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Energy Performance Evaluation of a Low-Energy Academic Building

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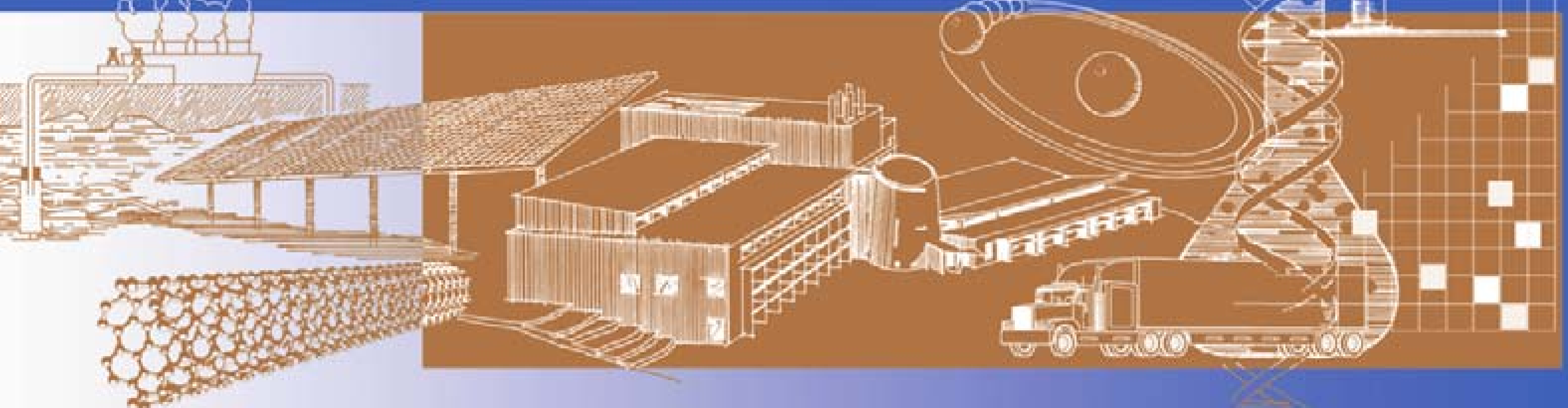

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Energy Performance Evaluation of a Low-Energy Academic Building

ABSTRACT

The Adam Joseph Lewis Center for Environmental Studies in Oberlin, Ohio, is a 13,600-ft^2 (1,263-m^2) academic building designed with a long-term goal of operating as a net energy exporter. The building was designed to consume significantly less energy than a typical building. Features to achieve the energy savings include daylighting, enhanced thermal envelope, ground-source heat pumps, energy recovery ventilators, a dimming lighting system, and natural ventilation. The building is equipped with a 60-kW photovoltaic array.

The annual energy performance of the Lewis Center was monitored and evaluated from March 2001 through February 2003. Documenting actual energy performance and evaluating design flaws and successes lead to important lessons that can be applied to the designs of future high-performance educational and commercial buildings.

During the third year of occupancy, the Lewis Center consumed 29.8 kBtu/ft^2·yr (94.0 kWh/m^2·yr), or 48% less energy than a conventional ASHRAE 90.1-2001 energy code-compliant building. On-site photovoltaic generation met 45% of this energy requirement, for a total net energy use intensity of 16.4 kBtu/ft^2·yr (52.1 kWh/m^2·yr).

INTRODUCTION

Educational buildings accounted for 12% of all energy used in commercial buildings in the United States in 1995, or 2% of all the energy used in the United States (EIA 1998). Commercial buildings as a group have an average site energy intensity of 90.5 kBtu/ft^2·yr (285.5 kWh/m^2·yr), and educational buildings consume 79.3 kBtu/ft^2·yr (250.2 kWh/m^2·yr). The total educational energy expenditure in the United States was $7.1 billion/yr, or $0.92/ft^2·yr ($10.2/m^2·yr) (EIA 1998). Educational buildings consumed 614 trillion Btu of combined site electricity, natural gas, fuel oil, and district steam or hot water (EIA 1998). They rank as the third highest category of energy consumers of all the commercial building types. According to an Oberlin College campus-wide energy consumption study, the college's average campus energy use intensity is 88.5 kBtu/ft^2·yr (279.2 kWh/m^2·yr, RMI 2001), which is slightly higher than the average for U.S. educational buildings.

The Adam Joseph Lewis Center for Environmental Studies houses classrooms and faculty offices on the campus of Oberlin College in Oberlin, Ohio. The two-story, 13,600-ft^2 (1,263-m^2) building was designed to be a model of "ecological design" and to serve as a practical teaching tool. The design process, led by David Orr, chair of the Environmental Studies Program, started in February 1996; construction began in September 1998 and the building was occupied in January 2000. To demonstrate that substantial energy production and conservation are possible in academic buildings, the design team set an aggressive long-term goal of developing a building to be a net energy exporter, sometimes referred to as a zero-energy building. This goal meant designing a building that minimizes energy use and produces electricity on site with photovoltaic (PV) panels.

This paper considers the energy performance analyses conducted to document and verify progress toward the building's design objectives. An earlier study, which used data from billing meters installed by the local utility, evaluated the first two years of energy production and consumption in the Lewis Center (Scofield 2002). An analysis of the financial and environmental payback of the Lewis Center's PV components has also been conducted (Murray and Petersen 2004). This initial study suggested that continued improvements are essential for the building to operate at its full potential. In this paper, we provide a comprehensive description of the building, of the data monitoring system that was installed, and of the procedures used to evaluate and improve building performance. The authors present and discuss energy performance data and draw lessons that can be applied to improve the design of this and future low-energy buildings.

LEWIS CENTER DESCRIPTION

The Lewis Center was designed to minimize energy consumption through energy-efficient building technologies and to meet a significant portion of the energy demand through on-site production. The 60-kW PV system is grid interconnected such that the building exports energy back to the utility grid when the PV system produces more than the building uses (see Figure 1, item 1). The design team chose an all-electric building, including mechanical systems and domestic hot water (DHW), so the energy generated on site by the PV system could potentially provide all the building's requirements.

The energy efficiency design measures incorporated into the Lewis Center and shown in Figure 1 consist of ground-source heat pump loops (item 2 shows the location of the geothermal wells), daylighting and efficient lighting designs (item 3), energy recovery from exhaust air, and an energy management system (EMS) to control these systems. As of 2005, the trellis pictured on the east side of the atrium (which was part of the initial design) had not yet been installed. An ecologically engineered wastewater system that treats and recycles water within the building is located in the greenhouse (item 4), and was designed to be an educational tool and research facility.

Figure 1. Low-Energy Design Features

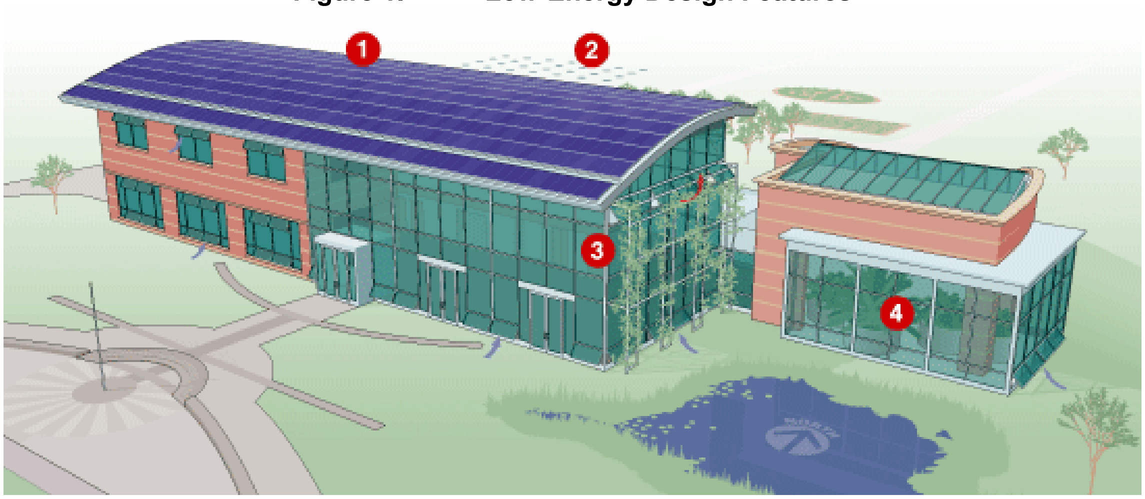


Figure 1 shows energy efficiency design features, including the 2.5-ft (0.76-m) overhangs of the curved roof and the atrium on the southeast of the building. Insulation values for the envelope include R-19 (R_{SI}-3.3) exterior walls and R-30 (R_{SI}-5.3) for the ceiling and roof. The atrium curtain wall includes tinted, argon-filled, low-e, triple-pane glass with thermally broken aluminum frames for the north, east, and south exterior wall surfaces. All other windows are double-pane, low-e, argon-filled with thermally broken aluminum frames. The entire 6-in. (15-cm) concrete slab in the atrium is insulated with 2-in. (5-cm) R-10 (R_{SI}-1.8) insulation. The perimeter footings are insulated with 4-in. (10-cm) R-20 (R_{SI}-3.5) polystyrene insulation. The south- and east-facing fenestration in the atrium is triple-pane, green-tinted glass with a visible transmittance of 46% and a solar heat gain coefficient (SHGC) of 0.26. The rest of the building glass is black-tinted double-pane insulating glass with a visible transmittance of 69% and a SHGC of 0.46. Table 1 summarizes the envelope components and thermal properties.

The design team oriented the building to face south and elongated the east–west axis to maximize the performance of the daylighting features and PV system. This orientation, combined with engineered window overhangs and fenestration, contributes to the solar heat gain in the winter, solar load avoidance in the summer, and the increased availability of natural light. The layout of the interior spaces was also designed with the orientation in mind (see Figure 2 and Figure 3). Public spaces, including the atrium and classrooms, are on the south side so that natural light can help fulfill lighting needs and reduce lighting loads. North-facing clerestories provide daylighting to offices and corridors on the north side. The minimally occupied spaces, such as the mechanical rooms and restrooms, are on the north side of the building. The greenhouse, used for the wastewater treatment system, requires solar access. The auditorium, programmed not to use daylighting because of presentation requirements, is on the north side.

Efficient fixtures, dimmers, and sensors provide automatic and occupancy control of lighting levels. The classrooms, offices, restrooms, and corridors have motion-controlled lighting. The corridor and classroom lights are also connected to photo sensors, which override the occupancy sensors if daylighting provides sufficient illumination. The installed lighting power density (LPD) is 1.26 W/ft^2 (13.6 W/m^2) in the classrooms and resource center, 0.88 W/ft^2 (9.5 W/m^2) in the offices, 0.93 W/ft^2 (10.0 W/m^2) in the atrium, and 0.45 W/ft^2 (4.8 W/m^2) in the corridors and transition spaces. The overall LPD for the building is 0.79 W/ft^2 (8.5 W/m^2), which includes exterior lights attached to the building, but not the parking lot and sidewalk lights. The total installed LPD for the site is 0.94 W/ft^2 (10.1 W/m^2), which includes 2.1 kW of parking lot and sidewalk lights that are connected to the building lighting panels.

Figure 2.   First Floor Plan of the Lewis Center

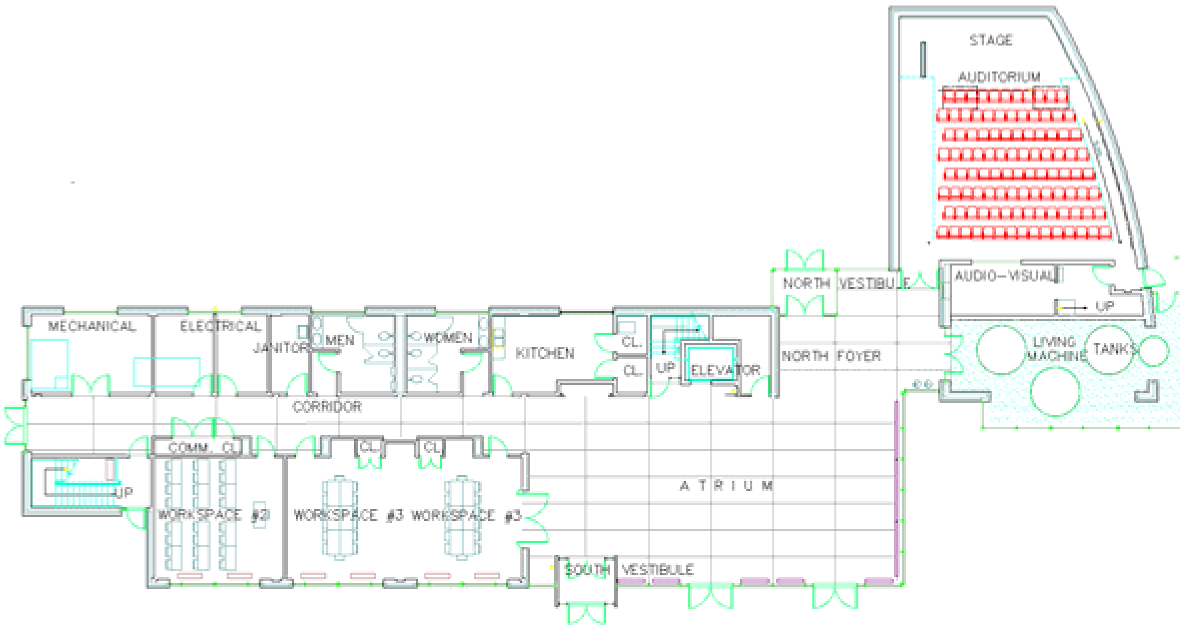


Figure 3.   Second Floor Plan of the Lewis Center

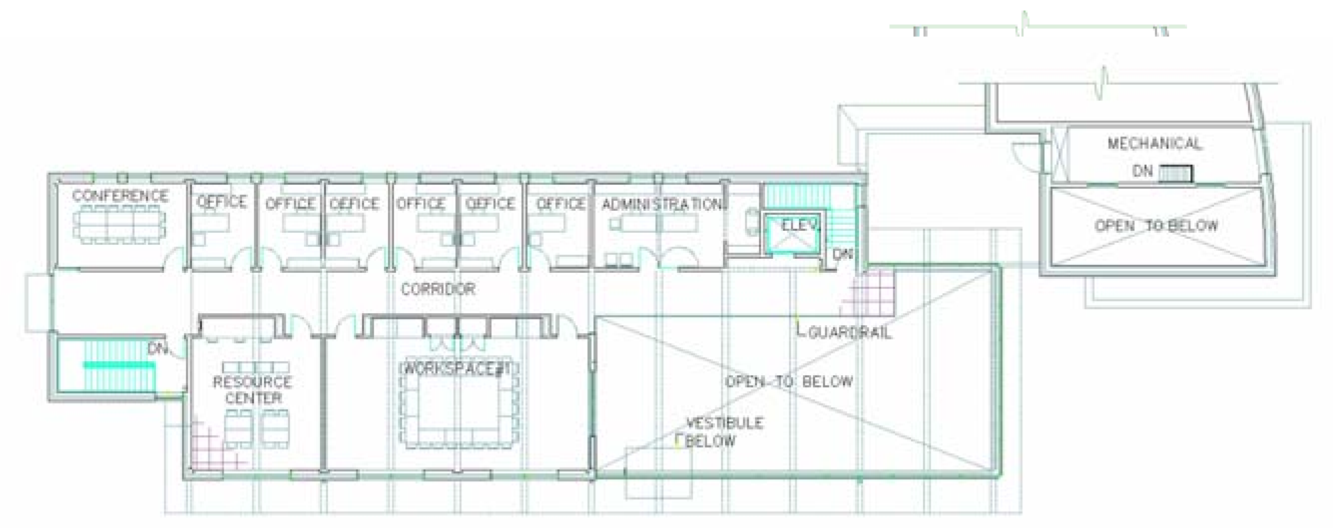


Table 1. Building Envelope Components and Thermal Properties (ASHRAE 1997)

Envelope Component	R effective ($hr \cdot ft^2 \cdot F/Btu$)	R effective ($m^2 \cdot K/W$)
Walls		
Atrium triple-pane, argon-filled, tinted insulating curtain glass walls with thermally broken frames	2.9 (assembly)	0.5
North side underground exterior wall	12.0	2.1
Auditorium walls	20.0	3.5
All other brick-faced exterior walls	19.0	3.3
Windows/doors		
Nonatrium windows with double-pane, argon-filled, tinted insulating glass with thermally broken frames	2.2 (assembly)	0.4
Roofs		
Curved roof sections (upper roof and auditorium)	27.0	4.8
Flat roofs (small slope)	20.5–40.5	3.6–7.1
Floors		
All perimeter footings	21.6	3.8
Atrium slab	11.5	2.0
First-floor classrooms	12.0	2.1

Photovoltaic System

Six hundred and ninety 85-watt modules are mounted to the curved roof for a rated capacity of 60 kW DC. The far northern rows of PV panels are tilted to the north at 3º and the southernmost rows are at a 20º tilt to the south. Excluding the northernmost rows, the building orientation allows for the tilted section of the PV array to be angled due south, as shown in Figure 1.

The PV system is wired in three separate but identically structured subarrays, each of which consists of 10 strings wired in parallel from north to south. Each string consists of 23 modules in series oriented east to west. Each subarray is rated at 19.54 kW (414 volts DC and 47.2 amps) at the peak output under standard test conditions and is connected to a three-phase, 15-kW grid-tied inverter. The inverters are connected to the building's main electrical distribution panel through three isolation transformers.

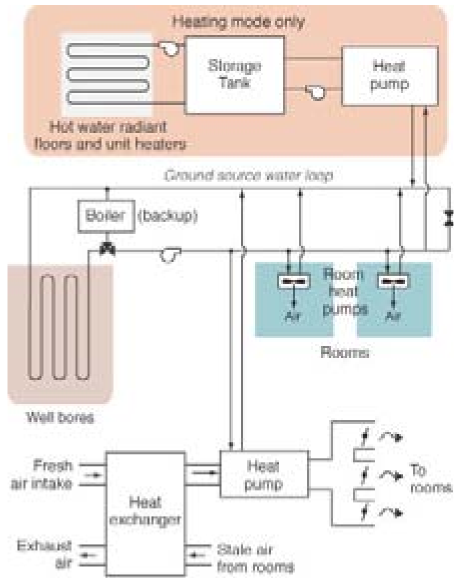
Mechanical Systems

The heating and cooling systems are decentralized by zone. To accomplish this, water-to-air room heat pumps are used for the individual classrooms and offices. A closed loop, geothermal well system acts as a heat source and sink for the glycol−water source side of the heat pumps. A set of variable speed drive (VSD) pumps circulates the glycol−water mix through 24, 240-ft (73-m) deep wells and to the heat pumps. A single, large, standard-range water-source heat pump, coupled to an energy recovery ventilator (ERV), handles the 100% outdoor ventilation air for the classrooms and offices. Control for this outdoor air system is with occupancy sensors in each classroom that open supply dampers when the space is occupied. A supply fan bypass loop in the outdoor air heat pump unit modulates based on flow requirements. Although CO_2 sensors are installed, they are not currently used to control ventilation in the classrooms or offices.

Another water-source heat pump and ERV heat, cool, and ventilate the auditorium. A separate hydronic loop provides heating through radiant floor tubing in the atrium and fin tubes and unit heaters in the wastewater treatment system. A water-to-water ground-source heat pump with an electric boiler backup provides heating to the hydronic loop. These heat pumps were not part of the original design; they were installed just before the 2002−2003 heating season. The pumps replaced a 112-kW electric boiler that provided the hot water to all the hydronic systems for the first two heating seasons. An EMS controls these HVAC systems. The HVAC system configuration is diagrammed in Figure 4.

A 0.5-hp (0.37-kW), 2,000-cfm exhaust fan extracts conditioned air from the wastewater treatment greenhouse to the outside throughout the year. Its speed can be manually controlled to limit unwanted odors from the wastewater treatment system's organic processes that might infiltrate the main spaces of the building. This exhaust fan airflow is 1,200–1,300 cfm under typical operation. Smaller exhaust fans at 75–300 cfm remove air from the restrooms, kitchen, and mechanical rooms. The restroom exhaust fans are controlled by an occupancy sensor; the kitchen and mechanical room fans are thermostatically controlled. All exhaust fans vent directly to the outside. Operable windows in the offices and classrooms can be used for natural ventilation at the user's discretion. In addition, low and high windows in the atrium are controlled automatically by the EMS.

Figure 4. HVAC System Configuration



Equipment Description

The wastewater treatment system includes multiple water pumps and water treatment equipment such as an ultraviolet light and bubblers. A 40-gal (151-L) electric water heater supplies DHW for the restrooms and kitchen. Office equipment includes computers and monitors, task lighting, a copier, a fax machine, and printers. The classroom equipment includes overhead and digital projectors. The elevator equipment includes controls, cabin lighting, hydraulics, and an oil heater. Other equipment includes automatic window openers, monitoring and control equipment, auditorium audiovisual equipment, and a microwave and refrigerator in the kitchen. An emergency generator in an adjacent building runs only when grid power is not available. Its circuits include telecommunications, fire alarms, emergency lighting, and exit signs.

EVALUATION PROCEDURES

The authors, in collaboration with students and faculty from the Oberlin College Environmental Studies Program, began the whole-building analysis process by installing permanent monitoring equipment that measures the energy consumption of multiple end uses as well as energy supplied to the building from the PV system and the utility company. For this analysis, the energy performance of the Lewis Center was monitored, evaluated, and documented from March 2001 through February 2003. Researchers verified that the energy meters were working properly through an energy balance at the building's main electrical distribution panel. After we confirmed that the meters were working properly, we calculated the energy performance metrics needed to assess progress towards achieving initial design goals. In addition to assessing energy production and consumption, we conducted a complete daylighting analysis to measure lighting performance.

Although no detailed monitoring was conducted during the first year of occupancy (March 2000 through February 2001), monthly utility bills provided some data for a summary analysis. During the first year, we considered annual energy cost intensity, site energy use intensity, and source energy use intensity (intensity is here defined as use of a resource per unit area). For the second year (March 2001 through February 2002), we also considered seasonal load shape profiles, detailed end use analysis, an electrical demand and cost analysis, specific systems performance, and the measured site weather. The results from the second year of whole-building analysis included annual energy cost intensity, measured site energy use intensity, measured PV production, measured net site use, and measured source use intensity. These metrics were also used for analysis of the third year of building operation (March 2002 through February 2003). Additional analyses of measured end use data and utility bills are provided for the third year to study changes made during the evaluation period.

Researchers then created a computer-simulated building model of a conventional energy code-compliant building (base-case) and a model of the Lewis Center building as constructed (as-built). We used computer energy simulations to establish energy benchmarks to assess opportunities for improving performance. The conventional and as-built buildings were modeled to calculate energy savings for typical weather years and to provide an energy benchmark. As-built models were calibrated against measured performance and driven by measured weather data. Performance metrics included site energy savings, source energy savings, and site cost energy savings. A single calibrated as-built model and a reference model were created for the second and third years of operation, with results provided for both years.

Building Energy Monitoring Methods

The evaluation team installed a permanent data acquisition system (DAS) to measure energy flows, which were measured with watt-hour meters installed on multiple electrical circuits within the electrical panels. The rated uncertainty of the energy meters is ±0.45%. The DAS recorded the meter pulses of each monitored circuit as minute and hourly totals. We calculated aggregate energy consumption of three end-use categories– HVAC, lighting, and equipment. Other aggregated measured variables that we considered were total consumption, total PV production out of the inverters and transformers, and net building use. Total electrical consumption was calculated by summing all the end use categories in the building, and included sidewalk and parking lot lighting and wastewater treatment system equipment. The net site use was calculated by subtracting the total PV production from the total building site consumption. When the PV system generates more electricity than the building consumes, net site use becomes a negative number, which indicates the building is exporting electricity onto the grid.

Redundant meters were used to ensure monitoring quality. A city utility meter and our DAS meter measured the PV production. An energy balance around the main electrical distribution panel required all the energy delivered to the building (as measured by the city utility meter) to be equal to all the energy used in the building (as monitored by the DAS plus building transformer losses).

The electrical end-use measurements are just a portion of the total measurements made with the DAS. We used measured weather data with a weather station to create a building simulation weather file. Additional measurements included air temperatures at the inlet and outlet of each ERV unit and the water temperatures in the heat pump loop to and from the ground wells.

The dedicated DAS proved functional and very reliable. Over the two-year period of monitored minute and hourly end use data, only 0.6% of the collected hourly electricity and weather data were incomplete or missing. Missing data points were estimated based on diurnal, weekly, and seasonal patterns in the end uses, combined with a driving variable such as weather and occupancy.

The monitoring team recorded and analyzed energy-related variables in minute and hourly totals or averages from March 1, 2001 through February 28, 2003. Monitoring and analysis of the Lewis Center remains an ongoing process that will continue and expand into the future. The energy data are currently available as real-time and historic displays on the Lewis Center website at http://www.oberlin.edu/ajlc. Subsequent research will consider longer term energy performance and the ecological performance of the wastewater treatment system and landscape components.

Building Energy Simulation Methods

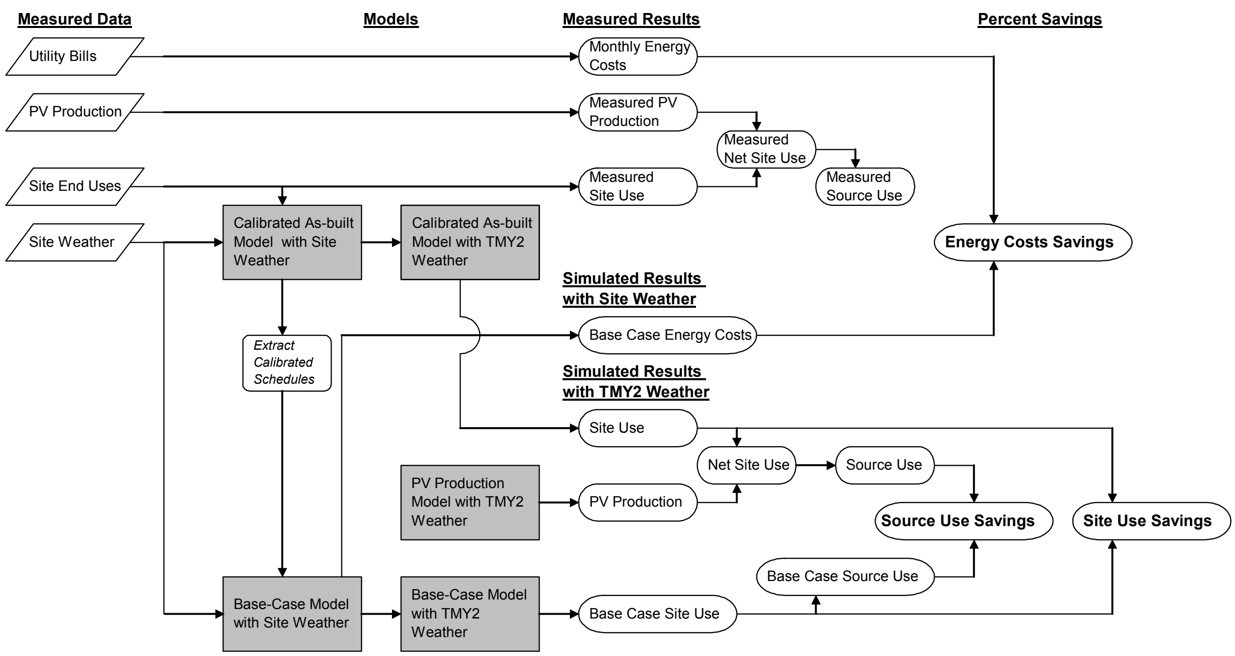
The whole-building evaluation also includes modeling the as-built building and a similarly sized and located code-compliant conventional building to determine energy savings for typical weather years. The conventional, or base-case building, was modeled to provide an energy benchmark. The as-built model was calibrated with measured performance. Scenarios for both the base-case and the as-built models were driven with weather data obtained from the DAS. We compared results of the base-case and as-built computer simulations, which reduced errors associated with comparing measured data to simulated data.

Performance indicators analyzed include site energy savings, source energy savings, and energy cost savings. Calibrated as-built and base-case models were created for the second and third years of operation, with results provided for both years. The flow chart in Figure 5 shows how the measured data were used in the models and the process used to obtain the simulation results.

Source energy or primary energy is the sum of the energy consumed at the site and all associated losses of useful energy that occur in the conversion and transmission of energy. Documenting primary energy consumption can be useful when emissions from energy sources are of concern, as they are at the Lewis Center. Source energy was calculated based on 31% electricity conversion and delivery efficiency from source to site. This efficiency was based on the conversion and distribution efficiency averaged over all sources of electricity generation in the nation, as reported by EIA (2000).

The uncertainty of the annual performance metrics based on simulations, such as site use energy savings and site energy use intensity for a typical weather year, are difficult to estimate with direct calculations. The processes used in the whole-building analysis attempt to reduce uncertainty related to building simulations. To reduce the uncertainty of the annual simulation metrics, we calibrated the models with measured end uses and site weather. We consider a building simulation to be calibrated when the simulated monthly energy use is within 12% of the measured monthly energy use. This ±12% criterion can be assumed to represent a base level of uncertainty in absolute annual performance metrics based on simulation results, such as simulated energy use intensity metrics. Uncertainties of the simulated performance can be much lower than ±12% for percent saving metrics. Percent energy savings metrics, such as site and source energy savings, result from comparing of one simulation to another (e.g., base case to as-built). Because difficult-to-know inputs are held the same in both simulations, such comparisons remove much of the uncertainty inherent in an hourly building energy simulation. Variables that change throughout the year, such as inconsistent occupancy, set-point changes, and equipment performance degradation, are difficult to account for in an annual building energy simulation. We compared a base-case model to an as-built model with the same schedules to reduce the uncertainty caused by these variables.

Figure 5. Whole-Building Evaluation Flowchart



Building Model Definitions

We used four versions of hourly energy simulation models to document the energy performance of the Lewis Center during the second and third years of operation and to suggest solutions for building system problems.

- *As-built March 01−February 02* – This model was simulated with measured site weather data and typical meteorological year weather (TMY2) data (NREL 1995). It was calibrated with measured end uses and represents each mode of building operation over the second-year monitoring period.

- *As-built March 02−February 03* – This model was simulated with measured site weather data and TMY2 weather data. It was calibrated with measured end uses and represents building operation over the third-year monitoring period.

- *Base-case* – This model represents a conventional building of similar size to the Lewis Center that meets American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 90.1-2001

(ASHRAE 2001). This code-compliant *Base-case* model established a benchmark to compare and quantify the energy performance of as-built models.

- *Optimized* – This model includes solutions for identified building system problems and provides a potential energy performance objective for a typical weather year. This model also provides an estimate of possible energy savings with current and future changes. The authors used the *Base case* modeled with *As-built March 02−February 03* operational schedules for benchmarking purposes.

To ensure the adequacy of the as-built model and accompanying modeling assumptions, the *As-built March 01−February 02* modeled energy performance was compared to the actual measured energy performance. For a proper comparison, the measured local weather data from March 2001 through February 2002 were used as the weather file in the as-built simulation. All primary measured end uses (HVAC, lighting, and equipment) were compared to the simulated end uses to allow for the model calibration. To calibrate the model, assumptions such as heating and cooling schedules, occupancy schedules, and unoccupied infiltration were slightly tuned until the energy performance of the calibrated *As-built March 01−February 02* model described the measured energy performance. These calibrated schedules were also used in the comparison *Base-case* model. Based on measured ground loop temperatures, heat pump efficiencies and capacities were also tuned to help calibrate the model. For the model to describe the actual building energy performance within expected simulation accuracy, the difference between modeled and measured monthly energy totals should be less than 12%. The authors also used daily load shape profile comparisons of the lighting, equipment, and HVAC to ensure appropriate as-built model representation. The results of the calibration of the *As-built March 01−February 02* model are provided in Table 2. The *As-built March 02−February 03* model was calibrated in a similar fashion, using measured monthly end use data and site weather from March 2002 through February 2003.

Table 2. Simulated Use and Measured Use Monthly Comparison

	Simulated Total Use (kWh)	Measured Total Use (kWh)	Percent Difference
March-01	25,019	25,878	-3
April-01	10,121	10,060	1
May-01	7,534	8,174	-8
June-01	5,285	4,780	10
July-01	6,977	7,740	-11
August-01	7,152	7,509	-5
September-01	6,291	7,270	-16
October-01	8,824	7,530	15
November-01	7,562	8,232	-9
December-01	10,644	9,782	8
January-02	12,137	11,969	1
February-02	12,236	13,175	-8
Totals	119,782	122,099	-2

To establish a benchmark, the evaluators created an all-electric *Base-case* model of a conventional, ASHRAE Standard 90.1-2001 energy code-compliant building (ASHRAE 2001). The *Base-case* model was developed as specified in Addendum E of ASHRAE 90.1-2001. Although the building was designed and built before 2001, the 2001 version of ASHRAE 90.1 was used because future renovations and upgrades are expected. The evaluators used this model to generate baseline energy performance data for a conventional building for comparison with data from the calibrated as-built models with TMY2 weather data. The *Base-case* building is a solar-neutral, two-story building of equal size and space use. Its footprint is a square of 82.5 ft by 82.5 ft (25 m by 25 m), with a gross floor area of 13,600 ft^2 (1,263 m^2). This model included the same amount of glass as the as-built building. The window-to-wall ratio is 43%, equally distributed over all sides of the building. This results in the solar-neutral model. The

Base-case building does not take advantage of daylighting to reduce the lighting and has no overhangs. Table 3 summarizes the allowable thermal characteristics of the envelope, which we used in the *Base-case* model.

Table 3. *Base-case* Envelope Minimum Allowable Thermal Characteristics

Envelope Component	Assembly Minimum
Roof with insulation above decking	R_{eff}-15.9 (R_{SI}-2.8)
Exterior mass walls above grade	R_{eff}-8.1 (R_{SI}-1.4)
Slab-on-grade floor	F-factor = 0.84 with R-10 (R_{SI}-1.8)vertical perimeter insulation
Operable double pane windows with thermally broken frames	R_{eff}-2.1 (R_{SI}-0.4) with solar heat gain coefficient = 0.49

The *Base-case* model included packaged single-zone, air-cooled heat pump heating and cooling systems with supplemental electric resistance heaters. The *Base-case* heat pump systems were modeled with cooling seasonal energy efficiency ratio of 9.7 and a heating coefficient of performance (COP) of 2.0. The heating and cooling equipment types were based on typical electrical HVAC equipment and the efficiencies were specified by ASHRAE 90.1-2001. A dry-bulb economizer was also modeled. The energy code specifies maximum LPD, and these and other space conditions are included in the *Base-case* model (see Table 4). The equipment power density (W/ft^2) was modeled based on the installed equipment in each space.

Table 4. *Base-case* Space Conditions

Space Type	Area (ft^2)	Occupancy Density (people/1,000 ft^2)	Ventilation (cfm/person)	LPD (W/ft^2)
Offices	1,590	7.0	20.0	1.5
Classrooms/auditorium	4,210	30.0	15.0	1.6
Corridors/transitions/other	6,000	0.0	0.0	0.7
Atrium	1,800	0.0	0.0	1.3

The occupancy schedules for the Lewis Center vary greatly by space and time of year. The classrooms and auditorium assumed occupancy based on scheduled classes from February through May and from September through December. The total number of occupants (occupant density as shown in Table 4) selected for the model was based on available office, auditorium, and classroom seats and their expected use. The occupancy schedule for the atrium and all other spaces depends on occasional functions, but was assumed to be unoccupied.

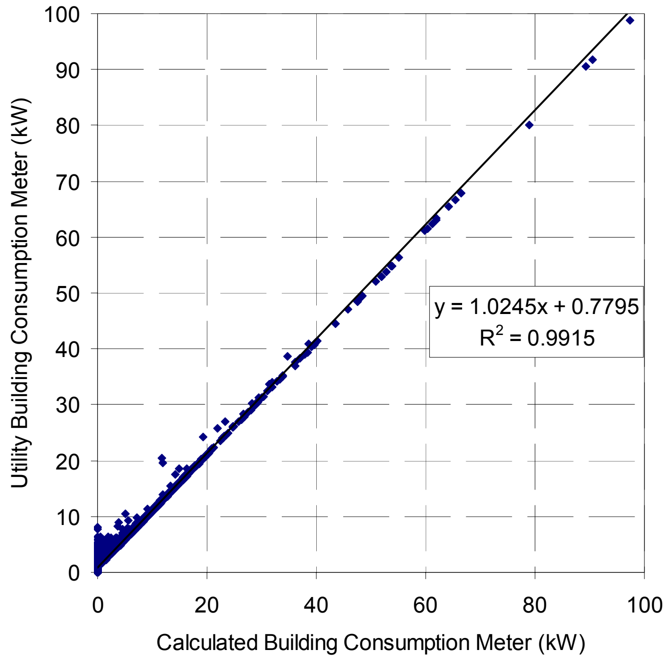
For the *Base-case* model, the equipment and lighting schedules were based on the actual occupancy schedules for each space. For each space, the lights were assumed to be on from the first until the last occupied hour of the day. Thus, the *Base-case* lighting model does not assume either occupancy or daylighting controls. Also included in the lighting schedule for the *Base-case* model were the 2.1-kW sidewalk and parking lot lights and 0.5 kW of emergency/entrance lighting scheduled to operate at night. The heating and cooling set points in the atrium, offices, wastewater treatment system, classrooms, and auditorium zones were modeled based on the actual set points (which changed over the analysis period). Plug loads were determined based on actual measured data from the building. The *Base-case* model was simulated with a TMY2 weather file from the Cleveland airport, located 25 miles (40 km) to the northeast.

MEASURED PERFORMANCE AND EVALUATION

Meter Verification

Figure 6 was created to compare the two independent metering systems to ensure that each meter in the DAS was measuring properly. This figure is an X-Y plot of the whole building utility meter hourly demand on the y-axis and the hourly demand as calculated by our submeters with the DAS on the x-axis for a full year. This energy balance requires the assumption that the utility meter properly monitors the building consumption. The trend line slope of 1.02 demonstrates that the DAS meters are working within acceptable accuracy compared to the utility meter. The y-intercept of the trend line is 0.78 kW. The utility measurement of site consumption included the step-down transformer losses; the DAS measurements did not. The intercept and slope of the trend line correspond to expected losses of the 500-kVA building transformer. The high variability of the building transformer at low load (zero net building consumption) is shown by the 2.0–8.0 kW discrepancy of the energy balance in this operating range. Although not the case for this building, the utility company generally meters the secondary side of the transformer in a building of this size, which leaves the responsibility for the transformer loss to the utility rather than the building owner. For this reason, the site energy use reported in this paper is based on consumption on the building side of the transformer, not the utility meter. The source energy accounts for the transformer losses as part of the distribution losses.

Figure 6. X-Y Plot of Calculated Building Electricity Utility Supply (CM1) versus Utility Meter Electricity Supply (UM1)



Measured Whole-Building Performance

Figure 7 summarizes monthly energy consumption and production (expressed as average daily consumption during each month) from January 1, 2000 through February 28, 2003. Using a daily average effectively normalizes consumption and production by the number of days in the month. For the first 14 months of occupancy (January 2000 through February 2001), the monthly energy performance was determined from the utility bills. These values include 20 to 25 kWh/day of building transformer losses not included in the aggregated end uses monitored by the DAS. After February 2001, when the permanent DAS became operational, aggregated end uses were measured.

For the first year of occupancy (January 2000 to January 2001), the Lewis Center energy consumption intensity was 54.4 kBtu/ft^2·yr (171.3 kWh/m^2·yr). There was minimal PV production, as the PV system was not installed until November 2000. The Lewis Center consumed 21.4% less site energy during the first year of operation compared to the *Base case*. Even though this energy use is less than that of a conventional building, the significant energy savings expected for this building were clearly not achieved during the first year of occupancy. An early energy performance analysis (Scofield 2002) documents and discusses this initial performance.

From March 2001 through February 2002, the Lewis Center consumed 122,283 kWh of electricity. At a gross floor area of 13,600 ft^2 (1,263 m^2), the site consumption energy intensity was 30.7 kBtu/ft^2·yr (171.3 kWh/m^2·yr). The PV system produced 59,518 kWh, or 14.9 kBtu/ft^2·yr (47.0 kWh/m^2·yr). On an annual basis, the PV system produced 49% of the electricity that was consumed.

As Figure 7 illustrates, the electricity consumption during March 2001 was dominated by heating requirements. Most of this month's heating was supplied by the operation of a 112-kW hydronic system electric boiler (EB-1). The hydronic system heats the atrium floor, the wastewater treatment greenhouse, restrooms, kitchen, and corridors. In March 2001, this electric boiler consumed 14,489 kWh, or 56% of the Lewis Center's monthly energy use. A large portion of the hot water from the hydronic boiler was used in the unit heater and radiators in the wastewater treatment greenhouse to keep the zone temperature at 70ºF (21ºC). A constant 2,000-cfm exhaust fan that vented conditioned greenhouse air also contributed to this heating load.

The operation of the hydronic system was the primary reason for higher than anticipated electricity consumption before March 2001. To reduce the demand for the 112-kW electric boiler during the next winter (2001–2002), the heating set point in the wastewater treatment greenhouse was reduced from a constant 70ºF (21ºC) to 50ºF (10ºC). To heat the atrium, the auditorium heat pump (rated at a COP of 3.8) was controlled to heat the atrium and the radiant floor system was disabled. The electric boiler was still used to heat the wastewater treatment greenhouse, along with restrooms, kitchen, and corridors. This setup allowed a more efficient atrium heating system to operate during the winter of 2001–2002. The decrease in site energy use seen from the first year to the second was primarily due to operational changes in the control of this heating equipment. Thus, energy use was reduced substantially through better information and management.

Figure 7. Monthly Site Energy Use and Production, January 2000–February 2003

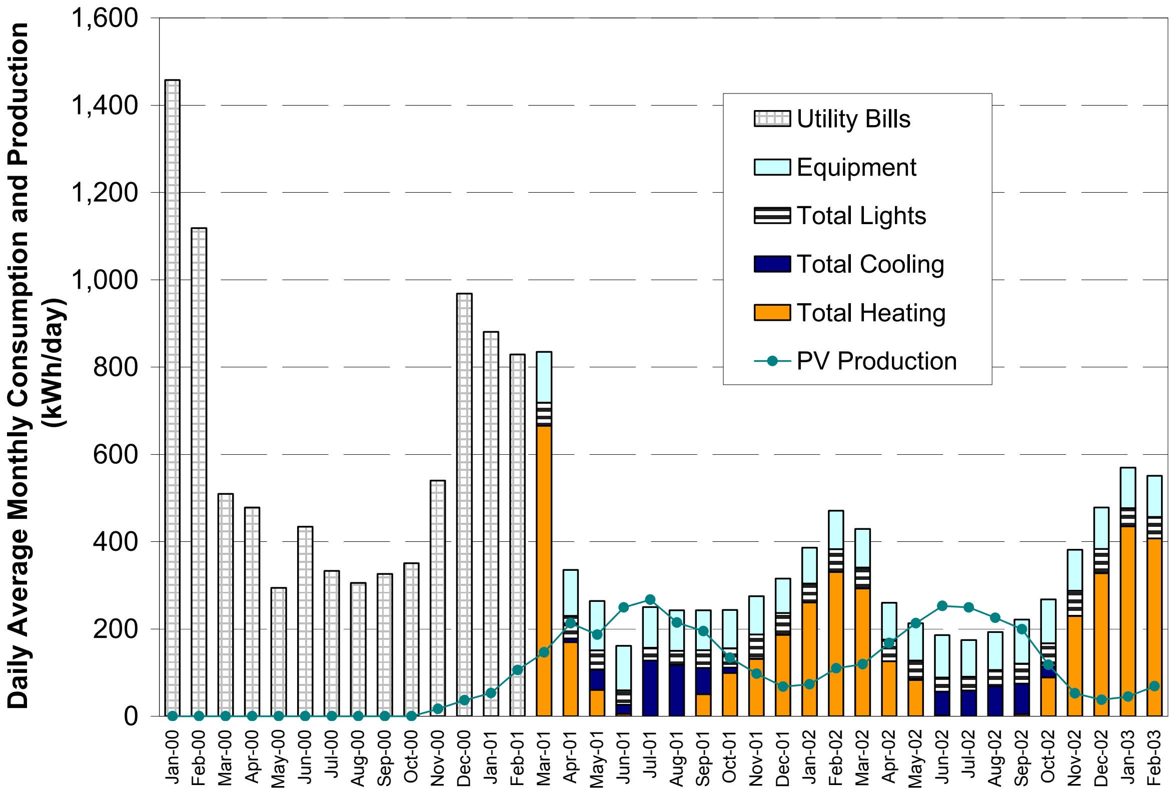


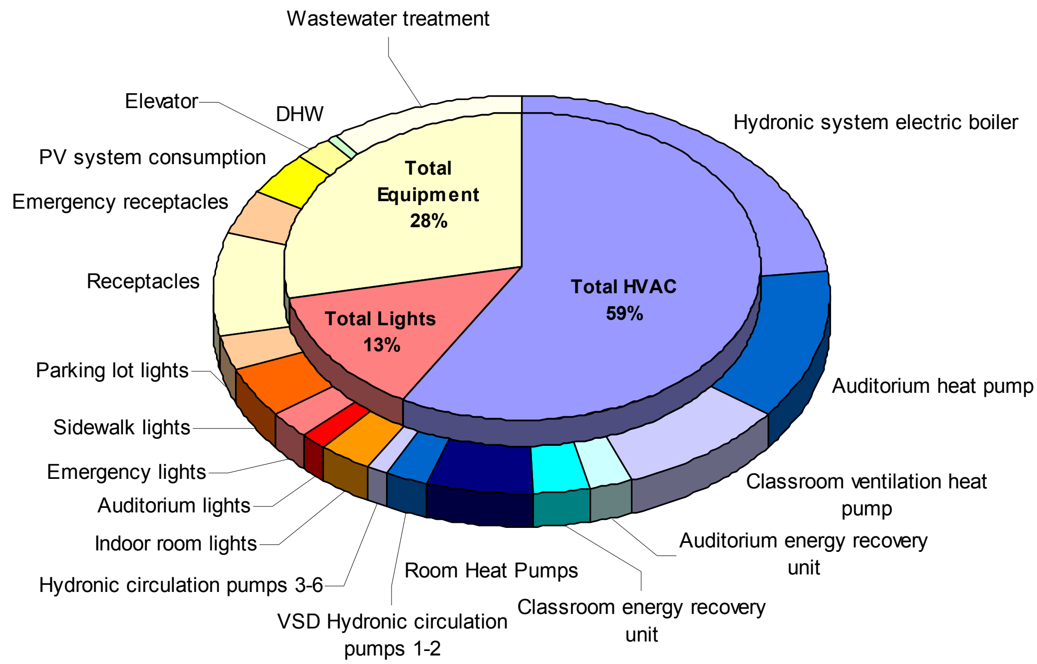
Figure 8 illustrates the annual distribution of electricity consumption at the end use. From March 2001 to March 2002, HVAC accounted for 71,396 kWh, or 59% of the total consumed. As previously discussed, the hydronic boiler EB-1 was the largest HVAC end use because of large heating loads during the spring of 2001. Lighting end uses comprised 13% of total consumption (16,093 kWh), of which 53% was sidewalk and parking lot lights. This is discussed further in the lighting and daylighting evaluation. The equipment end uses comprised 28% of total consumption (34,649 kWh). Wastewater treatment equipment loads were responsible for 36% of the equipment end uses, or 10% of the total consumption. The wastewater treatment loads do not include the heating requirements for this space, as hydronic heat delivered to the greenhouse was not measured separately from other parts of the building. The largest equipment load in the wastewater treatment system was the user-controlled exhaust fan. This fan was typically left on as specified in design and permitting documents. As most commercial buildings do not process their own wastewater, this represents an atypical electrical energy load that will be discussed later.

For June and July 2002, and for the summer months in 2003, the PV system produced more electricity than was consumed by the building, and therefore building operated as a net energy exporter. Since the classrooms are typically unoccupied during the summer, they would normally not be conditioned. However, to assess cooling system energy performance under occupied conditions during the summer months, the building was conditioned according to a typical 9:00 a.m. to 5:00 p.m. occupancy schedule. This manipulation of conditions occurred during

July and August 2001, as shown by increased cooling energy use in Figure 7. It is important to note that the load associated with genuine human occupancy was not present during this time. Even with the building in occupied cooling mode, the PV system was still able to meet the entire building load during this summer.

On an annual basis, the Lewis Center is a heating-dominated building. Data indicate that the PV system has not been able to meet the monthly winter load. In the worst-case month after the DAS was installed, (March 2001 when the hydronic boiler was operating) the PV system met only 17.5% of the building load.

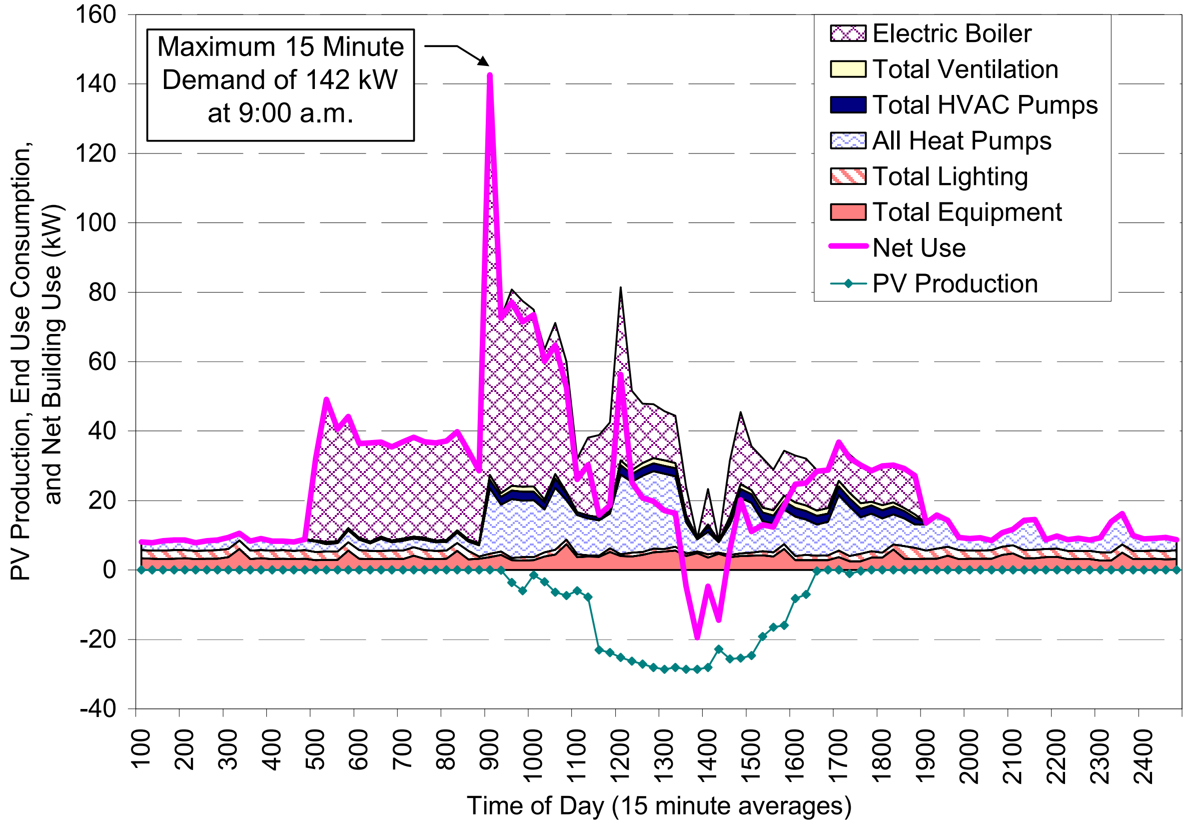
Figure 8. Energy End Use Summary, March 2001 through February 2002



Operation of the hydronic electric boiler increased the energy loads and created high energy and demand charges. With a utility rate structure of \$0.023/kWh consumption rate and \$8.59/kW demand rate with a 15-minute demand ratchet, the electric utility bills are strongly influenced by the demand charges. During the winter, when heating was required from the 112-kW boiler (EB-1), the average virtual rate for electricity including demand charges was \$0.183/kWh. Even with a consumption offset from the PV production, the operational energy costs were \$1.17/ft^2 (\$12.59/m^2) over the year. When the boiler operated at 112 kW for 15 minutes at a time, the demand charges of \$8.59/kW resulted in high utility bills. The monthly demand charge for operating this unit continuously for 15 minutes or more was \$962. The utility bills are driven by demand because the PV system offsets a significant portion of the energy charges without significantly offsetting demand charges, which is evident on the peak-heating day during the winter of 2001–2002. The heating load end use components, PV production, and resulting purchased electricity (net use) are shown in Figure 9. The 15-minute heating season peak demand occurred during a high heating load day when the 112-kW EB-1 operated during the morning warm-up period when no PV production was available.

The PV system has reduced some peak demands during the cooling season, but not during the swing seasons and heating season when the building peaks during the morning warm-up period when no PV output is available. Significant cost savings could be realized by sequencing the heating equipment to meet the heating loads and operate within demand limit constraints. The building could be preheated when PV capacity is available to maximize the benefit of this system. Similar benefits could be achieved during the summer by precooling the building when extra onsite generation is available.

Figure 9. Peak Heating Season Utility Demand, PV production, and End Uses (January 4, 2002)



The nighttime base loads ranged from 8 kW to 17 kW over the year. Excessive equipment operation and parasitic loads were responsible for high nighttime consumption in the spring of 2001. Nighttime heating provides an example of excessive equipment operation. Because of unnecessarily high temperature set points in the atrium and wastewater treatment system, the nighttime average base load for hydronic boiler was 15 kW during this period. The PV isolation transformer provides an example of a parasitic load; during the entire year, the transformer consumed 0.9 kW at night when the system was in standby mode. Other nighttime loads include 2.5 kW of exterior parking lot and sidewalk lights, 0.85 kW for the wastewater treatment exhaust fan, 0.5 kW of emergency equipment, 0.2 kW for the variable speed controller for the ground-loop pumps, and 1.0 kW of plug loads.

The total equipment category includes all plug loads, the elevator, DHW, nighttime PV transformer standby losses, and wastewater treatment equipment, as shown in Figure 8. The total annual equipment consumption from March 2001 through February 2002 was 34,649 kWh, or 7.5 kBtu/ft^2·yr (23.7 kWh/m^2·yr). This equipment consumption is not directly comparable to the equipment loads of typical educational buildings, which do not include loads such as PV transformers and wastewater treatment process loads. As a comparison, plug loads in all U.S. educational buildings were 4.4 kBtu/ft^2·yr (13.9 kWh/m^2·yr) (EIA 1998). The measured plug loads, not including the PV transformers or wastewater treatment equipment, were 4.5 kBtu/ft^2·yr (14.2 kWh/m^2·yr).

HVAC was responsible for 59% of the Lewis Center's total energy consumed from March 2001 through February 2002. Controlling heating loads therefore offers the greatest potential for energy and demand savings. As the operational changes made during the second year of operation were only temporary, a permanent solution was implemented. In response to the documented problem of the electric hydronic system, Oberlin College decided to upgrade the hydronic electric boiler with two 8 ton (28.2 kW) extended-range, ground-source heat pumps. The hydronic system heat pumps were installed before the 2002–2003 heating season. This change increased the site heating efficiency of the hydronic heat supply and took advantage of the ground wells. As the ground well system was not sized for this additional capacity, the backup electric boiler was left in place and reconfigured to provide extra source capacity, if needed.

For the third year of operation (March 2002–March 2003), the Lewis Center consumed 118,973 kWh with a site consumption energy intensity of 29.8 kBtu/ft^2·yr (94.0 kWh/m^2·yr). The PV system produced 53,540 kWh, or when normalized with building area, 13.4 kBtu/ft^2·yr (42.3 kWh/m^2·yr). For this year, the PV system produced 45% of the electricity. The site net energy density was 16.4 kBtu/ft^2·yr (52.1 kWh/m^2·yr). Unlike the previous warm winter, the winter of 2002–2003 contained 4% more heating degree-days than a typical heating season. With the hydronic system upgrade, and for a cooler than normal winter, the site energy use was still less than the previous year during a warm winter with the electric boiler hydronic system. Table 5 provides a summary of the first three years of measured energy performance data.

Table 5. Measured Whole-Building Results: First, Second, and Third Years of Operation

	Measured Site Use Intensity kBtu/ft^2 *(MJ/m^2)*	**Measured PV Production Intensity kBtu/ft^2 *(MJ/m^2)* [1]**	**Percent of Building Load Met by PV**	**Measured Net Site Use Intensity kBtu/ft^2 *(MJ/m^2)***	**Measured Source Use Intensity kBtu/ft^2 *(MJ/m^2)***	**Energy Cost Intensity \$/ft^2 *(\$/m^2)***
First Year (from Utility Bills)	47.5 *(539)*	1.6 *(18)*	3%	45.9 *(521)*	148.1 *(1,682)*	1.21 *(13.02)*
Second Year	30.6 *(348)*	14.9 *(169)*	49%	15.7 *(178)*	50.6 *(575)*	1.17 *(12.59)*
Third Year	29.8 (338)	13.4 *(152)*	45%	16.4 *(186)*	53.0 *(602)*	0.85 *(9.15)*

1. PV production normalized by building floor area for comparison to site use intensity

Site versus Source Energy Consumption

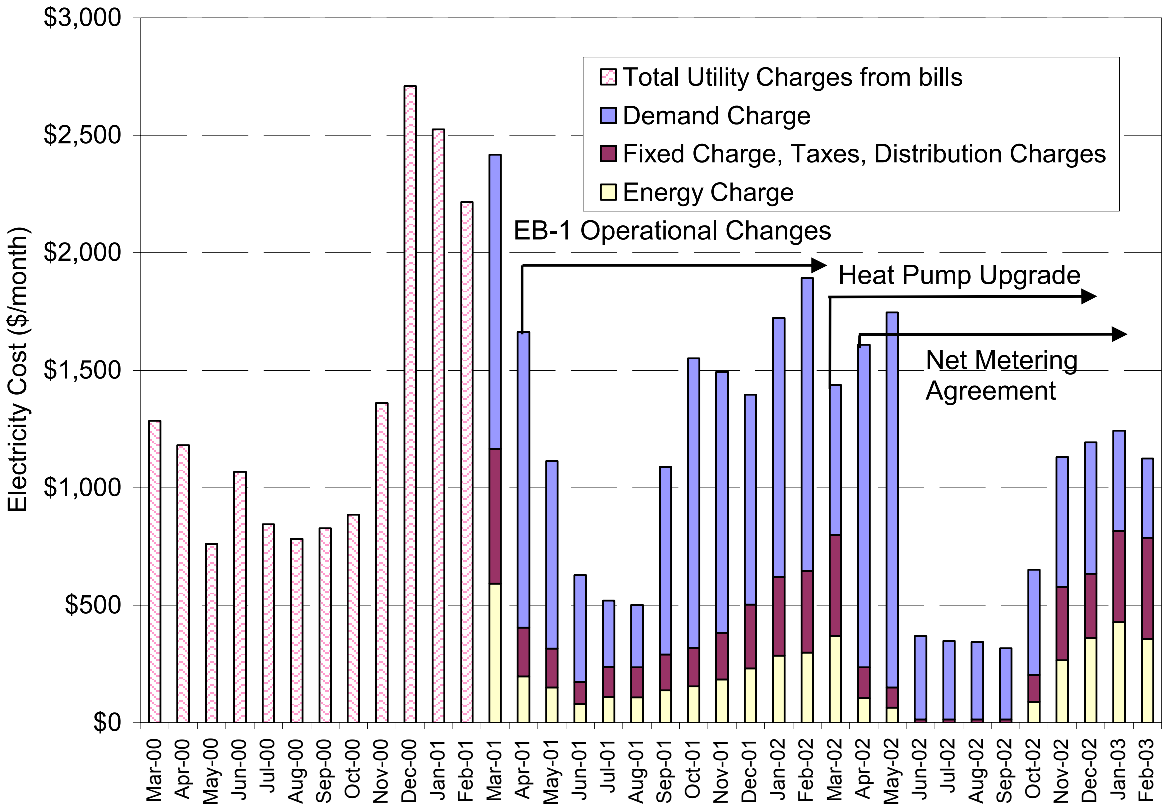
An important consideration in the Lewis Center source energy consumption calculation was the electricity that the PV system produced on site. The building was designed with electric heating and DHW so that on-site generation could potentially meet all the loads. This on-site electricity generation offsets the consumption of site electricity and the corresponding conversion and transmission losses. The net consumption (total consumption minus PV production) represents the full environmental loading that the building places on the utility. Therefore, the net energy consumption was used to calculate the total source energy required to meet the site electricity load. From March 2002 through February 2003, the measured annual net site energy use was 65,432 kWh, or 16.4 kBtu/ft^2·yr (52.1 kWh/m^2·yr). From the net site energy use, the source energy consumption was calculated to be 210,691 kWh, at a source energy intensity of 53 kBtu/ft^2·yr (168 kWh/m^2·yr). It is also interesting to consider the source energy consumption and savings without the PV contribution. If the Lewis Center did not generate on-site electricity, the source energy consumption intensity would have been 96.0 kBtu/ft^2·yr (302.9 kWh/m^2·yr) for 2002–2003.

Whole-Building Energy Cost Performance

From March 2001 through February 2002, the electricity cost intensity was \$1.17/ft^2·yr (\$12.59/m^2·yr). Monthly electric utility bills are shown in Figure 10. A minimal energy cost saving was realized from March 2001 through February 2002, even with consumption offset from the PV production. The annual energy cost is higher than the average educational building, as documented by the EIA (1998). For the second year of operation, the PV system did not significantly reduce the energy costs. The Lewis Center did not receive credit for PV energy exported back to the grid, nor did the PV system dramatically reduce peak demands. Without a net metering agreement, the PV system exported 28,879 kWh, or 49% of the total production, without financial credit from the utility. The second-year utility bills would have been reduced by \$1,415 with a net metering agreement and an energy and distribution rate of \$0.049/kWh. The high demand charges and uncredited power exports were the primary reasons for no initial energy cost savings.

The energy cost intensity for the third year was \$0.85/ft^2 (\$9.15/m^2), down from \$1.17/ft^2 (\$12.59/m^2) the previous year. April and May 2002 had high demand charges associated with installing and testing the upgraded heat pumps and backup electric boiler heating system. The demand charges for the third-year heating season were significantly reduced because the hydronic boiler was replaced. In fact, after May 2002, the monthly demand charges did not exceed \$560, while the previous heating season the demand changes ranged from \$637 to \$1,248. Third-year energy charges were reduced by a net-metering agreement implemented in April of 2002 with the local utility company. This allowed the Lewis Center to receive credit for any PV electricity exported back to the grid. As shown in Figure 10, the net consumption and resulting energy charge for the months of June through September 2002 was $0.

Figure 10. Monthly Site Energy Costs, March 2000 through February 2003



Simulated Whole-Building Performance

Over the first three years of operation, the Lewis Center's energy performance has improved from a site energy consumption intensity of 47.5 $kBtu/ft^2 \cdot yr$ (539 $MJ/m^2 \cdot yr$) to the current 27.5 $kBtu/ft^2 \cdot yr$ (312 $MJ/m^2 \cdot yr$). With the long-term vision of operating as a net energy exporter, the crucial energy performance metrics are the site energy consumption and production. For the second year of operation for a typical year, the site consumption savings were 30% compared to the energy code-compliant *Base case*. PV production met 41% of the building load. Other energy performance metrics that were applied were source energy savings and energy cost savings. For the second year of operation, the source energy savings were 58% compared to the *Base case*. These savings were primarily due to the on-site PV system production. Because of high demand charges and no credit for exported PV production, minimal energy cost savings were realized for the first two years of operation. Even with a large PV system, the demand charges were generally not reduced because peak demands typically occurred at times of no PV production. Furthermore, with total installation costs of $386,000, is has been estimated that the financial investment in the Lewis Center's PV system cannot be recovered during its useful life (Murray and Petersen, 2004). However, it is important to note that the design goals were to reduce net electrical energy consumption, reduce pollution associated with energy consumption, and demonstrate the possibilities for on-site production—not to reduce first cost or utility cost.

Based on the performance of the third year, the site energy savings were 48% for a typical weather year compared to the *Base case*. On-site PV production would have met 59% of the building load for typical weather. Of these annual site energy savings, the lighting system provided the greatest savings. For the third year, the lighting design combined with daylighting saved 44,033 kWh (46% of the total savings). A saving of 26,629 kWh resulted from the cooling system (28% of the total savings). The cooling system savings are primarily due to the expected increased COP of the ground-source heat pumps, combined with reduced internal heating gains from the lights, and a better thermal envelope. The more efficient ground-source heat pumps, combined with a better thermal envelope, resulted in 24,405 kWh of heating savings (26% of the total savings). When net source energy performance is considered, the building consumed 79% less energy at the source than the all electric *Base case.* The net source energy consumption intensity, including PV, was calculated at 36.5 kBtu/ft^2·yr (415 MJ/m^2·yr).

The current measured and simulated energy performance significantly exceeds the documented performance of typical educational buildings (EIA 1998) and other Oberlin campus buildings. Although this is considered a low-energy building and one of the better performing academic buildings in the country, there is considerable room for improvement if it is to help reach its goal of net-zero energy consumption.

The calibrated *As-built March 02−February 03* DOE-2 model was modified to determine the effect on annual energy performance of specific recommendations. This model represents the optimized performance of the Lewis Center. The *Optimized* model included the recommendations of reducing the heating demand for the wastewater treatment greenhouse by lowering the exhaust air for this space. A VSD exhaust fan controlled to keep the wastewater treatment space depressurized with respect to the atrium would reduce the 2,000-cfm exhaust from this space. Also recommended is replacing all the standard-range heat pumps with extended-range heat pumps. The classroom, ventilation, and auditorium/atrium heat pumps are standard-range heat pumps, which are not rated for ground-source water temperatures. The installed standard-range heat pumps typically operate outside the recommended source water temperature range. To rectify this problem, properly sized and rated extended-range ground-source heat pumps are recommended to increase the operational efficiency as well as provide expanded heating and cooling capacity.

The model also included 4,500-kWh savings that accrued from reducing the power requirements of the wastewater treatment exhaust fan with a VSD, 4,263 kWh of savings from parking lot and sidewalk lighting rescheduling, and 2,600 kWh savings resulting from replacing the PV isolation transformers with energy-efficient isolation transformers. The *Optimized* model predicts an annual energy consumption of 76,703 kWh with an energy intensity of 19.2 kBtu/ft^2 (218 MJ/m^2). Based on optimized models incorporating recommend changes, we predict the site energy savings could be increased to 64%, with 85% of the building load met by PV.

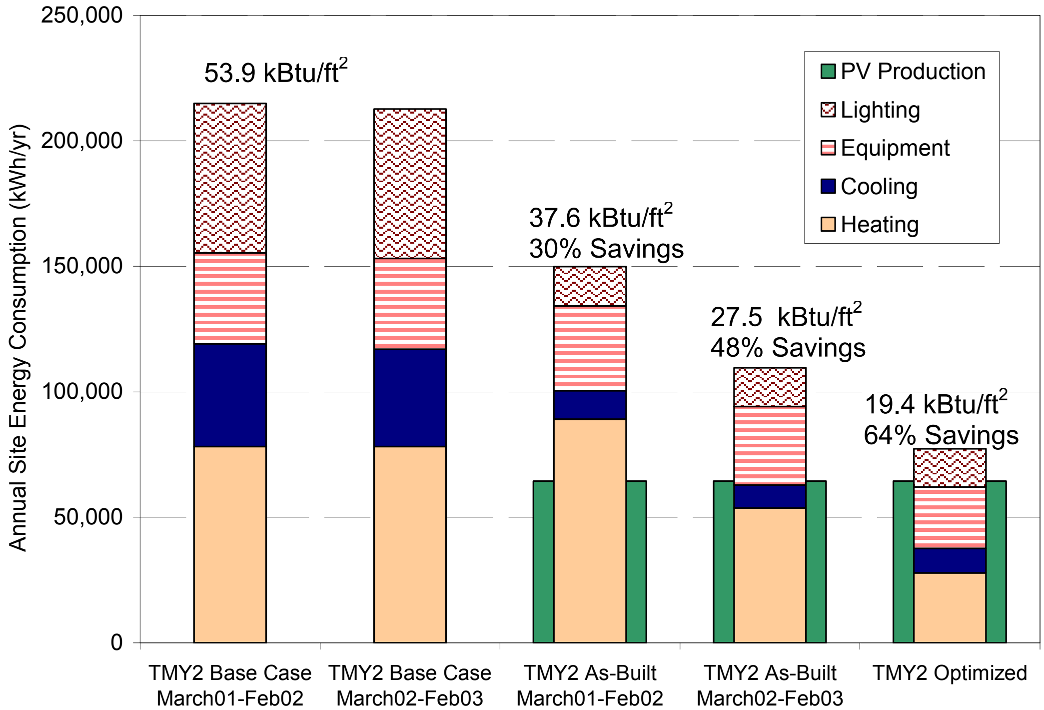
The performance of the *TMY2 Base-case, TMY2 As-built March 01−February 02, TMY2 As-built March 02−February 03, and the TMY2 optimized model* are summarized in Table 6 and Figure 11.

Table 6. Annual Energy Performance Summary for Each Model Version

Building Version	**Site Consumption Energy Intensity kBtu/ft^2 *(MJ/m^2)***	**Percent Site Savings Compared to *Base case***	**Percent of Building Load Met by PV**	**Site Net Use Energy Intensity kBtu/ft^2 *(MJ/m^2)***	**Source Net Use Energy Intensity kBtu/ft^2 *(MJ/m^2)***
TMY2 *Base case* with *March 01−February 02* schedules	53.9 *(612)*	N.A	0.0%	53.9 *(612)*	173.5 *(1,970)*
TMY2 *Base case* with *March 02−February 03* schedules	53.3 *(605)*	N.A	0.0%	53.3 *(605)*	171.6 *(1.949)*
TMY2 *As-built March 01−February 02*	37.6 *(427)*	30.0%	43.1% [1]	21.4 *(243)*	68.9 *(782)*
TMY2 *As-built March 02−February 03*	27.5 *(312)*	48.0%	59.0% [1]	11.3 *(128)*	36.5 *(415)*
TMY2 *Optimized*	19.4 *(220)*	63.6%	84.5% [1]	3.2 *(36)*	10.3 *(117)*

[1]Calculated using typical PV performance without degradation with TMY2 weather data

Figure 11. Annual Performance for TMY2 *Base-case* Models, *As-built* Models, and *Optimized* Model



Lighting and Daylighting Evaluation Results

Daylighting and good lighting design were perhaps the best implemented energy-saving features employed in the Lewis Center, as these systems were responsible for the greatest reduction in energy use. The lighting energy savings can be attributed to good lighting and daylighting design and operation, as the Lewis Center incorporates a reduced LPD and daylighting design strategies with occupancy controls that are not included in the conventional *Base-case* simulation. The occupancy sensors, combined with daylighting sensors and proper occupancy control of the atrium and auditorium lights, turned off and dimmed lights according to available daylighting. Because not all lighting zones use daylighting or occupancy sensors, a portion of these daylighting savings can be attributed to effective occupancy control that minimized unnecessary light use. There is, however, room for further improvement in manual control of lighting. Specifically, monitoring data indicate a number of incidents in which lights have been left on at night when the space was unoccupied.

Figure 8 shows the contribution of the site lighting load to the total building load from March 2001 to March 2002. The total as-built interior and exterior lighting was responsible for 13% of the total building load, and consumed 16,058 kWh. The lighting consumption intensity for the site (interior and exterior lights) was 4.0 $kBtu/ft^2 \cdot yr$ ($12.6\ kWh/m^2 \cdot yr$). The outdoor and parking lot lights were responsible for 47% of the total lighting load for the site. These outdoor lights were operated constantly during nighttime hours. The interior lighting load (emergency, indoor, and auditorium lights) comprised 6.2% of the total building consumption and consumed 7,568 kWh or 1.9 $kBtu/ft^2 \cdot yr$ ($6.0\ kWh/m^2 \cdot yr$). In comparison, the lighting site energy intensity in all educational buildings is 15.8 $kBtu/ft^2 \cdot yr$ ($49.8\ kWh/m^2 \cdot yr$) (EIA 1998).

The interior LPD for the *Base case* is 1.2 W/ft^2 ($12.9\ W/m^2$) and 0.79 W/ft^2 ($8.5\ W/m^2$) for the as-built. The as-built LPD is 34% less than ASHRAE 90.1-2001 code minimum. Even with the lights on, savings result. The as-built LPD is lower than ASHRAE 90.1-2001 recommends because the lighting design accounts for a daylighting contribution during the day and includes appropriate placement of task lighting. To ensure that the as-built LPD was not too low, we verified the quantity of lighting and daylighting through multiple illuminance measurements.

A second type of lighting energy savings can be attributed to appropriate control of the as-built luminaires. Currently, the lighting control strategy in the Lewis Center involves occupancy sensor technologies, often combined with a daylighting sensor. Also considered in the lighting control strategy was appropriate occupant management of the manual dimming lighting circuits. For instance, in the atrium, the occupants typically leave the lights off during the day when daylighting can supply all the necessary illumination for the space. For zones that are controlled through occupancy sensors with a minimum illuminance threshold, such as the second-floor corridor, the lights are disabled if the zone receives enough daylight. Because the daylighting control and occupancy control are integrated into a single sensor, the savings resulting from these controls were not independently considered. The measured building lighting consumption was compared to the *Base-case* run with the actual LPD to determine the lighting savings that result from occupancy and daylighting controls. The authors predict that the daylighting and occupancy controls reduce the lighting energy use by another 77%. Daylighting savings combined with the reduced LPD resulted in the largest source of energy use savings at the Lewis Center, reducing lighting energy use by 72% relative to a typical code-compliant building and saving 44,033 kWh annually.

RECOMMENDATIONS

Based on the analysis of measured data and observations of the authors and occupants, the following recommendations are provided. Many of these recommendations apply to other commercial buildings as well.

- Minimize or eliminate the PV isolation transformer losses, which represent 7% of the total PV production. This can be accomplished by replacing the transformers with more efficient units and/or by disconnecting the PV system and transformers at night. If the units are disconnected, inrush issues when the transformers are energized as well as transformer condensation issues must be considered. Designing systems without these transformers may require changes in the electrical code, but would be beneficial.
- Install a VSD exhaust fan on the wastewater greenhouse and a control system that maintains only a small negative pressure between the atrium and the greenhouse. This will minimize excessive exhaust of conditioned air.
- Replace the auditorium heat pump, which is not rated for extended-range water-source temperatures, with a heat pump rated for ground-source water temperatures. This will increase the capacity and efficiency of this unit.
- Use the CO_2 sensors to control outside air to the classrooms. Operate room dampers based on these settings. Control outside air fan based on the position of these dampers in addition to a weekday schedule for the offices.
- Separate the controls of the classroom ventilation heat pump, the enthalpy wheel motor, and the fan for the enthalpy wheel to allow for an economizer control and staged operation of the classroom ventilation heat pump. As a design consideration, economizer cycles should not be eliminated from building designs because of the use of ground-source heat pumps or ERVs.
- Operate the enthalpy wheel and related fans only when the outside air temperature is lower than 65ºF (18ºC). The energy required to operate this system is greater than the recovered energy at outdoor temperatures higher than 65ºF (18ºC). These set points were based on actual measurements from this building.
- Develop a demand-limiting strategy that integrates on-site generation with HVAC controls. This requires advanced controls that allow the temperature of the building to float based on instantaneous consumption and production. This will enable further utility demand savings.
- Classroom lights should be programmed to automatically dim according to the available daylighting. Lights should be manual on, automatically dim according to available daylight, and automatic off when unoccupied.
- The atrium should have daylighting controls to keep the lights off during the day. The lights should be manual on with an automatic off for occupancy. Similar automatic off controls based on occupancy should be installed in the auditorium as well.
- On the south windows in the classrooms, the blinds should be changed so that the orientation of top and bottom sections of the blind can be separately controlled. This would allow the open upper windows to provide daylighting while the closed lower section would control glare.

Many of the deficiencies in building performance stem from disconnects in goals and knowledge among the building designers, the engineers, the programmers of the building energy management system, the operators of this system and the building users. It is critical for everyone involved in the design to understand the design intents. For example, energy efficiency was a critical design goal, but the primary short-term goal of the facilities personnel who manage the building is to keep the building running without complaints. Maximizing the energy performance of the building requires that building managers and occupants accept this as an operational goal.

CONCLUSIONS

During the third year of occupancy, the Lewis Center consumed 48% less site energy (not including PV production) than a conventional *Base-case* building. Because of continuous monitoring, analysis, and owner's willingness to fix identified problems, energy savings have increased significantly over the three-year life of the building. This demand-side energy performance, combined with 53,540 kWh of annual PV production, resulted in a net site energy intensity of only 16.4 $kBtu/ft^2 \cdot yr$ (52.1 $kWh/m^2 \cdot yr$), representing a 66% source energy reduction relative to the *Base case*. Forty-five percent of the building load was met by on-site PV production. Even though this is already a low-energy building and at the leading edge of the U.S. building stock, there is considerable room for additional improvement if the building is to reach its goal of net-zero energy consumption.

The lighting systems resulted in the greatest source of energy savings for the Lewis Center because of good daylighting design and lighting operation. This was evident in the low building lighting energy use of 16,058 kWh, at an equivalent energy use intensity of 4.0 $kBtu/ft^2 \cdot yr$ (12.6 $kWh/m^2 \cdot yr$). Compared to the simulated lighting performance of the conventional *Base-case* model, the Lewis Center consumed 72% less lighting electricity. These savings can be attributed to good lighting and daylighting design and operation, as the Lewis Center incorporated a reduced LPD, along with daylighting design strategies with occupancy controls. Also important to these lighting consumption savings was the appropriate manual operation of the lighting zones that were not automatically controlled. In addition, the daylighting reduced cooling loads on the building and partially contributed to this building being winter load dominated, on both demand and energy.

Lessons Learned

The Lewis Center remains an icon of low-energy educational buildings in the United States. By understanding and documenting its flaws and successes, lessons can be learned for the design of the next generation of high-performance buildings. The specific lessons learned can be separated into three categories: design process issues, technology issues, and lessons related to the evaluation process of the building.

The design process was not explicitly examined as part of this paper; however, specific mistakes were made in the integrated design approach. Further discussion of the design process is included in Malin (2002), Orr (2001), and Scofield (2002). The owner's strong goals early in the design process were key to driving the project. Even though the long-term goal of producing a building that is a net exporter of electrical energy has yet to be met, the building has made substantial strides. An important objective of the design process was to carefully integrate the engineer, energy consultant, and architect, so that they all worked toward a common goal.

Lessons learned from application of technology are:

- A high-performance academic building is possible in a heating dominated climate such as northern Ohio. This idea is contrary to the trend of cooling-dominated buildings in traditionally heating-dominated climates. Even at this level of high performance, a zero-energy building in this climate would be difficult to realize, especially with on-site wastewater treatment. Additional PV capacity, extending beyond the footprint of the building, and optimal performance would be required to reach the zero-energy goal.
- PV systems must be engineered to minimize transformer and balance of system losses. These losses can represent a significant portion of the overall system production.
- PV systems may not significantly reduce the peak building demand. In this case, the small demand reduction caused by the PV is from load diversity.
- During the summer, on average, large PV systems in educational buildings can export electricity from 8:00 a.m. to 6:00 p.m. From the utility perspective, the building was net positive during daylight hours in the summertime and provided power when it was most needed by the grid.
- Control strategies should take full advantage of the capabilities of the equipment, including CO_2 sensors, motion sensors, natural ventilation control, and thermostats. An appropriate balance must be achieved between control by the human operators and the building automation system. The particular balance that optimizes building performance will depend on the degree to which building users understand and embrace the goal of energy-efficient building operation.
- Daylighting sensors are needed in all daylit areas so that lights cannot be turned on unless they are needed. Manual controls are insufficient.
- Daylighting must be designed into all internal spaces. Areas like the auditorium need daylighting combined with full shading mechanisms to maximize lighting energy savings.

- Tall, dark ceilings should be avoided, as they do not work well with daylighting and are difficult to use with indirect lighting systems and with natural lighting.
- Daylighting glass and view glass should be designed independently. Daylighting glass must be designed to provide uniform lighting in the space. The east side of the building is overglazed. Even with advanced glazing technologies, this area accounts for excessive heat gain and loss. The design objective of creating views should be carefully weighed and balanced with the objectives of maximizing energy performance.
- Heat pumps should be carefully specified to match groundwater temperatures.
- Electric boilers can be used for backup heating during extreme weather conditions. However, systems should be designed so that use is sparing and managed so as to minimize peak demand charges on the building. Controls and staging are essential for integrating limited use systems.
- Air balances must be done to ensure that heat-recovery systems will be effective. These recovery systems must be controlled properly to achieve maximum benefit. At the Lewis Center, a significant amount of the energy from the building's exhaust air is not recovered because of directly vented exhaust, which limits the effectiveness of these systems.

Lessons learned on the evaluation process include:

- A complete high-performance building should realize significant site energy savings, source energy savings, and energy cost savings. A building can excel in the energy performance indices most important to the building owners, but fall short or exaggerate other performance indices. The Lewis Center performed well in site savings, realized minimal energy cost savings, and excelled in source savings (mostly because of PV production and benchmarking techniques). A building energy performance evaluation should focus on the metric the building was designed to optimize, but should also consider other significant performance indicators.

- A complete energy balance on metering is essential to find faults in monitoring. A dedicated DAS for monitoring energy performance can provide 99% data availability over a two-year monitoring period. Missing data can be minimized with error checking routines and reasonable data filling techniques. Fifteen-minute data logging is appropriate for a wide range of evaluations. In cases where we found equipment issues, one-minute data sets were valuable for system diagnostics. For example, continuous monitoring at a minute time step interval was valuable for detecting PV inverter faults. Overvoltage inverter faults would temporarily shut down the inverters during times of peak PV output. Minute time step monitoring was required to identify this problem. Without this monitoring, PV system downtimes may have been much longer.

- Detailed monitoring, which is beyond the scope of typical commissioning projects, is needed to fully evaluate the building and identify additional areas of energy savings. With this level of analysis, the building energy load was cut in half compared to the building at the end of the detail monitoring and evaluation process.

- To calculate energy savings of a building, a model must be calibrated against actual building data. Too many changes occurred to use the models developed during the building design process as accurate predictors of energy consumption. Schedules and plug loads vary widely from original assumptions. A calibrated *As-built* simulation compared to a conventional *Base case* can provide a confident prediction of annual site, source, and cost savings. A *Base-case* model must also be modified to reflect the *As-built* schedules and plug loads. A whole-building evaluation should consist of a combination of monitored energy use data and hourly building simulations. Using typical meteorological year weather data allows long-term savings calculations with relatively short-term data. A corollary of this is that models used for design should be carefully reviewed to ensure that current practice for plug loads and schedules are used, as they will affect design decisions.

- A whole-building simulation tool is needed that can adequately model subhourly energy use, site utility costs, and on-site production. We could not model the *As-built* energy costs of the Lewis Center because of the limitations of the DOE-2 program. With a simulation tool such as EnergyPlus (2005) that could model energy use, PV production, and peak demand on a 15-minute time step, we could research and develop demand responsive controls that enable on-site PV production to reduce peak demand and optimize energy costs.

In general, the mechanical design of the electric boiler hydronic system did not meet the design intent of the rest of the building. Through a detailed energy performance evaluation, continuous commissioning, and owner's dedication to improve the energy performance, the energy savings have substantially increased. The Lewis Center is now one of the better energy performing academic buildings in the country. The evaluation shows that an academic building in a heating-dominated climate can operate as a low-energy building. The Lewis Center may be able to reach net zero, or possibly become a net energy exporter in the near future with further efficiency improvements and when more solar arrays are installed. Further work is needed to improve the energy cost savings, as the PV system did not significantly reduce demand charges. Continued improvements and monitoring, combined with advanced controls understanding and implementation, will ensure the Lewis Center operates at its full potential. Finally, many of the design techniques and lessons learned should be applied to future commercial buildings to reduce energy use in the commercial sector.

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