period, except for the east ERV fans, which only ran during the day. The ground-source loop is difficult to model because of the many unknowns and complex heat and moisture transfer in the soil. The compressor model is the default one and not that of the actual compressor operation. The UFAD system is also difficult to simulate because the mathematical models assume a well-mixed zone at a single temperature. Some of the variation in the HVAC loads is caused by the difference in the lighting and plug loads. The underprediction of the lighting and plug loads in January means that more heat will have to come from the HVAC system. The overprediction of the lighting and plug loads in May requires more cooling from the HVAC system.

The next step was to update the Design Baseline Model to reflect the calibration used in the As-Built Model. This process was completed in accordance with ASHRAE 90.1-2001 Addendum e. The building size and schedules were changed to match the As-Built Model, and the new model was named the As-Built Baseline Model.

6.4 Whole-Building Energy Performance Results

Once the energy simulation models were calibrated, they were run with the Pittsburgh TMY2 weather file to predict the energy performance of the building with typical year weather data. Results from this modeling are shown in Table 6-8. Note that these numbers represent the energy consumption in the building and do not include the energy supplied by the PV systems.

Table 6-8 Facility Energy Performance from Calibrated As-Built Models with Pittsburgh TMY2 Weather File

Performance Metric	Baseline	As-Built	Savings
Total Site EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	57 *(642)*	34 *(386)*	40%
90% Total Source EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	63 *(715)*	38 *(428)*	40%
31% Total Source EUI – kBtu/ft^2·yr *(MJ/m^2·yr)*	180 *(2,044)*	108 *(1,226)*	40%
Total Site Energy Cost Intensity – \$/ft^2·yr *(\$/m^2·yr)*	1.80 *(19.38)*	1.02 *(10.98)*	43%

The baseline modeling allows the energy performance of the Cambria building to be characterized as a percent level of savings. The results for 2002 indicate that the building is 40% better in terms of total energy use and 43% better in terms of energy cost than the energy code-compliant building.

6.5 ENERGY STAR Performance Rating

The U.S. Environmental Protection Agency (EPA) has developed a method of rating the performance of commercial buildings (EPA 2004). The ENERGY STAR Portfolio Manager can be used to rate the performance of a building based on basic information about its size, location, function, and utility bills. The rating is on a scale from 1 to 100 representing the percentile ranking of the building energy performance with other commercial buildings of the same type. Buildings must receive a rating greater than 75 to earn an ENERGY STAR certification. ENERGY STAR uses a statistical analysis of the CBECS data from EIA as the basis for the rating. CBECS contains information from more than 5,000 buildings from all commercial building sectors across the United States.

We rated the Cambria building using the energy consumption from the utility bills with the Portfolio Manager. The ENERGY STAR ranking for the building from 2001 to 2003 is shown in Table 6-9. The

ENERGY STAR rating of 88 states that this building would rank 88 out of 100 in energy performance compared to the building stock adjusted for size, function, use patterns, number of occupants, and climate. The Cambria building's EUI is shown in the third column, and the EUI for an ENERGY STAR rating of 50 for the same building is shown in the fourth column. An ENERGY STAR rating of 50 represents average performance. The Cambria building performs 40% better than the average office building, which is the same performance predicted from the energy simulations in Table 6-8.

Table 6-9 ENERGY STAR Rating of the Cambria Building

Year	ENERGY STAR Rating	Measured EUI kBtu/ft^2·yr *(MJ/m^2·yr)*	EUI for ENERGY STAR Rating of 50 kBtu/ft^2·yr *(MJ/m^2·yr)*
2001	80	42 *(480)*	60 *(680)*
2002	88	36 *(410)*	60 *(680)*
2003	88	36 *(410)*	60 *(680)*

7 System Evaluations

NREL evaluated the energy systems at the Cambria building to determine their individual performance. The mechanical systems, lighting, plug loads, and PV systems were evaluated to determine the performance at a detailed level.

7.1 Analysis of the Heating, Ventilation, and Air Conditioning Systems

NREL evaluated the mechanical systems to determine if they were properly sized and operated optimally for comfort and energy efficiency. In addition, we evaluated the system design to see if changes could be made to improve performance.

NREL first inspected and initiated monitoring of the HVAC systems in July 2001. Several issues were noted from visual inspections, spot power measurements, and evaluation of the 15-minute power data.

1. ERV Control: The west ERV ran continuously. The controller for the east ERV was off by one day, ran Tuesday through Saturday, and was off Sunday and Monday.
2. Heat pump control: The thermostats for the heat pump control ran the fans continuously and the temperature set points were constant with no setbacks or setups for unoccupied periods.
3. Groundwater Circulation Pumps: Each heat pump has its own bank of groundwater circulation pumps that are mounted in series of one, two, or three pumps and run continuously.
4. Excessive Ventilation Air: The outside air from the ERVs is constant and more than is required by the number of occupants in the building.
5. No Option for Economizer: There is no way to get outside air into the building except through the ERVs.

7.1.1 Impact of Heating, Ventilation, and Air Conditioning Controls on Energy Use

As shown in Section 6.2.2, the HVAC systems consume about 55% of the total energy; therefore, operational changes can have a large impact on the building energy performance. The average daily HVAC load profiles for July 2001 to April 2002 and July 2002 to April 2003 are shown in Figures 7-1 and 7-2. The differences in the load profiles from Figure 7-1 to Figure 7-2 are mainly caused by changes in the control strategies and somewhat by weather differences. Table B-1 presents a summary of changes to the control settings.

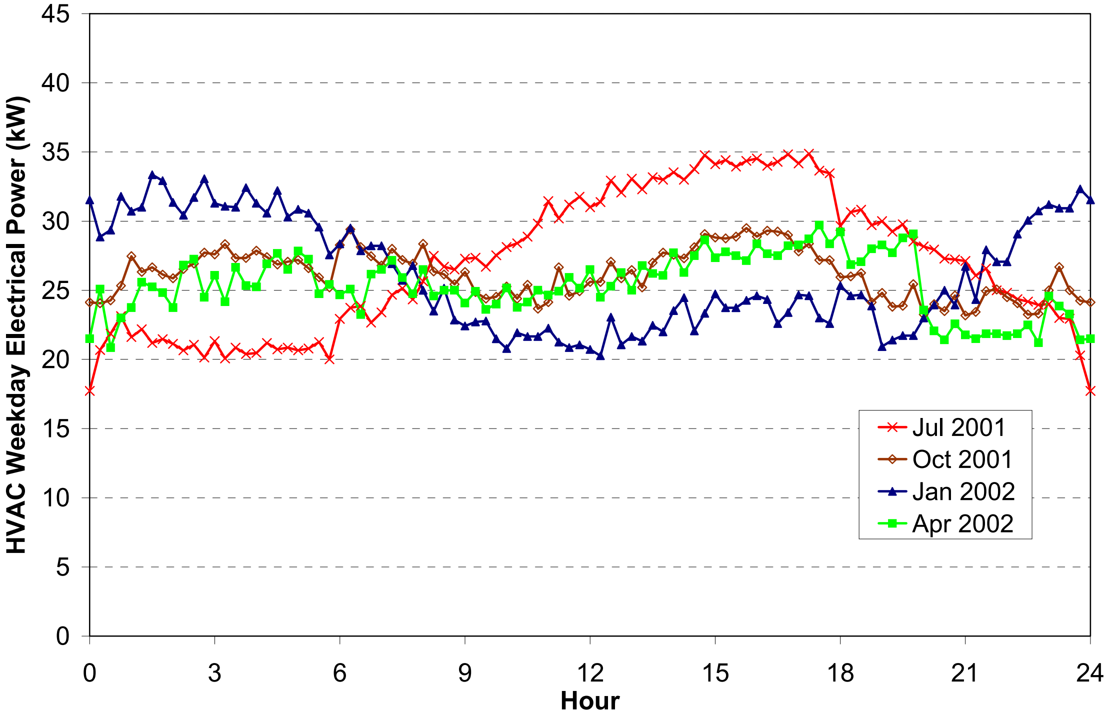

Figure 7-1 **Average daily HVAC load profile for weekdays (2001–2002)**

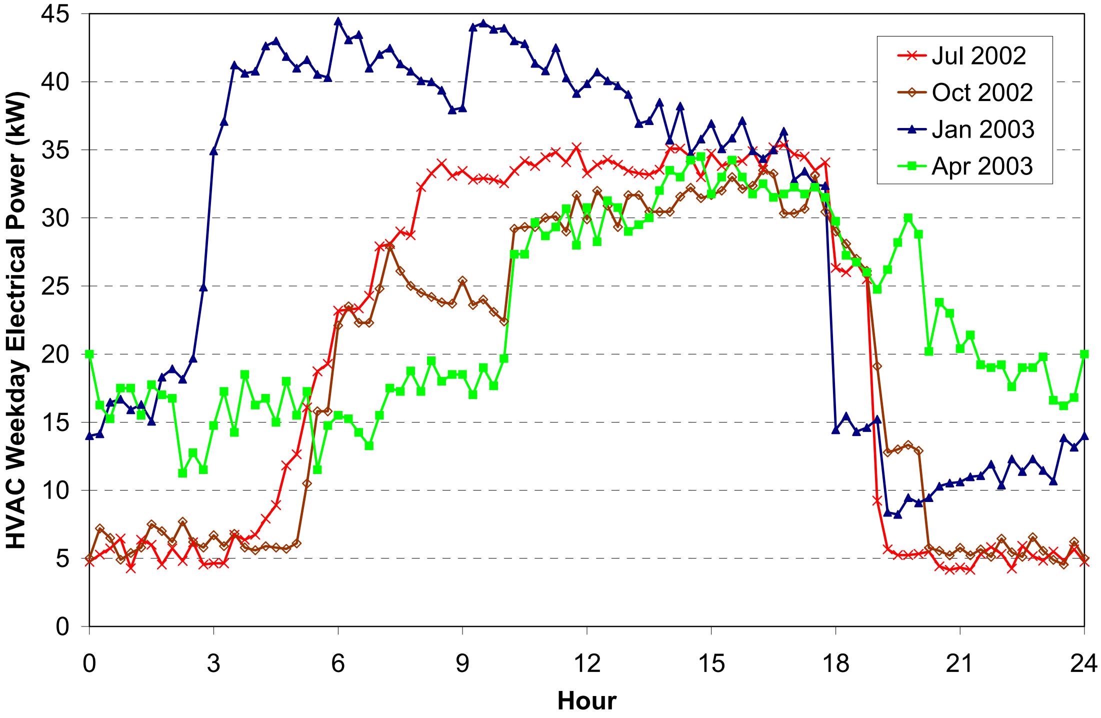

Figure 7-2 **Average daily HVAC load profile for weekdays (2002–2003)**

When the building was first occupied, the west ERV ran continuously, the heat pump fans ran continuously, and the heat pump thermostats were controlled to constant temperatures. The west ERV ran continuously because the controller was not set correctly, the thermostats for the heat pumps were not set correctly to allow the heat pump fans to cycle on demand during unoccupied periods, and the temperature set points were constant because it was thought the system would not respond well to temperature setbacks. This control scheme led to very high nighttime loads as seen in Figure 7-1. The winter weekday daytime loads were smaller than nighttime and weekend loads as the heat pumps had to heat large amounts of cold air brought into the building by the ERV when there were little internal gains.

The heat pump fans were set to cycle-on-demand during unoccupied periods in December 2001. However, this setting had little effect because the west ERV ran continuously and the temperature set points were constant. At the end of May 2002, we programmed the west ERV controller to run from 5:00 a.m. to 5:00 p.m. EST Monday through Friday. In addition, we reprogrammed all of the thermostats to have heating set points of 70°F and 66°F (21°C and 19°C) and cooling set points of 72°F and 78°F (22°C and 26°C) during occupied and unoccupied periods. The occupied period was set from 5:00 a.m. to 6:00 p.m. EST Monday through Friday. These time settings were set to provide adequate conditioning for both standard and daylight saving times. The thermostat and ERV controller clocks should stay on EST.

The thermostat settings were changed multiple times between November 2002 and June 2003 in response to comfort complaints from the occupants. The occupants complained that the second-floor women's restroom was too cold in the mornings and that some offices were too hot on Monday mornings during hot weather. The exact changes are unknown, but the temperature setbacks and setups were removed and some of the thermostats had higher unoccupied heating set points. In addition, all of the heat pump fans were set to run continuously. In July 2003, we reset the clock on the west ERV, which was off by approximately three hours, and reset the thermostat set points and heat pump fan control. The temperature setbacks and setups were set to smaller values than were set in May 2002, and the occupied period was set to start an hour earlier to allow more time to recover before occupants arrive.

The effects of changing the ERV controller and the thermostat set points are immediately apparent in the July and October profiles. The nighttime loads for July and October 2002 are much lower than for 2001, and the daytime load profiles are similar. January 2002 and January 2003 have very different profiles because of the control changes and weather differences. The nighttime loads were much higher in 2002 than 2003 because the west ERV ran continuously in 2002. The daytime load was higher in 2003 than in 2002 because 2003 was significantly colder than 2002 (1,084 HDD versus 667 HDD base 55°F [602 versus 370 base 13°C]). There was a 63% increase in the HDDs for January from 2002 to 2003 but less than a 1% increase in the HVAC energy consumption. A summary of the differences in the HVAC energy and total heating and CDDs for each period is presented in Table 7-1. There were many changes in the thermostat set points during the two years; however, the main difference was turning the west ERV off during unoccupied periods. This change shows the large energy penalty for running the ERV continuously, especially in the winter.

Table 7-1 Monthly HVAC Energy Comparison

Comparison Months	% Change in HVAC Energy	% Change in HDD + CDD
July 2001 to July 2002	–31%	54%
October 2001 to October 2002	–38%	17%
January 2002 to January 2003	0.5%	62%
April 2002 to April 2003	–17%	-15%

The hourly HVAC energy plotted against the outdoor temperature for 2001, 2002, and 2003 is shown in Figures 7-3 to 7-5. The data are separated by weekdays and weekends/holidays. The 2001 and 2002 graphs show a minimum in energy use between 50°F and 55°F (10°C and 13°C); below this temperature range, the building is predominately heating, and above this temperature range, the building is predominately cooling. In 2001, the building ran with a constant temperature control and the west ERV ran continuously. Therefore, the weekend/holiday heating loads were similar to the weekday heating loads. The weekend/holiday cooling loads were smaller because the internal heat gains were smaller. The west ERV was reprogrammed beginning in June 2002 to turn off during unoccupied periods. The effect of reprogramming the west ERV is evident in Figure 7-4 for June to October (there were no data for November and December). The hourly energy requirement during most of the unoccupied hours drops below 2 kWh when there are moderate outdoor temperatures. The building requires heating during unoccupied periods when the weather is cold.

The data for 2003, shown in Figure 7-5, are more scattered than 2001 and 2002 for a number of reasons. This was the first winter with the west ERV off at night and weekends, and it was much colder than the previous winter. There are some weekday nighttime hours and weekend hours with cold temperatures that required no heating and some hours that required a small amount of heating. In addition, the thermostat settings were changed (probably more than once) during this period. At some point, the heat pump fans were set to run continuously and the temperature set points were set to constant values, or, in some cases, to higher heating set points at night. Finally, the time clock on the west ERV was off by three hours, causing the system to come on earlier in the morning.

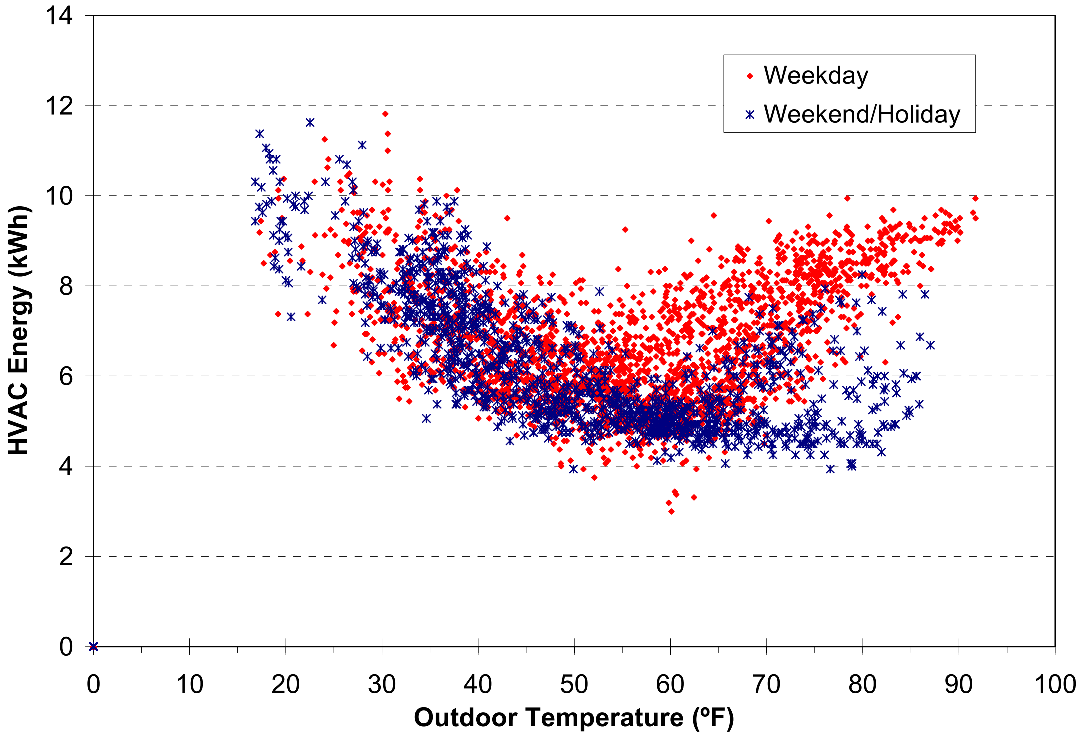

Figure 7-3 Hourly HVAC energy versus outdoor temperature (July–December 2001)

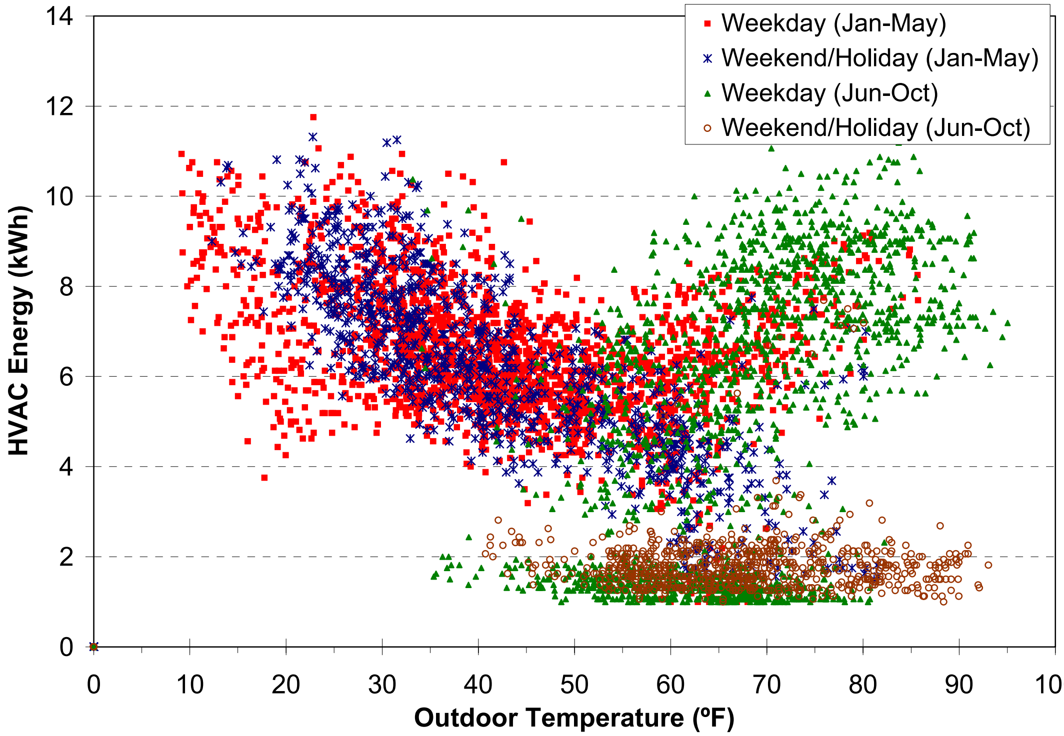

Figure 7-4 Hourly HVAC energy versus outdoor temperature (January–October 2002)

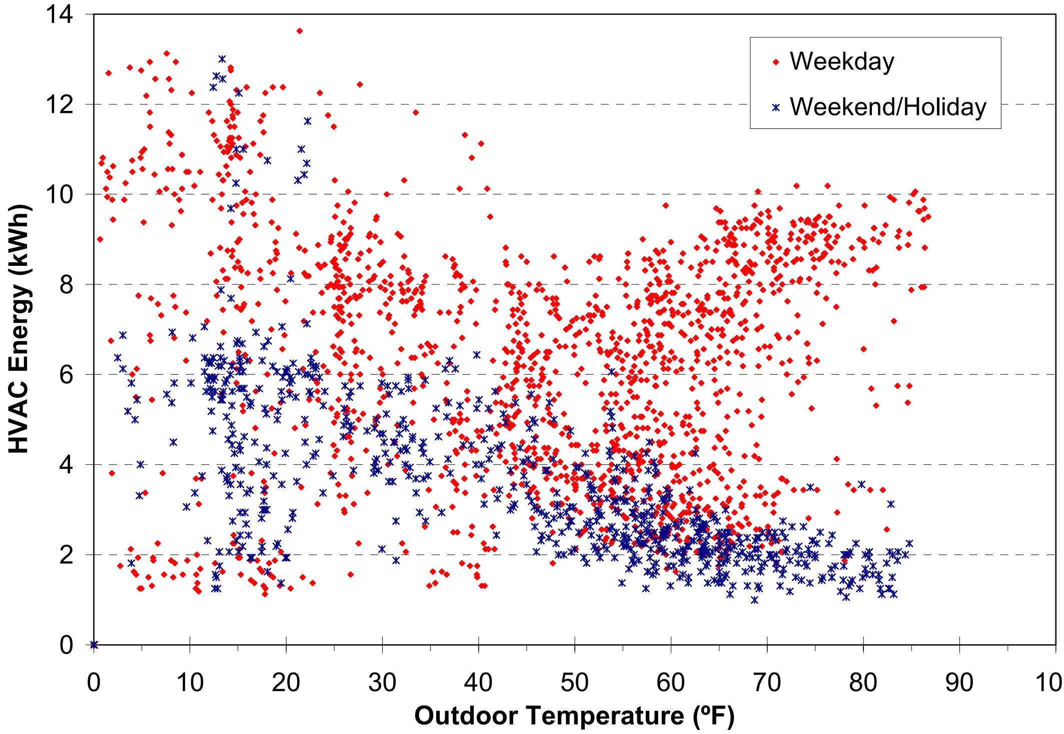

Figure 7-5 Hourly HVAC energy versus outdoor temperature (January–June 2003)

The calibrated As-Built Model was used to examine the energy impacts of ERV controls. One simulation was completed with both ERVs running continuously and another was run with the ERVs replaced by airside economizers. The results of these simulations, along with the As-Built Model with Pittsburgh TMY2 data, are shown in Table 7-2. Running the ERVs continuously increased the energy cost by $4,260, replacing the ERVs with airside economizers saved $2,940. There were more hours outside of the throttling range with the economizers because the heat pumps were not resized to make up for the lost energy recovery. If the heat pumps were sized correctly, the energy costs would have gone up slightly for the economizer case. The best option would be to use smaller ERVs (half the current size) with bypass dampers for economizer operation. For 2002 and 2003, there were 440 and 390 hours when the outside air temperature was 50°F–60°F (10°C–16°C) on weekdays between 5:00 a.m. and 5:00 p.m., which is when economizer operation could be used. This represents approximately 13% of the weekday hours between 5:00 a.m. and 5:00 p.m. Above 55°F (13°C), the heat pumps may have to provide some cooling, but the ERV fans would not have to be used. Above 60°F (16°C), the outside air may have high moisture levels that would have to be removed by the heat pumps. Enthalpy control on the economizer would expand the economizer operation range and provide more hours for using outside air for cooling. The outside air temperature range at which ERV operation recovers more energy than the fans use is probably below 50°F (10°C) and above 60°F (16°C).

Table 7-2 Energy Impacts of Changes to the ERV Control

Model	Annual Energy (MWh)	Annual Energy Cost	Energy Savings	Cost Savings
As-Built Model	344	$35,473		
As-Built Model with ERVs running continuously	397	$39,737	–15.7%	–$4,260
As-Built Model with ERVs replaced by airside economizers	315	$32,533	8.2%	$2,940

7.1.2 Heating, Ventilation, and Air Conditioning Sizing

Another question about the HVAC systems was whether they were properly sized. The heat pump cooling capacity is 54 tons (189 kW), which may be slightly undersized because they take a long time to recover from a setback condition. This situation is compounded by the control of the ERVs, which should not be used on cold winter mornings until occupants arrive and could be used in warmer weather to help cool the building before occupants arrive. However, the ERV controllers are very simple and only allow a fixed time schedule. The one area of the building that was definitely undercooled was the telecommunications room, which contains the telephone switchgear, computer servers, and two personal computers for energy monitoring. This room was cooled by a heat pump serving other areas with very low internal gains. The heat pump was controlled by the conditions in the areas with low internal gains, which was very different from the telecommunications room. The solution was to install a 2.5-ton (9-kW) heat pump directly to the telecommunications room, which is about 100 ft^2/ton (2.5 m^2/kW). This was probably a little oversized, but it keeps the room cool and is more efficient than running the larger heat pump just to keep this room cool. It also allows more electronic equipment to be added in the future.

7.1.3 Groundwater Circulation Pumps

The groundwater circulation pumps are mounted in series to match the flow and head requirements of each heat pump. This configuration is not the most efficient, but it is often used because pump sizes may have limited availability and many contractors want to use only one type of pump. The pumps are rated at 230 W each, but they were measured to draw approximately 200 W each. The pumps run continuously; however, they only need to operate when the compressor is running. There was a concern that the capacitance effects of the ground might adversely affect the system when the pumps run in a cycling mode. According to a study done by Kavanaugh and Rafferty (1997), this is not a concern, and the best method of operating the circulation pumps is to tie them to the compressor operation. A conservative estimate is that the compressors run an average of 50% of the time. The annual saving of linking the pumps with the compressor operation would be 18 MWh and approximately $1,300.

7.1.4 Outside Air

The ERVs represent one of the largest factors in the HVAC energy use. The ERV fans consume a considerable amount of energy to bring in large amounts of outside air, which must be conditioned. According to ASHRAE Standard 62-1999 (ASHRAE 1999), the minimum outside air for an office is 20 cfm/person (10 l/s·person). When both ERVs are running, there are 4,500 cfm (2,125 l/s) of outside air. The average daily peak occupancy is approximately 70 people. A conservative estimate of the design maximum is 100 occupants. At 100 occupants, the ERVs deliver 45 cfm/person (21 l/s·person), more than double the minimum required. An accidental test of the amount of outside air required occurred when the west ERV was inadvertently turned off on July 30 and left off until August 29, 2002. The measured CO_2 levels during the month before, during, and after the ERV was turned off are shown in Figure 7-6.

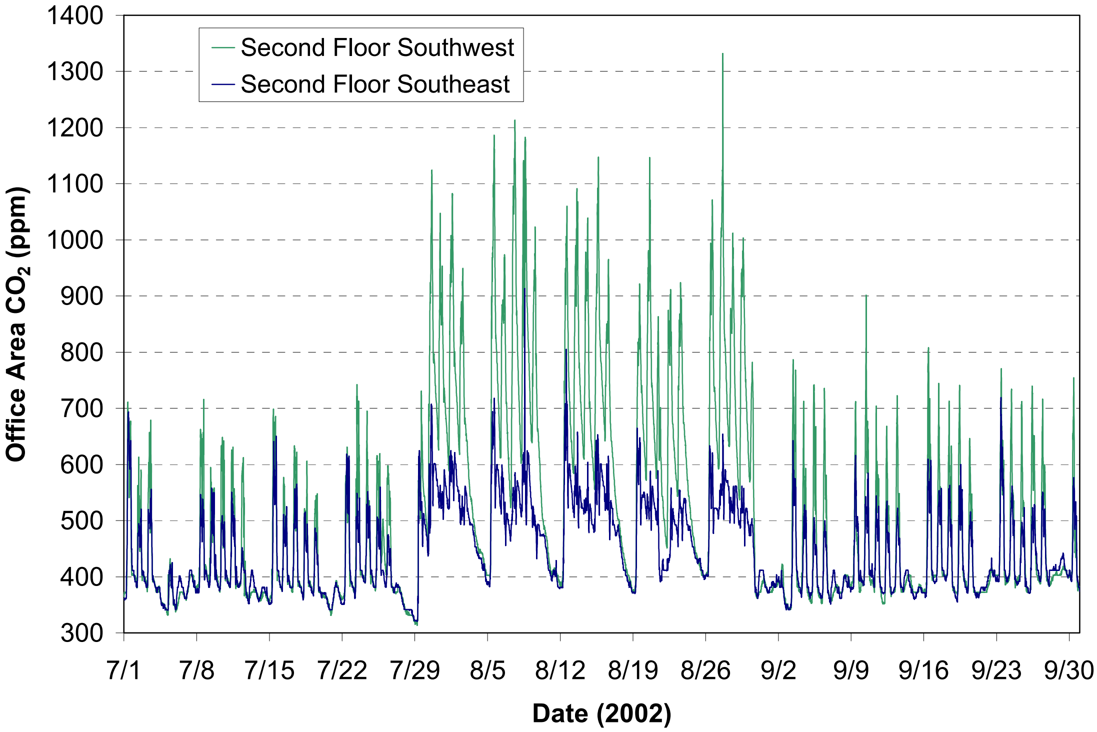

Figure 7-6 Office space CO_2 concentrations with the west ERV off during August

The west side was affected the most, but the CO_2 levels on the east side also increased. ASHRAE 62-1999 recommends that the CO_2 concentrations should remain below 700 ppm above the ambient CO_2 levels to maintain comfort with respect to human bioeffluents. The ambient CO_2 concentration is approximately 380 ppm, so the recommended maximum is approximately 1,100 ppm. The second-floor, southwest sensor exceeded 1,100 ppm CO_2, a total of 10 hours during the 23 working days when the west ERV was off. The first-floor, southwest CO_2 sensor exceeded 1,100 ppm for 3 hours, and the second-floor, northwest CO_2 sensor never exceeded 1,100. The east ERV is half the size of the west unit and provides about 21 cfm/person (10 l/s·person) for 70 people, which meets the minimum standard for normal occupancy, but the outside air is not evenly distributed throughout the building when it runs on only one ERV.

There was also a noticeable difference in the energy consumption when the west ERV was turned off. We used a linear regression of the weekday HVAC energy use and daily outdoor temperatures in June, July, and September to estimate the weekday HVAC energy use in August with the west ERV in normal operation. Energy data were missing for 7 of the 24 weekdays when the west ERV was off, so another linear regression was used to estimate the actual weekday HVAC energy use during this period. The estimated HVAC energy saving during the 30 days that the west ERV was off is 2.2 MWh ± 0.05 MWh, which is approximately $250 in energy and demand savings. This number represents approximately 8% of the total building energy during this period.

7.1.5 Thermal Comfort

The space temperatures for the second-floor, southwest and southeast quadrants are shown in Figures 7-7 and 7-8 for summer and winter periods. Figure 7-7 shows the performance during the warmest day in 2002, and Figure 7-8 shows the space temperatures during one of the coldest periods in 2002. These temperature readings were taken from the permanent monitoring system. The data from this system were checked and compared with data from a hand-held sensor during the summer of 2002. The permanent system consistently logged temperatures that were 1°F–2°F (0.5°C–1°C) higher than the hand-held system. The temperatures shown were adjusted to more closely match the temperatures measured on the hand-held system.

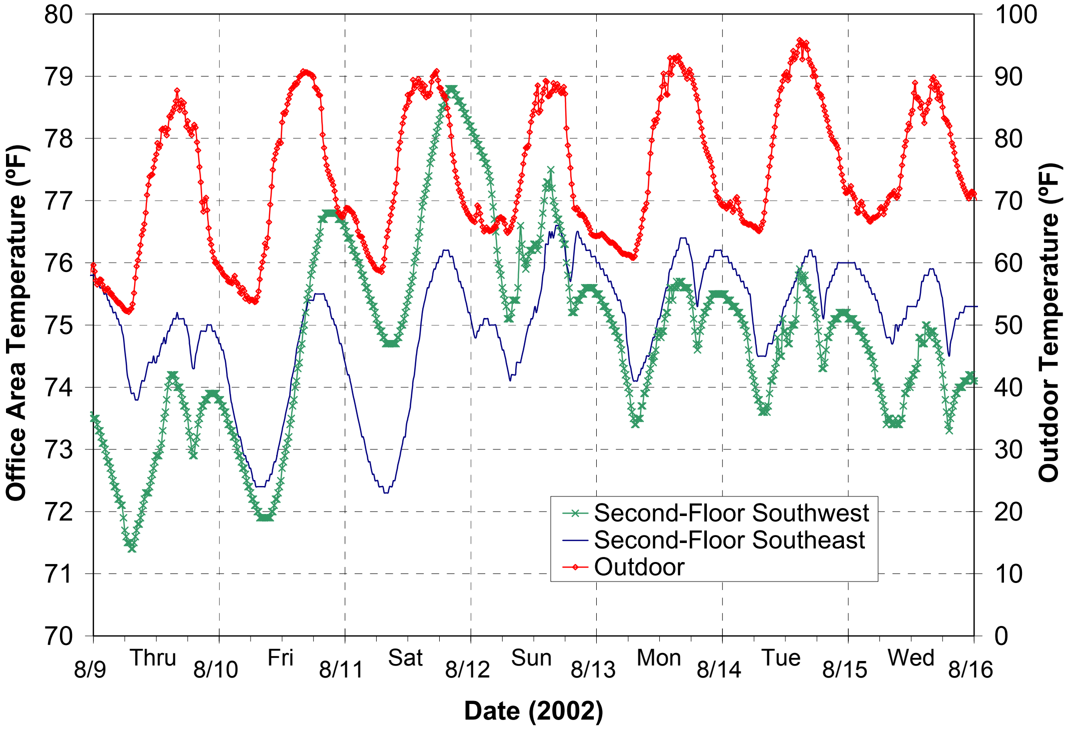

Figure 7-7 Office and outdoor temperatures for the summer of 2002

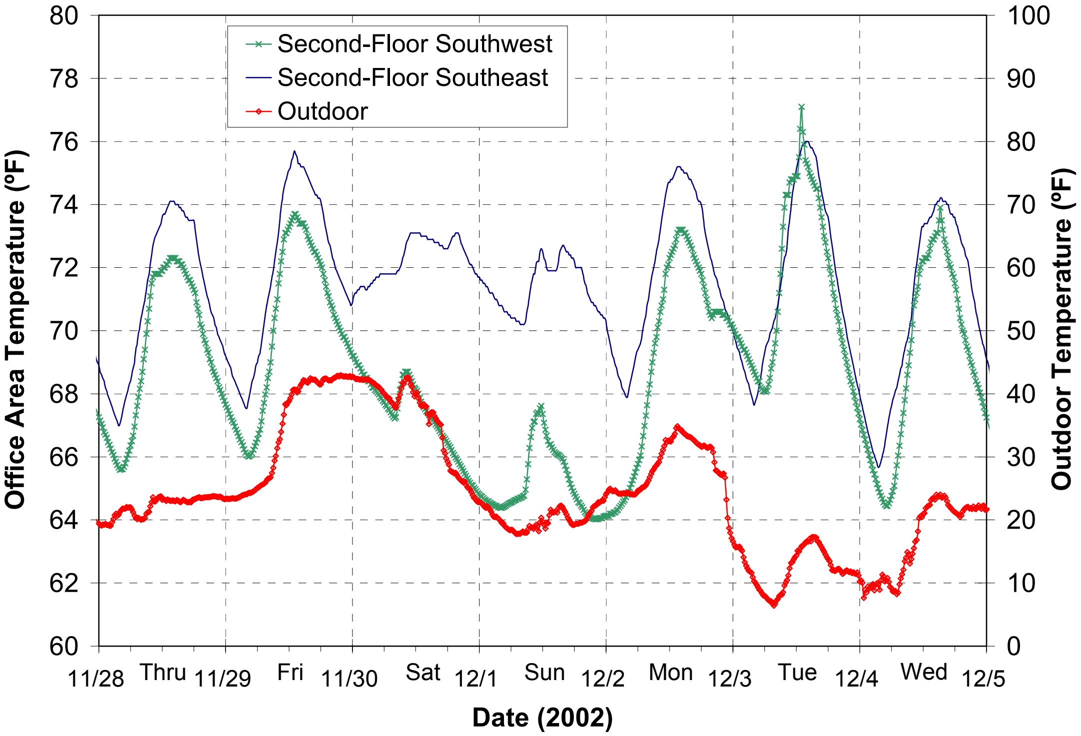

Figure 7-8 Office and outdoor temperatures for the winter of 2002

The recommended thermal comfort limits for light office work are approximately 70°F–80°F (21°C–27°C) (ASHRAE 2004). The range depends on the amount of clothing, activity level, air movement, and RH. This comfort range assumes that the occupants are dressed in light clothes at the high end and warmer clothes at the low end. A more likely acceptable comfort range is 72°F–76°F (22°C–24°C) in the summer and 70°F–76°F (21°C–24°C) in the winter. For the summer week in Figure 7-7, the temperature in the southwest sensor never exceeded 76°F (24°C) hours during normal working hours, and the temperature in the southeast sensor exceeded this comfort limit by less than 0.5°F (0.25°C) on Monday and Tuesday. In the winter week in Figure 7-8, the temperature from the southwest sensor was below 70°F (21°C) for one to two hours every weekday morning, and the temperature from the southeast sensor was below 70°F (21°C) for one hour on December 4.

Interior humidity also influences thermal comfort; however, the comfort range from ASHRAE Standard 55-2004 is quite broad. The upper limit is stated as a humidity ratio of 0.012, which is approximately 80% RH at 70°F (21°C) and 55% at 80°F (27°C). There is no lower limit, but experience has shown that people in humid climates expect a higher humidity level and may be dissatisfied below 20% RH. The average daily RH levels in the office spaces are shown in Figure 7-9 for July through December 2002. The summer RH levels for the southwest space are 30%–40%, which is low, but acceptable. The southeast summertime RH levels are consistently 40%–50%, which provides a comfortable environment. The RH levels from both sensors start dropping in October and reach levels below 20% in December. The cold winter air has a low moisture content, and when the air is warmed to the building temperature, it has a low RH. There have been some complaints in this building about the dry air in the winter. Reducing the amount of outside air introduced to the building in the winter would help keep the humidity levels higher.

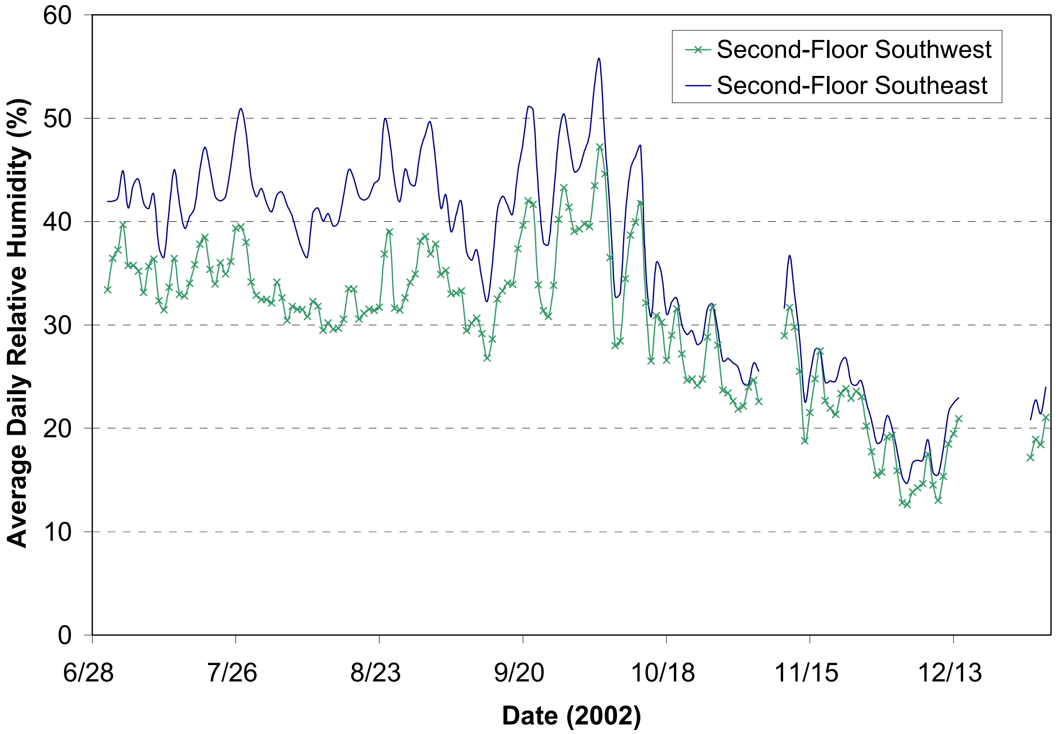

Figure 7-9 Average daily RH levels in the second-floor offices

A study of the effectiveness of the UFAD system was completed by Lawrence Berkeley National Laboratory researchers in 2004 (Fisk et al. 2004). They found that the air change effectiveness was about the same as a zone with well-mixed air, but the pollutant removal efficiency for CO_2 was 13% better than expected in a zone with well-mixed air. The thermal stratification in the zones during cooling mode operation was only 2°F–4°F (1°C–2°C) between just above the floor and the return air registers. This low thermal stratification is caused by low internal gains (partially occupied building) and higher than necessary supply airflow rates. It is expected that the thermal stratification would increase if the building were fully occupied or if there was a variable air volume system that reduced airflow with reduced zone loads. Thermal stratification is desirable because it can lead to energy savings during cooling.

7.2 Lighting and Daylighting Evaluation

The lighting systems at the Cambria building were evaluated to determine the illuminance distribution delivered by the lighting design and to determine the energy performance. The *Procedure to Measure Indoor Lighting Energy Performance* (NREL 2005b) provides performance metrics and procedures for evaluating lighting designs including the effects of daylighting. In addition, procedures were followed from the International Energy Agency (IEA) protocol established under Daylight in Buildings Task 21 (Atif et al. 1997). The goals of the monitoring plan were the following:

1. Quantitatively assess the illumination distribution.
2. Determine the energy savings due to 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 daylighting design and optimize its performance.
5. Document successes and weakness of the lighting design.

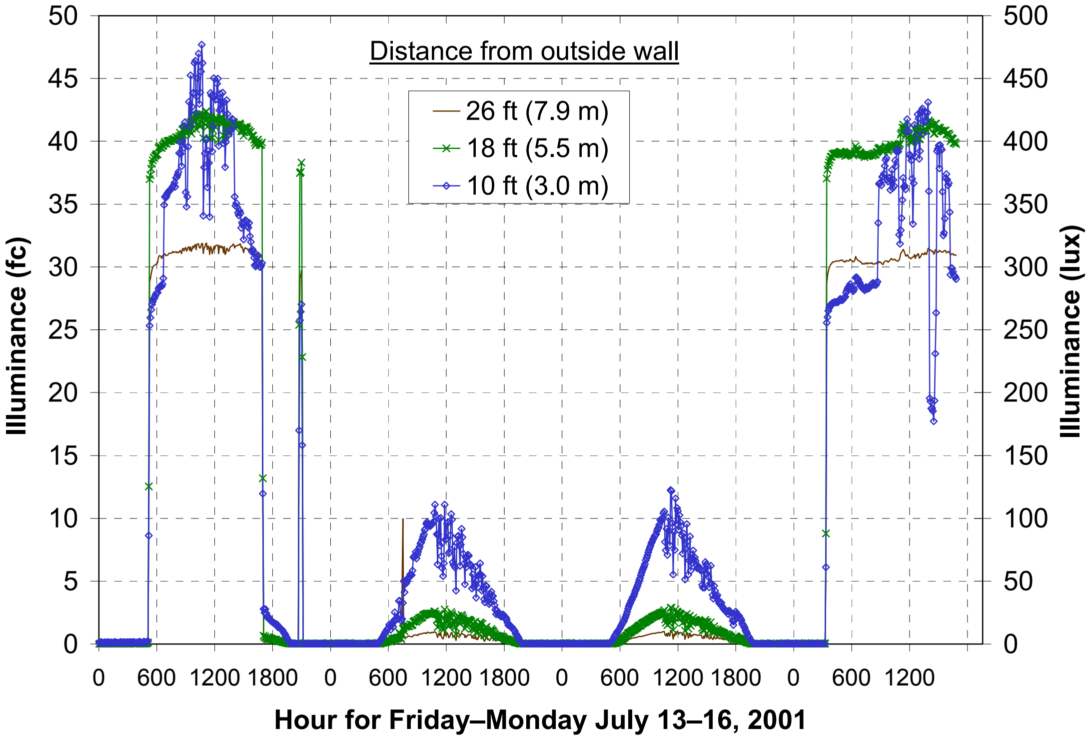

Figure 7-10 Outdoor illuminance for July 13–16, 2001

7.2.1 Illuminance Measurements

NREL monitored the outdoor and indoor illumination levels continuously from Friday to Monday, July 13–16, 2001. Figure 7-10 shows the outdoor illuminance. The first three days were mostly sunny with occasional cumulus clouds, and the final day was cloudy in the morning with some clearing by the afternoon.

The indoor light levels were measured on the working surfaces in cubicles along a north-south cross section in the first-floor, southwest quadrant and the second-floor, southwest and northwest quadrants. On the first floor, three photometers were placed in each cubicle—one in front of the keyboard and one on the working surfaces on either side of the cubicle (see Figure 7-11). The three photometers in front of the keyboards were 10, 18, and 26 ft (3.0, 5.5, and 7.9 m) from the inside surface of the outside wall. On the second floor, two photometers were placed in each cubicle—one in front of the keyboard and one on the working surface to the left of the keyboard (see Figures 7-12 and 7-13). The photometers in front of the keyboards were again 10, 18, and 26 ft (3.0, 5.5, and 7.9 m) from the inside surface of the outside wall. Measurement of the illuminance from the electric lights only was taken between 9:00 p.m. and 10:00 p.m. on Friday, July 13. The recommended minimum illuminance level on a horizontal surface for open offices is 30 to 50 fc (300 to 500 lux), depending on the task (IESNA 2000). For general reading of handwriting with a pen or printed materials in 8–10 point font, the recommended minimum illuminance is 30 fc (300 lux). For reading lighter copies or smaller fonts, the recommended minimum illuminance is 50 fc (500 lux).

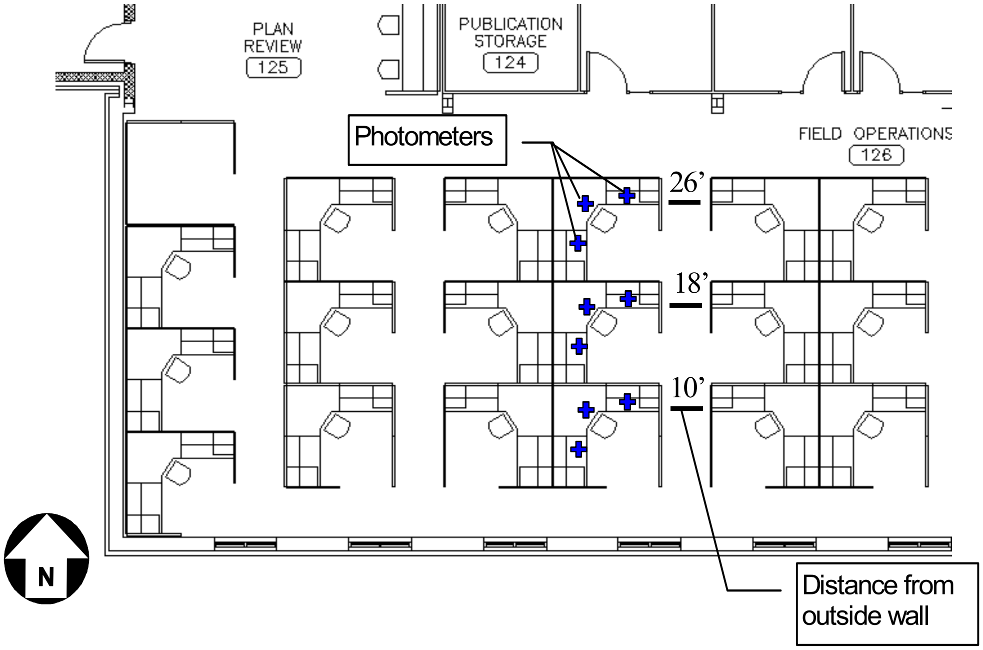

Figure 7-11 Photometer placement in the first-floor, southwest corner of the building

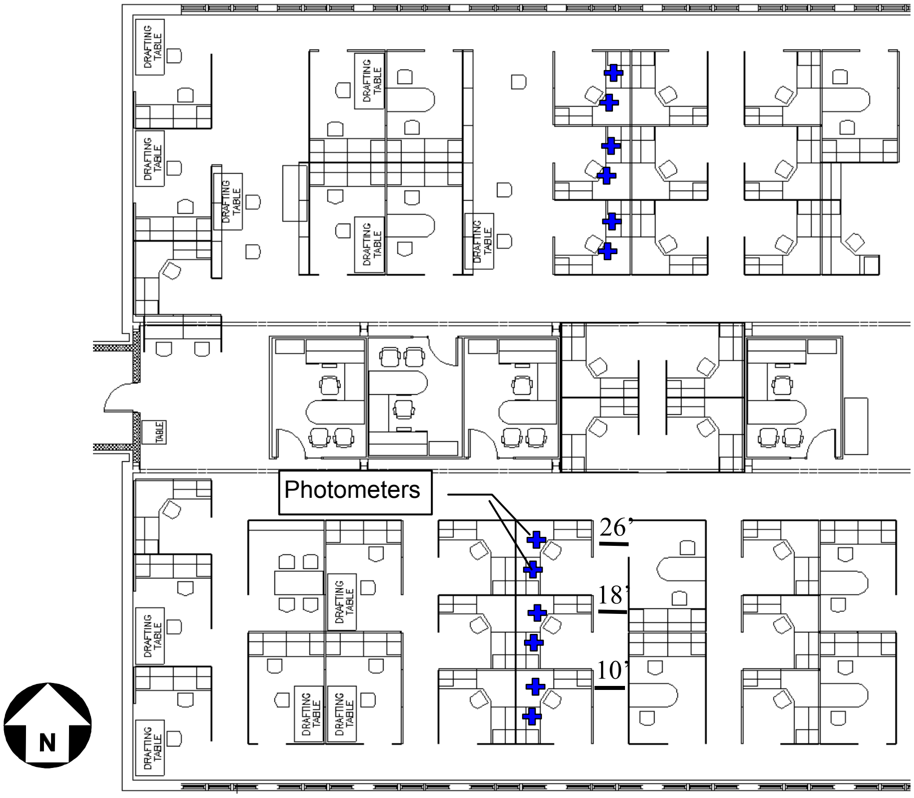

Figure 7-12 Photometer placement in the second-floor, west end of the building

Figure 7-13 Placement of two photometers (shown circled) on the working plane of a cubicle

Measured illuminance levels in the first-floor office area are shown in Figure 7-14. The ambient electric lights were on Friday and Monday during working hours and Friday evening for testing. The task lights were off in the cubicles 18 and 26 ft (5.5 and 7.9 m) from the south wall, and they were on for part of the testing period in the cubicle 10 ft (3.0 m) from the south wall. The ambient electric lights provided 25–35 fc (250–350 lux) on the working planes. The natural light added 10 fc (100 lux) at the cubicle closest to the outside wall to 3 fc (30 lux) at the cubicle furthest from the outside wall. These light levels are at the minimum levels for working at a computer terminal and performing easy reading tasks; however, some individuals prefer more light for reading. The task lights raise the light levels on the side working surfaces to 60–100 fc (600–1,000 lux).

Figure 7-15 shows the lighting conditions near midday on June 7, 2001, which had similar sky conditions to those during the illuminance measurements. The reflected light from the light shelves only penetrates approximately 3 ft (1 m) along the ceiling. The light shelves are not effective because of the small amount of glass area (the wide window frames block much of the light), low reflectance off the light shelves, and the high angle of the summer sun. There was no useful daylighting (i.e., dimming of electric lighting) in the first-floor office area during this testing period.

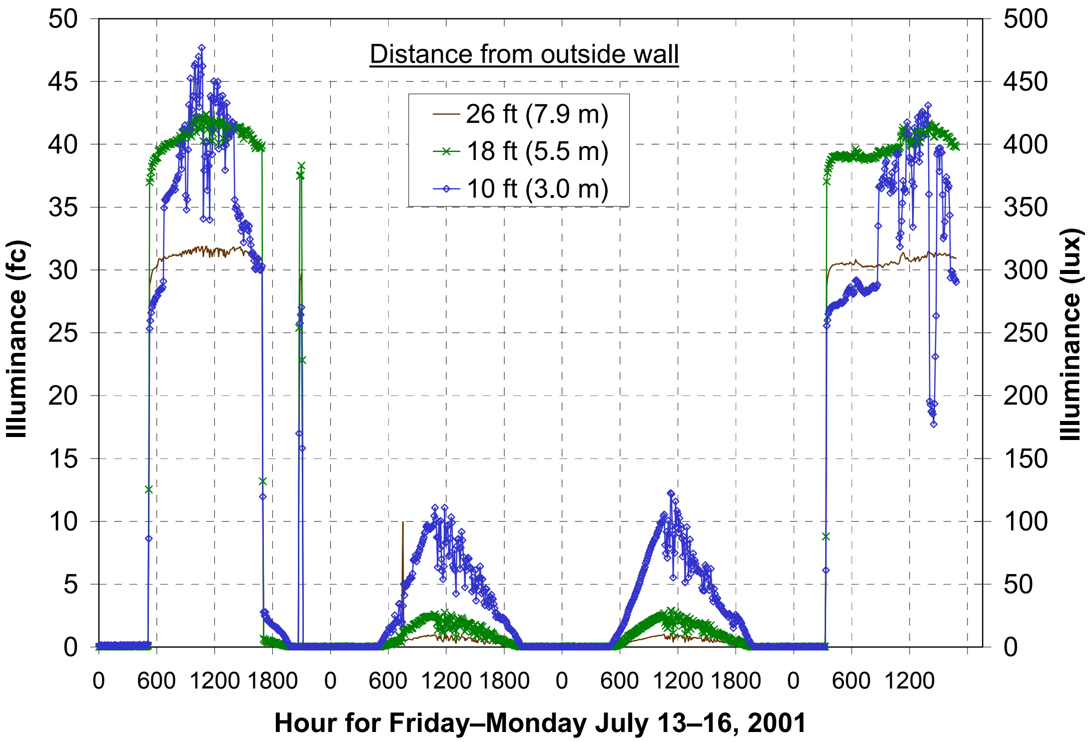

Figure 7-14 Illuminance measurements at workstations for the first-floor, southwest office area from July 13–16, 2001 (task lights used in cubicle 10 ft [3 m] from outside wall)

Figure 7-15 Lighting conditions on the first floor on June 7, 2001

The measured illuminance for the second-floor, southwest and northwest office areas from Friday to Monday, July 13–16, 2001 is shown in Figures 7-16 and 7-17. The task lights were off except in the cubicle that is 18 ft (5.5 m) from the north wall in the northwest office area. The electric lights were off over the weekend, except for the period between 5:30 a.m. and 9:00 a.m. on Saturday in the northwest office area. The natural light levels on the north side were slightly reduced because the east half of the clerestory sun shades was in the down position for maintenance. The light levels with daylighting and the ambient electric lights are below the recommended minimum levels in all the areas except for the cubicles on the south side that are 10 and 26 ft (3.0 and 7.9 m) away from the outside wall. Therefore, task lighting would probably be used to increase the illuminance on the working surfaces. We determined from an informal walk-through survey that approximately half of the task lights are used at any given time.

Illuminance from the ambient electric lights was measured Friday evening between 9:00 p.m. and 10:00 p.m. Illuminance levels at the workstations with only the ambient electric lights were approximately 15 fc (150 lux). This is lower than the first floor because the indirect luminaires do not reflect well off the high ceiling with trusses. The combination of the ambient electric lights and daylighting provided 20–40 fc (200–400 lux) at midday. The natural light levels over the weekend were 10–25 fc (100–250 lux) on the working surfaces and 20–30 fc (200–300 lux) in the open circulation areas. The daylighting on the second floor is reduced because of the poor reflection off the high ceiling, blockage by the roof trusses, the dark floor, and the windows on the outside walls are too low to provide light beyond the first row of cubicles. In addition, the illuminance levels on the second floor would be improved with direct lighting luminaires.

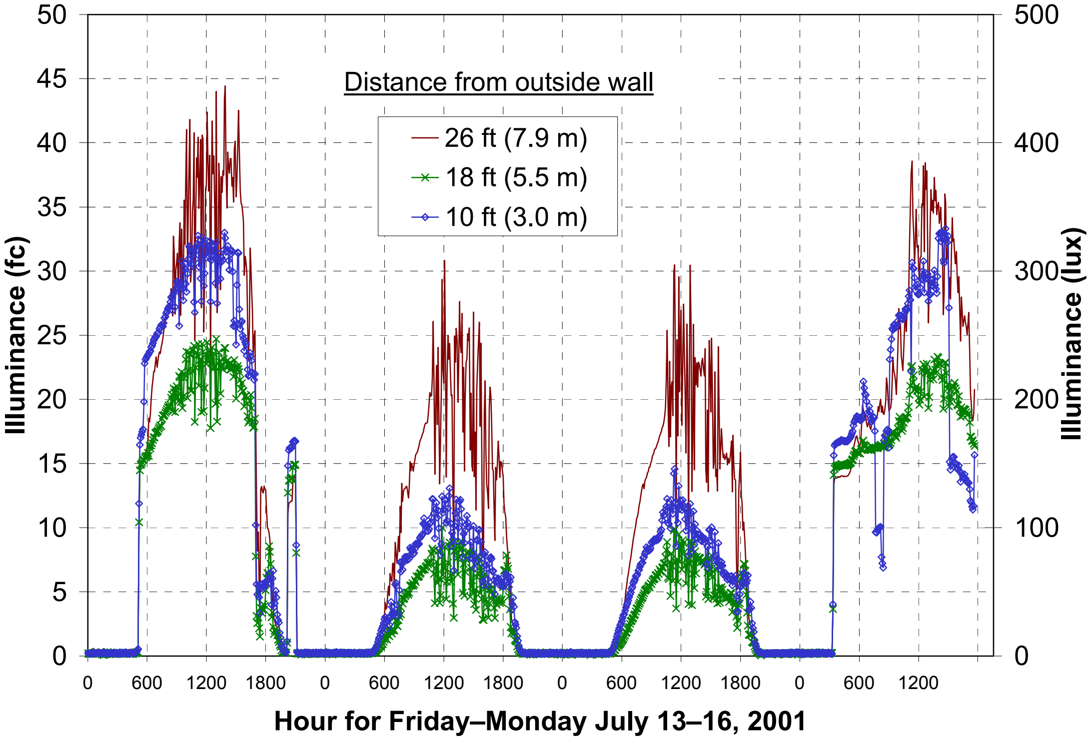

Figure 7-16 Illuminance measurements at workstations for the second-floor, southwest office area from July 13–16, 2001 (no task lighting)

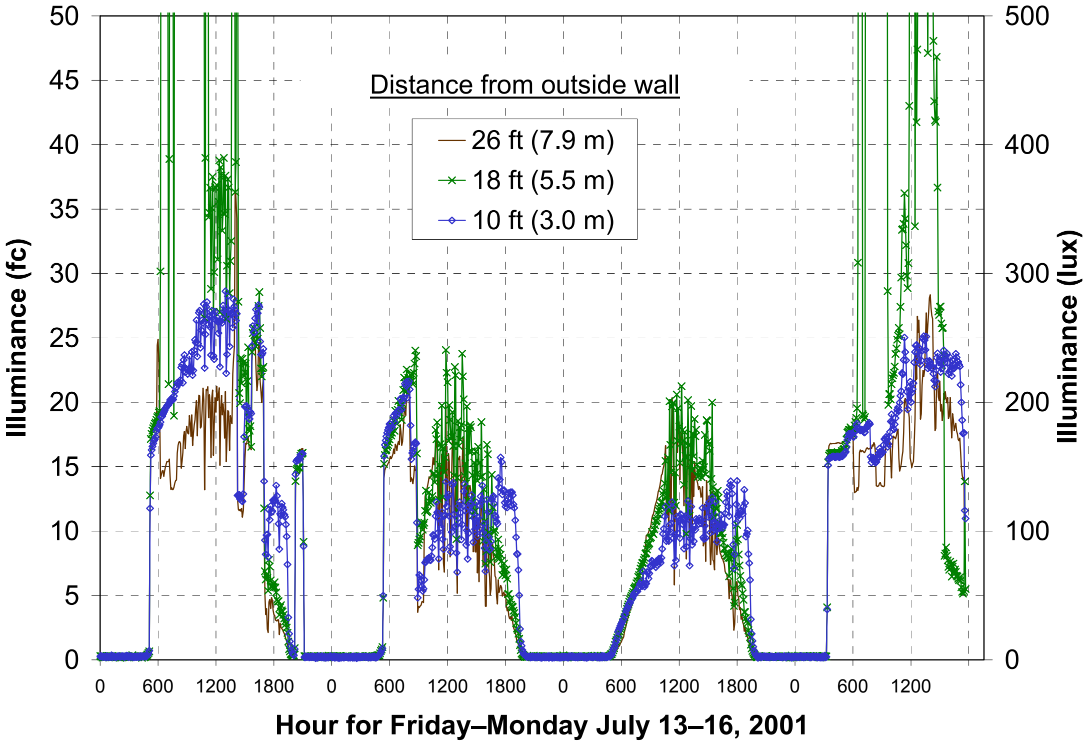

Figure 7-17 Daylighting measurements at workstations for the second-floor, northwest office area on July 13–16, 2001 (task lights used in cubicle 18 ft [5.5 m] from outside wall)

Figure 7-18 shows the lighting conditions in the northwest office area near midday on June 7, 2001 with the ambient electric lights on. The light distribution is fairly even as expected from the illuminance measurements. The ceiling is bright near the clerestory windows and has a darker area in the middle. The south-facing clerestory windows can be the source of undesirable lighting conditions at times. At low sun angles, they can admit direct beam radiation, and they can be very bright at other times, causing contrast and glare problems. Automatic sunshades are installed on the interior of the windows to block the direct beam radiation. The sunshades are controlled by an exterior photosensor. The sunshades block an excessive amount of light and defeat the purpose of the clerestory windows. Other options for these windows are to diffuse the incoming light with frosted or patterned glass or a light-diffusing film on the glass or direct the beam radiation to the ceiling with a louver system. The drawback of these solutions is the view of the sky will be lost.

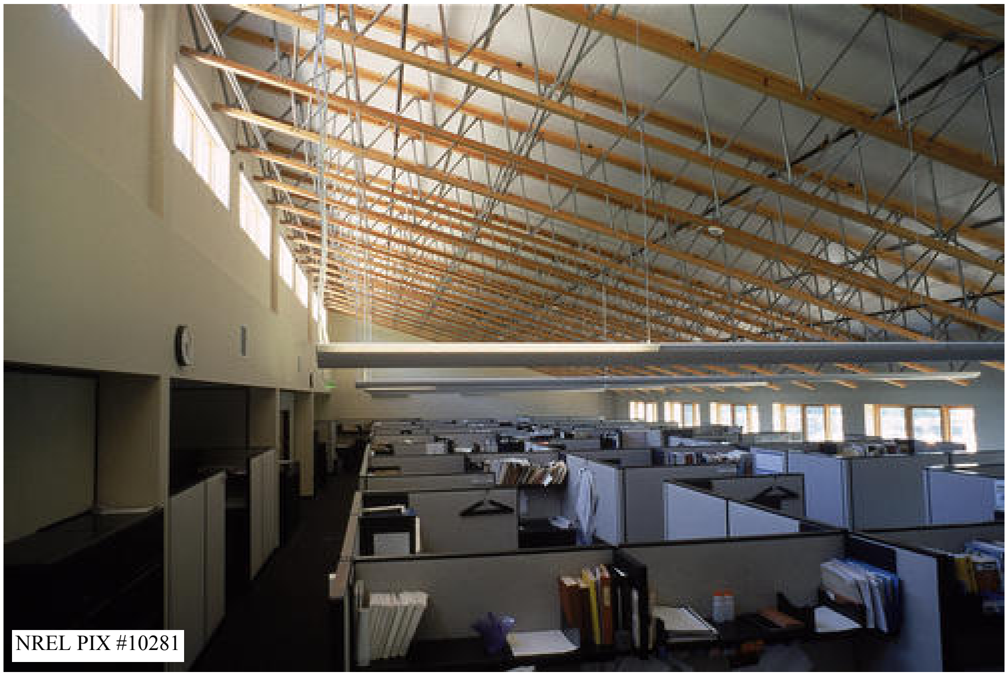

Figure 7-18 Lighting conditions in the second-floor, northwest office area on June 7, 2001, with the overhead electric lights on

7.2.2 Lighting System Energy Consumption

Average daily load profiles for the lighting loads are shown in Figure 7-19. The lighting loads exhibit very consistent patterns from month to month. The lighting loads consist of all the interior and exterior lights, exit signs, telephone system, and drinking fountains.

The interior lights are on from approximately 5:00 a.m. to 6:00 p.m. Most of the interior lights are controlled by timer circuits in the breaker boxes to turn on at 6:00 a.m. and turn off at 6:00 p.m. However, the cleaning crew comes in every morning around 5:00 a.m. and manually turns most of the lights on in the building. Between 2 kW and 4 kW of interior lights are manually controlled in enclosed offices and storage spaces. The slight drop in the power between 3:30 p.m. and 4:00 p.m. is when many of the occupants leave and some of the manually controlled lights are turned off. The variation in the early evening is due to the operation of the parking lot lights, which are used more in the winter and fall. The 3-kW nighttime load is from exterior lights on the building and exit signs in the building. The ambient lighting in the open office areas on the second floor is dimmable with the daylighting controls. Very little, if any, savings are realized by the daylighting controls. The weekend/holiday lighting load profiles are inconsistent from month to month. The weekend nighttime load profile is the same as the weekday load profile, but the weekend daytime load profile varies between 0 and 7 kW because of holidays that occur during the weekdays and occupants who occasionally work on weekends. The lighting controls have no provision for a holiday schedule; therefore, all the building lights turn on for holidays that fall on weekdays. An alternative option that has worked well in other buildings is a manual on switch with a timer controlled off for the normally unoccupied periods. The duration of the timer would be set by the person turning on the lights.

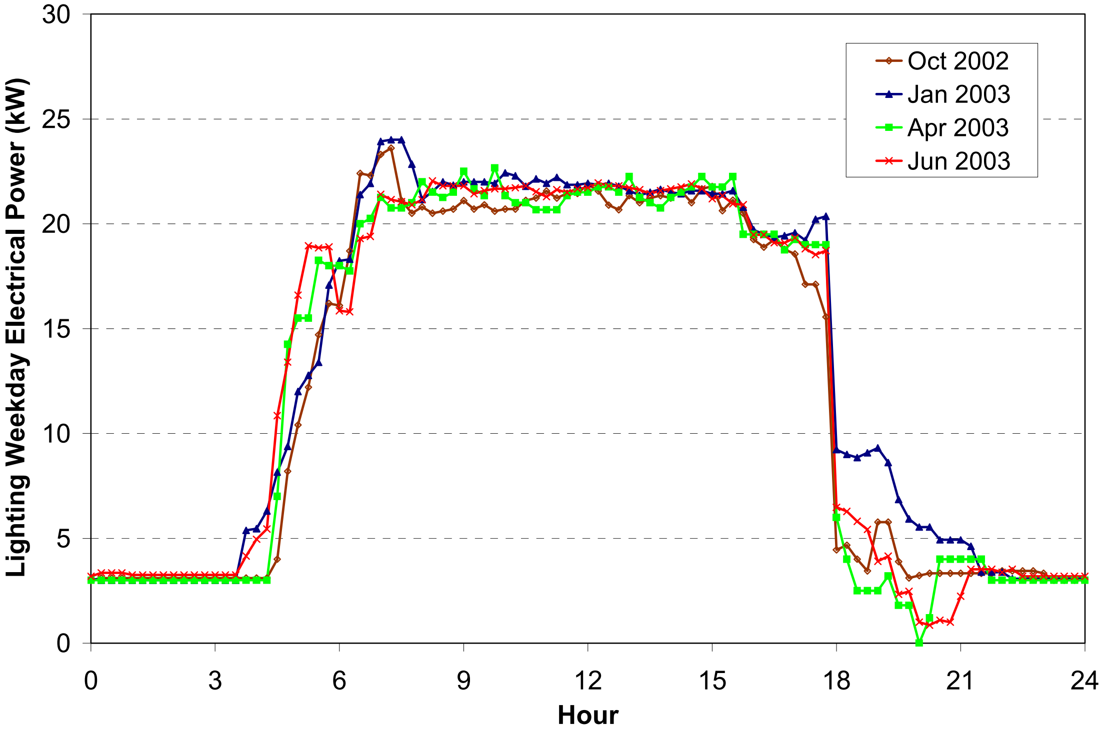

Figure 7-19 Daily interior lighting load profiles for weekdays

When NREL first monitored the building in July 2001, the lights were turned on between 3:00 a.m. and 4:00 a.m. by the cleaning crew and were turned off at 7:00 p.m. by the lighting control circuits. In October 2001, the cleaning crew changed their schedule to start at 5:00 a.m. and the lighting control circuits were changed to run between 6:00 a.m. and 6:00 p.m. These changes save approximately 12,000 kWh and $800 per year. Additional savings could be achieved by changing the cleaning schedule to start closer to normal business hours and turning the lights off earlier in the evening (most occupants leave by 4:00 p.m.).

Daylighting savings are defined as the fraction of the lighting electricity displaced by natural light contributions while maintaining the minimum illuminance levels (Atif et al. 1997). The illuminance measurements have shown that the light levels with the natural light and the electric lights are at or below the minimum illuminance level of 30 fc (300 lux) for a horizontal working surface in an office (IESNA 2000). On the first floor, the natural light levels are extremely low and contribute little to the overall levels. The illuminance levels on the second floor with only the electric lights are below the minimum levels, and the combination of daylighting and electric lights on a sunny day is close to the minimum levels. According to this definition and these measurements, there are no daylighting savings. In addition, daylighting savings would show a dip in the lighting power consumption during the daylit hours; however, this is not evident in the measurements as shown in Figure 7-19.

7.3 Analysis of Building Plug Loads

The plug loads in the building consist mainly of computers, monitors, printers, task lights, and other office equipment. Daily load profiles for the plug loads are shown in Figure 7-20. The total load is very consistent and varies between 9 kW at night and on weekends to approximately 17 kW during the occupied hours.

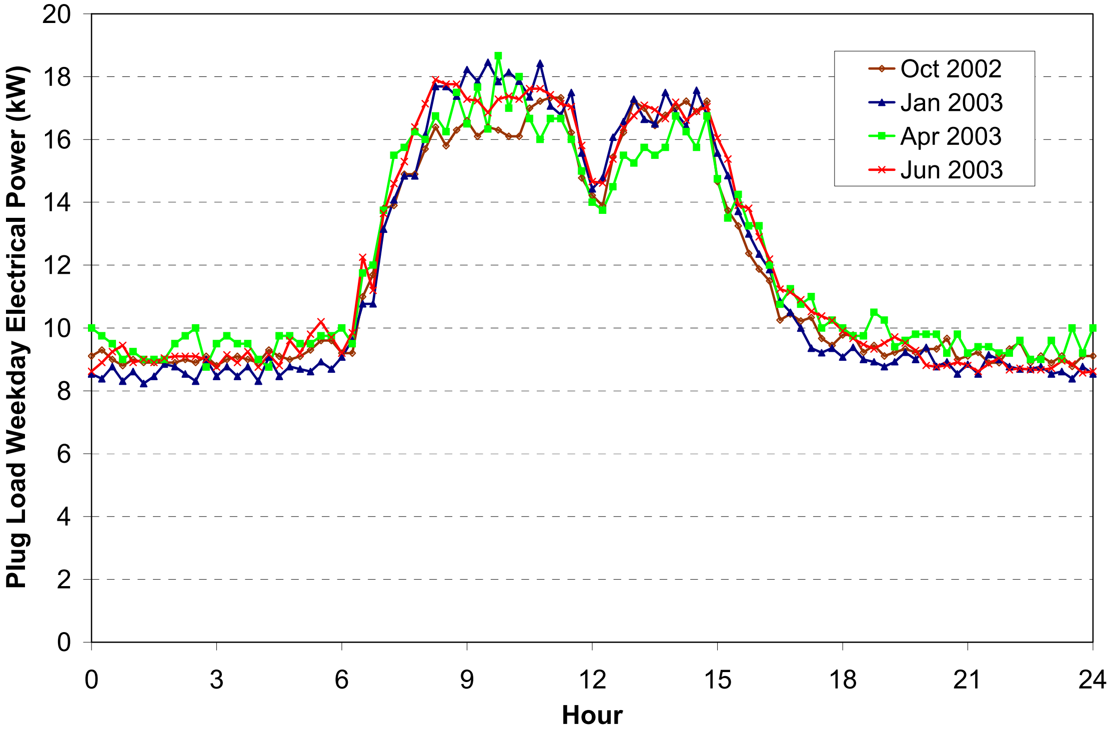

Figure 7-20 Daily plug load profiles for weekdays

The plug load profile closely reflects the occupant behavior. Most of the occupants arrive between 7:00 a.m. and 8:00 a.m. and leave between 3:00 p.m. and 4:00 p.m. The lunch break is consistently from about 11:30 a.m. until 1:00 p.m. The nighttime load is approximately half the daytime load, which is much higher than was anticipated during the design phase of the building. The high nighttime load is due to electronic equipment that is being left on, including computers, monitors, printers, and copiers. Much of this equipment goes into a standby mode, which still consumes a significant amount of energy when combining all of the equipment in the building. The weekend/holiday plug daily load profile is flat and at the same level as the weekday nighttime load profile.

NREL researchers conducted a survey of the plug loads in the office areas after business hours on the evening of Friday, July 13, 2001. Results are shown in Table 7-3. Some docking stations had no laptop computer attached; therefore, the actual number of laptop computers used in the building is higher than the total shown.

Table 7-3 Number of Office Area Plug Loads on July 13, 2001

Load	1st Floor	2nd Floor	Total	On or Standby
Desktop computers	13	72	85	54
Laptop computers	5	6	11	0
Monitors	17	82	99	90
Printers/scanners	10	64	74	74
Copiers	1	3	4	3
Fax machines	1	1	2	2
Plotters and misc.	0	4	4	1
Refrigerators	1 (break room, vol. ≈ 23 ft^3 [651 cm^3])	4 (vol. ≈ 6 ft^3 [170 cm^3])	0	5
Vending Machines	2 (break room)		2	2

The numbers and types of equipment left on or in standby mode were also noted during the survey. Most desktop computers were left on and were in standby mode. Their exact power draw is not known, but most desktop computers draw 40–80 W in normal operation. Most operating systems have a power management feature that will put the computer in standby after a certain period; however, these features only reduce the power consumption by about one-third when they are in operation. Many CRT monitors in standby mode use 3–10 W; however, older monitors do not have a standby mode and use around 40 W when turned on with a blank screen. The computer and monitor energy consumption can be reduced with manual or automatic control. Manual control relies on users to turn off their computers and monitors at night. If this approach is not successful, there are power management software options that can be implemented and controlled over a local network. Computer power management software can be very effective at reducing energy consumption during unoccupied periods. Energy savings have been shown to be an average of 200 kWh/yr per computer.

Computers are not the only large plug load; there are a large number of printers in this building with a printer for nearly every occupant on the second floor. Each printer consumes energy even on standby. Replacing 80% of these printers with five central networked printers would save money in the purchasing, maintenance, and operation of the printers. Additionally, reducing the number of printers down to five would make it easier to configure the printers to perform duplex printing to save paper. One more opportunity to save energy is to put power control devices on the cold drink vending machines. These devices reduce energy consumption by 30%–50% and usually pay for themselves in less than two years.

7.4 Photovoltaic System Evaluation

The PV systems in the Cambria building were evaluated to determine the energy produced by the systems, the effect on the building purchased electrical energy, and the performance of the systems. The *Procedure for Photovoltaic System Performance* (NREL 2005c) 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 the following:

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

The large PV system is monitored by a utility-type meter that is manually read each month for billing purposes. This energy is sold as green power at a premium rate. NREL installed an additional instrumentation in June 2002 on both PV systems that records the total energy every 15 minutes. Data collection for this monitoring system is automated and is used for analysis purposes. Because of problems with the building end use 15-minute data, there were no detailed building electrical demand data, and the third goal could not be accomplished

7.4.1 Photovoltaic System Measured Energy Production

The average daily purchased energy from the utility bills and the average daily energy from the large PV system are shown in Figure 7-21 for June 2001 to August 2003 and Figure 7-22 for January 2004 to December 2004. The main PV system was turned off in August 2003 due to inverter problems, and the inverter was replaced in late February 2004. The PV data for June 2001 through May 2002 are from the PV utility meter readings, and the remaining PV data are from the NREL installed monitoring system. The data from the PV utility meter represent the net PV energy production of the large PV system, that is, the PV energy produced minus the energy consumed by the isolation transformer when the PV system is down. The data from the NREL installed monitoring system are also the net energy and include the energy produced by the small PV system. The height of the columns is the total energy consumption of the building. The percent of the total building load met by the PV system is included as a line graph.

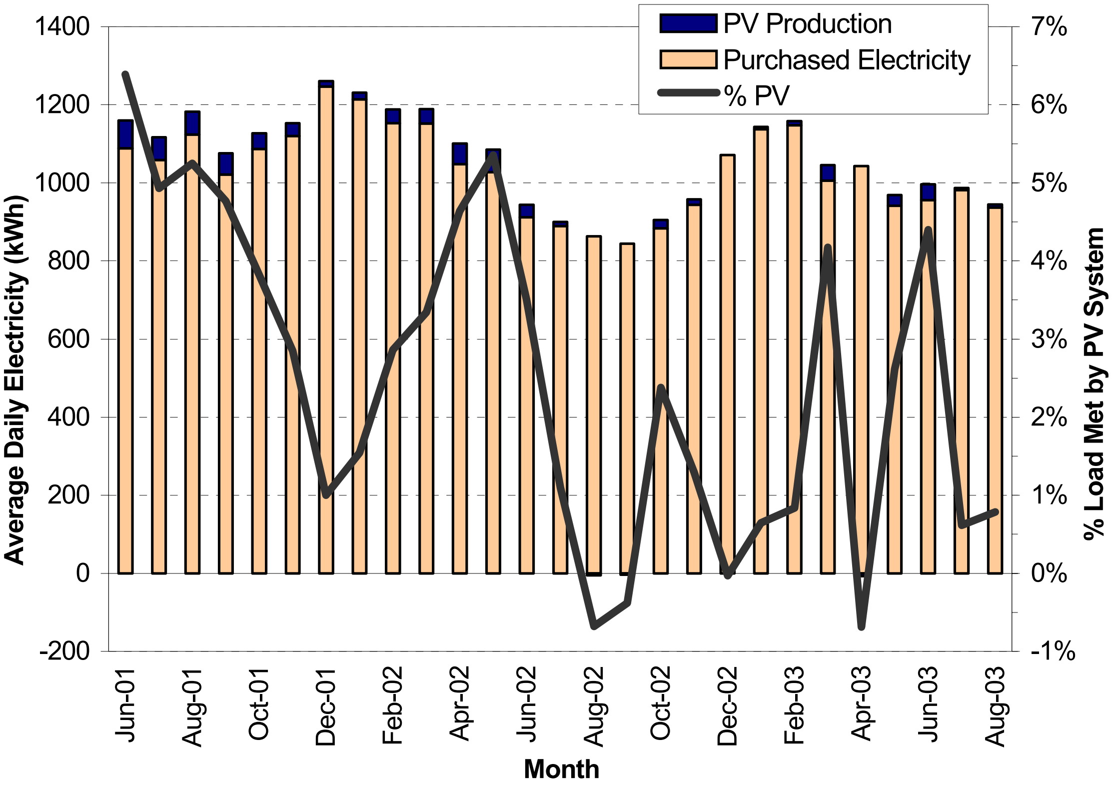

Figure 7-21 Average daily purchased energy and PV system performance for June 2001 to August 2003

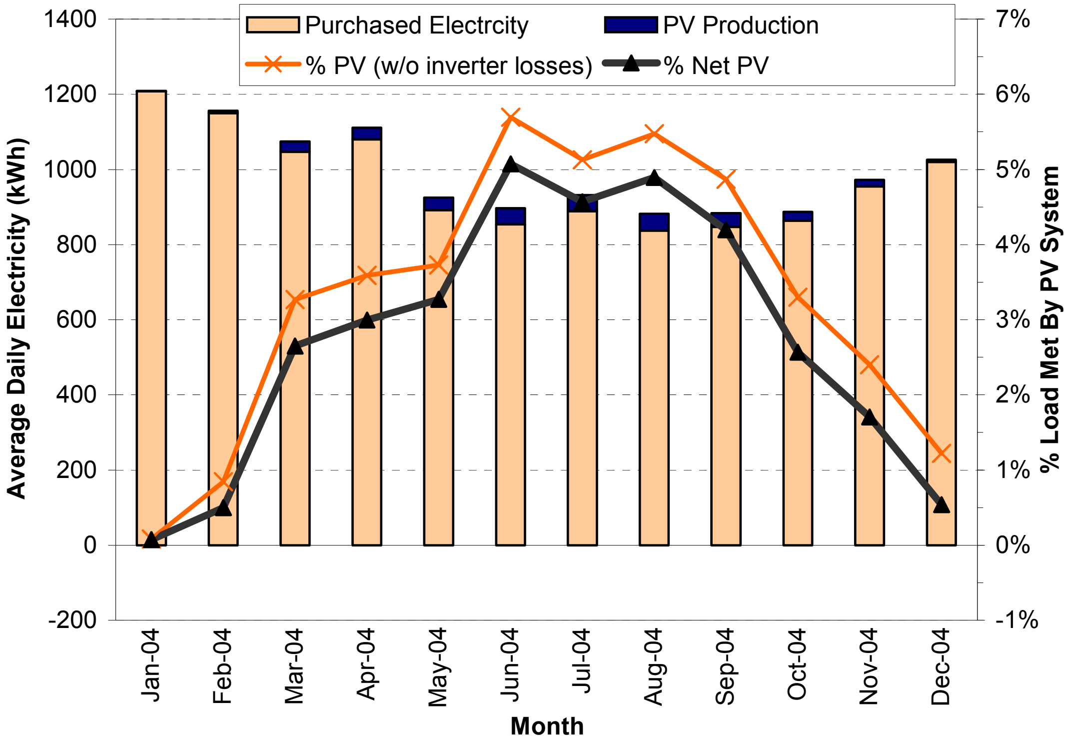

Figure 7-22 Average daily purchased energy and PV system performance for January 2004 to December 2004 (a new inverter was installed in late February)

Figure 7-23 shows the daily energy production and parasitic load for the main PV system for 2003. The daily global horizontal solar radiation is also shown as an area graph. The main PV system was shut down several times because of inverter faults and was finally disconnected from the grid on August 26, 2003. The causes of the faults were a high AC voltage and high temperature. The high temperature fault was the most severe because the system would have to be manually reset. The inverter was removed and sent to the manufacturer in December 2003 and replaced with a new unit in February 2004.

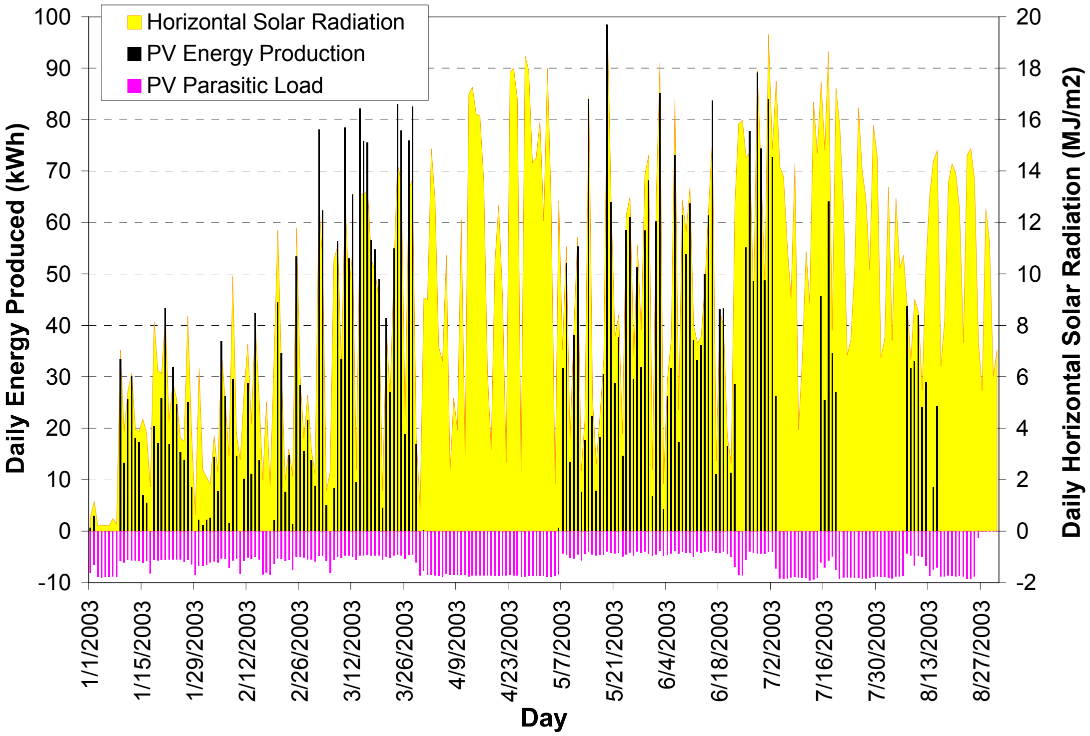

Figure 7-23 Daily PV system energy production, parasitic load, and horizontal solar radiation

During the period from May 31, 2002 to December 31, 2003, the main PV system produced no energy on 50% of the days because of inverter problems. There were many other days when the system was only operational for part of the day because of inverter problems. From May 31, 2002 to December 31, 2003, the parasitic load on the PV system equaled 40% of the energy delivered to the building by the main PV system. Most of the parasitic load (37%) occurred when the PV system was down at night or due to an inverter fault; the other 3% were transformer losses during PV system operation. From the time that the inverter was replaced on February 20, 2004 to December 31, 2004, the main PV system was down only three days because the whole system was shut down. During this same period, the parasitic load of the isolation transformer was 18% of the total energy delivered to the building. The monthly parasitic load varies from 11% in the summer to over 50% in the winter. A circuit that automatically disconnects the PV system from the grid when the PV system is down and reconnects when the PV system is operational should be implemented.

The small PV system has also experienced operational problems caused by blown fuses in the combiner box. From May 31, 2002 to August 31, 2004, the small PV system was operational only 103 days, which is 13% of the days. Most of the time, it has been operating on one-half of the panels. From February 8, 2004 to the end of 2004, there was no measured output from this system.

7.4.2 Photovoltaic System Performance Analysis

A simulation using PVSYST v3.2 (Mermoud 1996) was conducted to estimate the performance of the large PV system. The simulation was completed for 2002 using a weather file constructed from weather data measured on site. Figure 7-24 shows the net energy production from the simulation and the measured data.

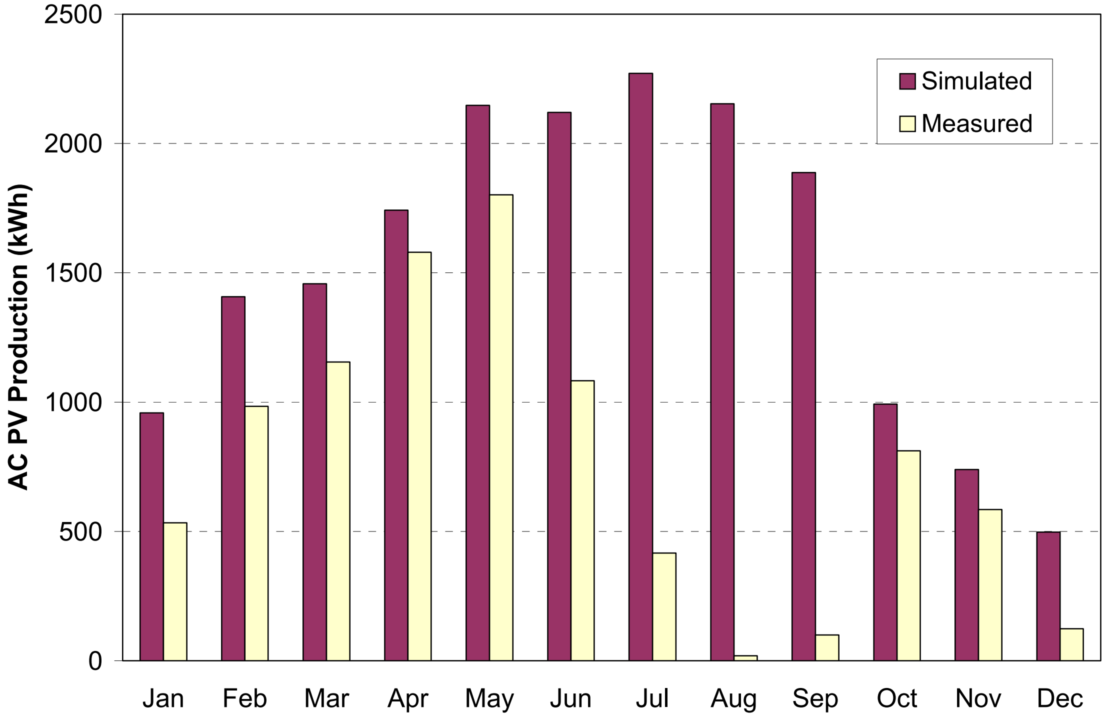

Figure 7-24 Simulated and measured PV performance for 2002

The performance from March to May and October to November was only slightly lower than predicted. However, the other months showed very poor performance. The annual total production was only 60% of the simulated value, which is mainly because of the inverter problems that shut the system down for long periods. The performance in the winter was lower than the simulation because of snow cover and lower than expected performance in the low radiation conditions.

8 Conclusions

At a construction cost of $\$93/\text{ft}^2$ ($\$1{,}000/\text{m}^2$), this building shows it is possible to pay extra attention to systems and materials to build a “green” office building within the same cost range as building a conventionally constructed office building. The building is economically viable in this location as it was developed by a private developer looking for a return on investment. This kept the costs in check. In many “green” buildings, other architectural elements add to the cost and it is difficult to separate amenities from the actual “green” elements.

The estimated performance of the Cambria building from calibrated simulations is shown in Table 8-1. The detailed monitoring and analysis have shown that the building uses 40% less energy and has 43% lower energy costs than typical, minimally code-compliant office buildings of similar size.

Table 8-1 Cost, Site, and Source Energy Savings Summary

	Cost		Total Site Energy		Total Source Energy	
	$\$/\text{ft}^2\cdot\text{yr}$ *($\$/\text{m}^2\cdot\text{yr}$)*	Percent Savings	$\text{kBtu/ft}^2\cdot\text{yr}$ *($\text{MJ/m}^2\cdot\text{yr}$)*	Percent Savings	$\text{kBtu/ft}^2\cdot\text{yr}$ *($\text{MJ/m}^2\cdot\text{yr}$)*	Percent Savings
Baseline	\$1.80 *(\$19.38)*	43%	57 *(642)*	40%	180 *(1,800)*	40%
As-Built	\$1.02 *(\$10.89)*		34 *(386)*		108 *(1,226)*	

8.1 Lessons Learned

Many things went well and many things could have been improved with this project. NREL has already applied lessons learned from the Cambria building to other research projects and the lessons will continue to be valuable for future projects as well.

In addition, the knowledge and information gained from the Cambria project have formed the basis for the Building Green in Pennsylvania program and they continue to provide baseline information for subsequent projects. Additional projects are the $21{,}000\text{-ft}^2$ ($1{,}900\text{-m}^2$) California Office Building with a small office at Philipsburg and an $110{,}000\text{-ft}^2$ ($10{,}000\text{-m}^2$) office in downtown Norristown. These third-phase projects started with established energy budgets, lighting budgets, as well as shell and glazing requirements, HVAC, and IAQ requirements that are required upon completion and that must be maintained during the life of the project.

The lessons learned from this project can be divided in to four categories: design and construction processes, technical, building operation, and energy monitoring.

8.1.1 Design, Construction, and Commissioning Lessons Learned

1. Setting specific performance goals that the whole design team believes in is critical to producing a building that operates efficiently. The estimated energy cost saving compared to ASHRAE Standard 90.1-2001 is 40%. The high-level performance was achieved through a concerted effort by the owner, occupant, and entire design team.
2. The design-build process can be efficient, saving time and money. In addition, the design-build process is dynamic and allows new ideas to be integrated quickly. New ideas can be evaluated at any time during the design and construction phases.
3. The design-build process can develop so quickly that there is not enough time to fully evaluate design options. Construction may begin before some systems are fully designed, which limits the options that can be considered and can have a negative impact on systems integration.

4. Documentation of the building process including plans, specifications, and operation sequences is not always fully completed in the design-build process. For example, there are no electrical drawings for the Cambria building, which makes it difficult to makes changes to the building electrical system or make monitoring plans.
5. The design-build process involves the contractor in the design process and the designers in the construction process. Both sides learn valuable lessons from working together. The collaboration allows many construction issues to be worked out during the design process and integrates the full costs into design solutions.
6. Integrated design solutions can lead to simpler, more effective, and lower cost systems. The building envelope and HVAC system went through many design iterations and resulted in a more effective, lower cost system because the architect, mechanical engineer, mechanical subcontractor, energy consultant, and owner worked together to find better solutions.
7. Energy simulations played an important part in understanding the forces that drive energy performance and allowed design alternatives to be investigated. However, the quick pace of the design-build process does not always allow enough time to complete the energy simulations and to inform design decisions.
8. Daylighting design should be analyzed carefully to ensure a high level of performance. The daylighting design at Cambria incorporated good daylighting design principles (i.e. orientation, clerestories, high reflectance ceilings, open office design), but the details were not analyzed to determine likely performance. Small changes could have improved the performance.
9. The construction process should be monitored for energy use concerns.
10. Commissioning is important, but it does not guarantee that the occupied building will operate efficiently. Monitoring building end use energy consumption provides valuable feedback to help maintain efficient performance of systems. Two main items missed during commissioning were the west ERV ran continuously and the HVAC fans ran continuously. These items may have been difficult to track without looking at the end use energy data. The end use energy data also allowed the timing of the lighting circuits and HVAC controls to be changed to save energy.

8.1.2 Technical Lessons Learned

11. The ERVs should include bypass dampers for economizer operation to use outside air for cooling without the overhead of the ERV fans. If bypass dampers for outside air were available, the ERVs should not be operated when its operating costs exceed the savings from the recovered energy. A conservative temperature range for not operating the ERVs is 50°F–60°F (10°C–16°C), which represents about 13% of the weekday hours between 5:00 a.m. and 5:00 p.m. in 2002 and 2003. Enthalpy control would expand this operating range.
12. The ERVs are more than twice as big as they need to be for outside air requirements.
13. Variable air volume fan control on the heat pumps would improve the energy performance as the system backs off supply air requirements with lower internal cooling or heating loads. The building is usually only partially occupied with approximately 70% of the designed occupancy.
14. The groundwater circulation pumps should not run continuously, but should be linked to the heat pump compressor operation. This would save approximately half the energy consumed by the pumps or about 18 MWh/yr.
15. There are trade-offs of using the simple thermostats on each heat pump. The thermostats are less expensive than a centralized control system and easier to program. However, it is difficult to keep the time and set points on all of them programmed correctly. The current system would work well, if only one or two people with proper training had access to the thermostats.
16. The heat loads of data center rooms are often underestimated. In many cases, these rooms should have a dedicated HVAC system because the loads are very different from surrounding zones. In the Cambria building, the heat pump installed in the telecom room should have an outside air damper to take advantage of cooling with outside air.

17. The illuminance levels are low due to lower than expected daylight contributions, low LPDs, indirect lighting used throughout the building, and high ceilings on the second floor.
18. Indirect lighting should only be used close to highly reflective ceilings. The indirect lighting on the first floor works well, but the indirect lighting on the second floor does not work well because the light source is too far from the ceiling and the roof trusses obstruct some of the light. Direct lighting or a combination of direct and indirect lighting would work better for the second floor.
19. The light shelves on the first floor are ineffective at providing light to the space. The ceilings are too low, there is not enough glass area, and the reflectance off the light shelves is too low to provide adequate light.
20. On the second floor, light from the clerestory windows does not penetrate beyond the first row of cubicles. There is not enough light entering through the windows and the roof trusses block some of the light. The daylighting along the perimeter walls is not very good because the windows are not high enough, the glass area is too small, the large wood frames limit the glass area and block some of the light, and the first row cubicle walls are too high and block daylight entering these cubicles.
21. The rows of electric lights should run parallel to the daylight sources and should be controlled separately so that they can be dimmed as necessary as the daylight levels vary with distance from the source.
22. The isolation transformer on the large PV system consumes approximately 18% of the energy delivered by the system. An automatic disconnect circuit should be added to this system to avoid the large losses when the PV system is down, or an inverter system that does not have high parasitic loads should have been chosen.
23. An automatic monitoring system for PV system operation should be installed. Poor operation of the PV system can currently be determined only if someone downloads and examines the power data from the detailed monitoring system.
24. The use of compact fluorescent luminaires should be limited and linear fluorescent luminaires should be used in most areas. Linear fluorescents have a higher efficacy and longer life.

8.1.3 Building Operation Lessons Learned

25. The UFAD system appears to work well from a comfort point of view; however, it is only slightly better at removing occupant pollutants than a well-mixed air delivery system (Fisk, et al. 2004).
26. This HVAC system has a slow response time; therefore, temperature setbacks should be small and have long startup periods.
27. Spaces that do not have a direct supply of conditioned air are very slow to respond to changing conditions. The restrooms rely on the exhaust fans to bring in conditioned air from the rest of the building. Therefore, the restrooms with outside walls can be cold in the mornings. These restrooms should have a direct supply of conditioned air or supplemental heating systems for morning warmup. The supplemental heating systems may be too expensive to run in an all electric building.
28. The ERVs should be controlled to operate only when the building is occupied.
29. The ERV time clocks should be installed in an easily accessible location inside the building to facilitate adjustments. The current location inside the units on the roof is not convenient.
30. The lights used during cleaning should not be all turned on at once. The cleaning crew should turn on the lights in only the sections they are cleaning and then turn them off when they have completed cleaning.
31. Computers and other nonessential electronic equipment should be turned off at night. Standby modes can consume a substantial amount of energy. In this building, the nighttime plug loads are more than half the daytime loads.
32. The building light controls have a manual on and off control; however, there should also be an automatic off switch controlled by a timer. The length of the timer would be set by the person turning on the lights.

33. A substantial amount of energy can be consumed while the building is being cleaned. Cleaning crews typically turn on all the building lights and leave them on until they are finished. Cleaning could be partially done during normal building operation, and the other cleaning should be done by zone with the lights on only in the zone being cleaned.

8.1.4 Energy Monitoring Lessons Learned

34. Performance monitoring systems need to be very robust and maintained by someone locally or monitored remotely with someone local to handle problems.
35. Electrical system monitoring should be performed with watt-hour (energy) meters or watt (power) meters with memory and not pure watt (power) meters. Watt meters that are read every 15 minutes only provide a snap shot of the instantaneous power and do not give a true measure of the energy used over the previous 15 minutes.
36. Personal computers should not be relied upon to be the only instrument of data retrieval and archiving. They are very unreliable compared to systems dedicated to data logging.
37. Include a weather station for extensive monitoring projects. The weather station should include a minimum of dry-bulb temperature, RH, and global horizontal solar radiation.
38. Carefully plan the monitoring system starting with an explicit list of questions to be answered.
39. The most effective daylighting analysis includes measurements taken a minimum of three times a year: near the summer and winter solstices and near either the spring or the fall equinox.

8.2 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 information that is more specific.

1. Install an automatic disconnect circuit on the large PV system to minimize the energy consumed by the isolation transformer, or install an inverter system that does not have the large parasitic loads. Annual energy savings would be approximately 2.3 MWh and $200.
2. The thermostat and ERV settings should be set and checked regularly by qualified personnel to ensure that the proper settings are maintained. The ERV controllers have been shown to be unreliable, and the thermostat set points have been found to have higher nighttime settings and clock settings that are off by 12 hours.
3. Reduce the airflow in the ERVs to approximately one-half of their current values. This could be accomplished with different pulley sizes, perhaps with different motor wiring, or new smaller fan motors. Reducing the ERV flow rate by one-half will reduce the fan energy consumption to about one-eighth of its current value because fan power is related to the cube of the fan flow rate. Additional energy savings would result from conditioning the lower amount of outside air. However, reducing the flow rate by half will adversely affect the energy recovery effectiveness.
4. 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 performances. Things to look for are sudden changes in energy consumption and gradual upward trends in energy consumption. In addition, track the monthly peak electrical demand to control utility costs. This will require staff to be trained and graphs to be generated automatically from the monthly data.
5. Consider the energy demand and energy use implications of adding loads to the building.
6. Install power management software on all computers. This type of program can be easily installed and controlled over a local area network. Annual energy savings have been shown to be 100–300 kWh per computer.
7. Install energy control devices on the cold drink vending machines. These units can reduce the energy consumption by one-third to one-half and typically pay for themselves in less than two years.

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Appendix A – Project Time Line

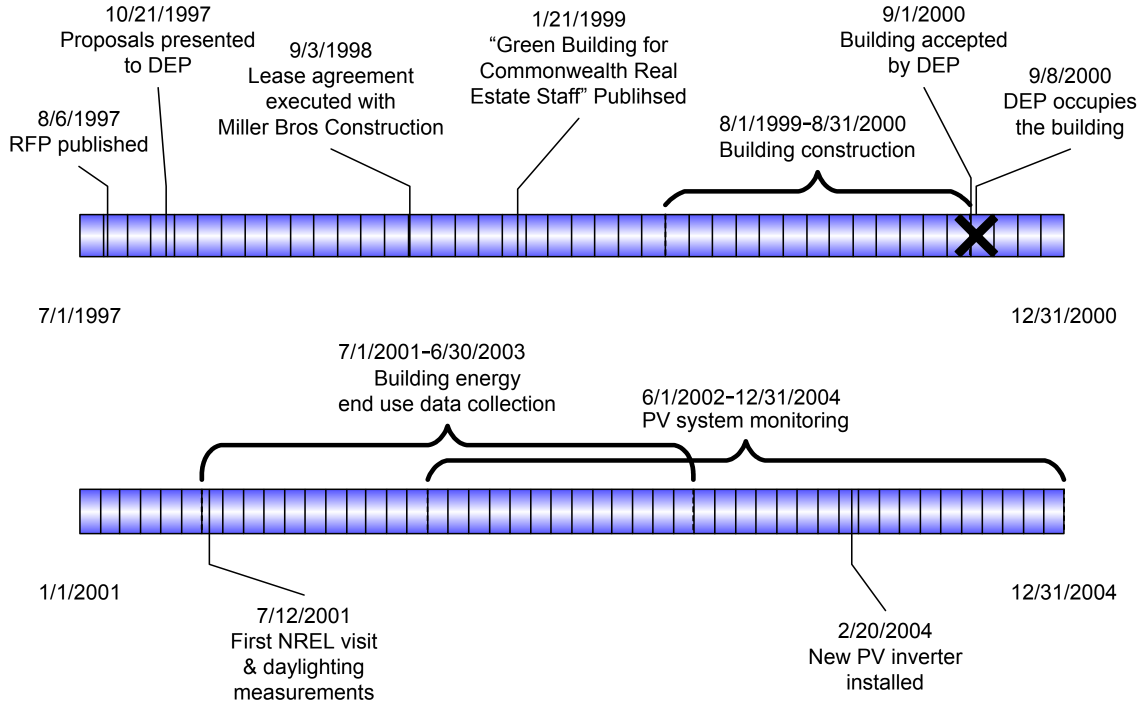


Figure A-1 Project time line from publication of RFPs to end of energy monitoring

Appendix B – Heating, Ventilation, and Air Conditioning Control Changes

Table B-1 Summary of HVAC Control Changes

Date	West ERV Operation	East ERV Operation	Heat Pump Fan Operation	Heating Set Points	Cooling Set Points
Sep 2000	Continuous	On Tues–Sat[1] 6:00 a.m. to 6:00 p.m.	Continuous	70°F (21°C)	72ºF (22°C)
July 14, 2001		On Mon-Fri 6:00 a.m. to 6:00 p.m.	Continuous	70°F (21°C)	72ºF (22°C)
Dec 11, 2001			Cycle-on-Demand for Unoccupied 6:00 p.m. to 6:00 a.m.	70°F (21°C)	72ºF (22°C)
May 30, 2002	On Mon–Fri 5:00 a.m. to 5:00 p.m.	On Mon-Fri 5:00 a.m. to 5:00 p.m.	Cycle-on-Demand for Unoccupied 6:00 p.m. to 5:00 a.m.	70°F (21°C) Occ. 66°F (19°C) Unocc. Occupied: Mon–Fri 5:00 a.m. to 6:00 p.m.	72°F (22°C) Occ. 78°F (26°C) Unocc. Occupied: Mon–Fri 5:00 a.m. to 6:00 p.m.
Sep/Oct 2002[2]	Clock 3 hours fast On Mon–Fri 3:00 a.m. to 6:00 p.m.				
Nov 2002 to Jun 2003[3]			Continuous	70°F (21°C) Occ. 72°F (22°C) Unocc.[4] Occupied: Mon–Fri 5:00 a.m. to 6:00 p.m.	72°F (22°C) Occ. 72°F (22°C) Unocc. Occupied: Mon–Fri 5:00 a.m. to 6:00 p.m.
Jul 15, 2003	Clock reset On Mon–Fri 5:00 a.m. to 5:00 p.m.		Cycle-on-Demand for Unoccupied 6:00 p.m. to 5:00 a.m.	72°F (22°C) Occ. 68°F (20°C) Unocc. Occupied: Mon–Fri 4:00 a.m. to 6:00 p.m.	72°F (22°C) Occ. 76°F(24°C) Unocc. Occupied: Mon–Fri 4:00 a.m. to 6:00 p.m.

[1] All times are EST.
[2] The time clock on the west ERV changed to be approximately 3 hours fast. The cause is unknown.
[3] Thermostats were changed to satisfy occupant complaints.
[4] Some of the thermostats were changed to have a higher heating set point at night than during the day.

Appendix C – Weather File Creation

A weather data file was created for Ebensburg, Pennsylvania for the year 2002 for the purpose of building energy simulations of the Pennsylvania DEP Cambria building. The file format follows the TMY2 format (http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/). The data for the file were taken from on-site weather data, nearby weather stations, and the TMY2 file for Pittsburgh.

A weather station, which consists of horizontal and in the PV plane Li-Cor pyranometers and a Vaisala humitter, was installed and connected to a Campbell Scientific, Inc., CR10X data logger on the west roof. The humitter was only reading temperature; however, a T-RH Hobo data logger was left on the east side of the building to get RH.

The missing data, sources of fill data, and reasons for the missing data are summarized in Table C-2. Most of the data were filled with measured data from nearby weather stations. Hourly data for the two weather stations were obtained from the Pennsylvania State Climatologist at http://pasc.met.psu.edu/PA_Climatologist/index.php. The weather stations are summarized in Table C-1.

Table C-1 Weather Stations

Station	Organization	Lat	Long	Elevation (ft)
Cambria DEP Office	NREL	40.47°	–78.67°	2,000
Johnstown (JST) – Cambria County Airport	FAA	40.317°	–78.834°	2,280
Altoona (AOO) – Blair County Airport	FAA	40.291°	–78.319°	1,504

Table C-2 Missing Data and Filling Source

Period	Hrs	Data	Fill Source	Notes
4/20 0400 to 4/21 0200	23	T_{db}	Data logger internal temperature adjusted to match T_{db}	Unknown source of error
4/21 0700 to 4/22 0200	20	T_{db}	Same	Same
5/03 1300 to 5/03 2000	8	T_{db}	Same	Same
5/28 1700 to 5/31 1000	66	T_{db}	Altoona FAA weather station, smoothed to match existing data	Data logger moved from roof to IS room
5/28 1700 to 5/31 1000	66	RH	Same	Same
5/28 1700 to 5/31 1000	66	I_{gh}	Filled from days with similar weather according to cloud cover data taken at Altoona weather station. Data smoothed to match existing data.	Same
11/4 0700 to 11/27 1000	556	RH	Altoona FAA weather station, smoothed to match existing data	RH sensor out of range
12/11 0900 to 12/14 2400	88	RH	Altoona FAA weather station, smoothed to match existing data	Same
11/5 1600 to 11/9 1600	97	T_{db}	Altoona FAA weather station, smoothed to match existing data	RH sensor out of range caused other readings to fail
11/10 0300 to 11/10 1700	15	T_{db}	Altoona FAA weather station, smoothed to match existing data	Same
11/6 0800 to 11/9 1300	97	I_{gh}	Estimated from cloud cover data from Johnstown FAA weather station	Same
11/14 1000 to 11/14 1800	15	I_{gh}	Same	Same
12/15 0100 to 12/28 1100	323	T_{db}	Johnstown FAA weather station	Computer down
12/15 0100 to 12/28 1100	323	RH	Johnstown FAA weather station	Same
12/15 0100 to 12/28 1100	323	I_{gh}	Estimated from cloud cover data from Johnstown FAA weather station	Same

Some of the weather variables in the final file were calculated from the measured data as summarized in Table C-3.

Table C-3 Calculated Weather Data

Variable	Source Variables	Method
T_{dp}	T_{db}, RH	ASHRAE Fundamentals Ch. 6
I_{dn}	I_{gh}	Perez model
I_{df}	I_{gh}, I_{dn}, θ_z	$I_{df} = I_{gh} - I_{dn} \cos(\theta_z)$
TotalSkyCover	I_{gh}, I_{df}, θ_z	TRNSYS Type 69 by Thomas Auer
OpaqueSkyCover		Assumed = TotalSkyCover

Appendix D – Site-to-Source Energy Conversion

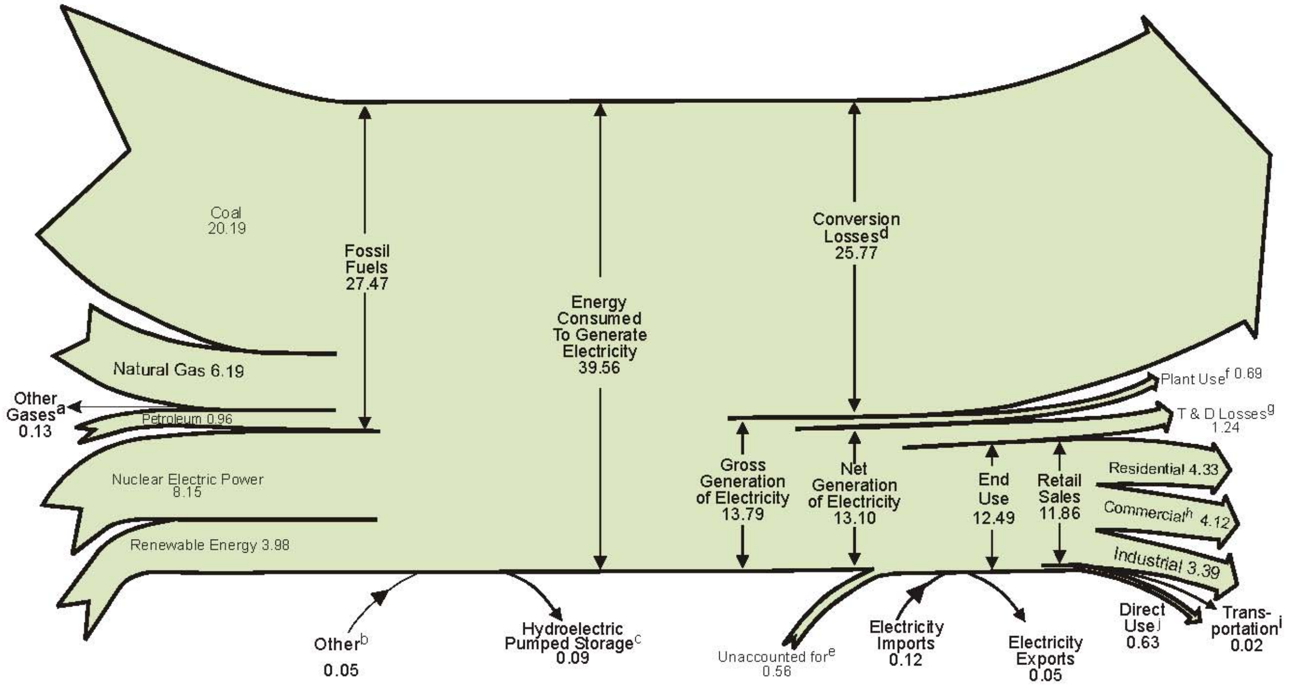
It is difficult to compare the consumption of different forms of energy at the building site. For example, heating with gas, electricity, or district heat cannot be compared, because electricity and district heat are nearly 100% efficient. However, this comparison does not account for the energy used to generate and deliver the electricity or district heat. A better comparison is to calculate the source (or primary) energy used to generate and deliver the energy to the site. But many of the important issues necessary to calculate source energy are often unknown at the local utility level, including energy source mix, generation efficiencies, and distribution and transmission efficiencies. A solution is to use primary energy based on total energy generation and consumption data for the United States. Using national average data is a good approach because the energy distribution network in the United States is highly interconnected. National energy data are compiled by the EIA and can be accessed through its Web site (http://www.eia.doe.gov/). The site-to-source conversion efficiencies for electricity are shown in Table D-1.

The average generation and delivery efficiency of electricity for 2002 was approximately 31.57%, or source energy is 3.167 times site energy consumption. The national energy flow associated with the production of electricity is shown in Figure D-1. Electricity efficiency is calculated by dividing end use electricity by energy consumed to generate electricity and accounts for conversion, transmission, and distribution losses. It is based on the average of all sources of electricity generation and distribution in the nation, as reported by EIA in the *2002 Annual Energy Review* (EIA 2003). This does not account for precombustion energy—energy to extract, transport, and process fuels used to generate electricity.

Table D-1 Site-to-Source Energy Conversion

Energy	Source-to-Site Efficiency	Site-to-Source Conversion
Electricity	31.6%	3.167

Diagram 5. Electricity Flow, 2002
(Quadrillion Btu)



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[a] Blast furnace gas, propane gas, and other manufactured waste gases derived from fossil fuels.

[b] Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, and miscellaneous technologies.

[c] Pumped storage facility production minus energy used for pumping.

[d] Approximately two-thirds of all energy used to generate electricity. See note at end of Section 2.

[e] Data collection frame differences and non-sampling error.

[f] Electric energy used in the operation of power plants, estimated as 5 percent of gross generation. See note at end of Section 2.

[g] Transmission and distribution losses, estimated as 9 percent of gross generation. See note at end of Section 2.

[h] Commercial retail sales plus approximately 95 percent of "Other" retail sales from Table 8.5.

[i] Approximately 5 percent of "Other" retail sales from Table 8.5.

[j] Commercial and industrial facility use of onsite net electricity generation; and electricity sales among adjacent or co-located facilities for which revenue information is not available.

Note: Totals may not equal sum of components due to independent rounding.

Sources: Tables 2.2a, 8.1, 8.5, and A6.

Figure D-1 Energy flow diagram for electricity generation for 2002 (EIA 2003)

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13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT** *(Maximum 200 Words)*

The Pennsylvania Department of Environmental Protection asked NREL to evaluate the energy performance of the Cambria Office Building to determine if it had met design goals. The focus of this report is the analysis of an integrated design process used to construct the facility and the postoccupancy energy performance. NREL collected energy use and other performance data and compared that data with a standard ASHRAE baseline computer model. NREL used this metered data and analysis to formulate recommendations to further improve building performance.

15. **SUBJECT TERMS**

Cambria; Pennsylvania; Pennsylvania Department of Environmental Protection; energy analysis; energy evaluation; energy performance evaluation; building design; low-energy design; energy performance; high-performance buildings; commercial buildings; building energy performance

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