Low Energy Building Case Study: The Rest of the Story

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ABSTRACT

Cost effective implementation of a low energy, sustainable design for a small office building requires commitment and planning, as well as an integrated application of advanced building technologies. The result can be exemplary low energy performance as a prelude to a zero energy building as demonstrated by this case study of the Iowa Association of Municipal Utilities (IAMU) Office Building and Training Complex.

This paper describes the design process, technology application and performance monitoring results for a small (12,500 square foot), single-story, commercial office building. The design process was driven by commitment to a low energy use goal and the application of computer simulation tools to evaluate building options supporting that goal. The energy efficient building technologies include: high performance envelope, daylighting, ground source heat pump system and energy recovery ventilation.

Actual building energy performance is monitored with separate metering for lighting, HVAC, general use (plug load) energy and other building loads. The rest of the story includes a performance analysis of actual energy consumption profiles; equipment performance patterns; and other operational issues accumulated during a five year monitoring project. Comparisons of actual energy use against common benchmarks are drawn. The discussion identifies what worked well and the lessons learned from this case study project. The results document that this exemplary low energy building has a site energy use index nearly 60% less than an equivalent, energy code compliant building and operates at half of the annual energy cost.

Introduction

The leadership of the Iowa Association of Municipal Utilities (IAMU) made a commitment to sustainable and energy efficient building practices when they initiated the design of their office and training complex near Des Moines, IA. After considerable challenges in balancing design requirements, energy efficiency, sustainability, and construction cost issues, their dedication resulted in a high performance, low energy and sustainable facility on a speculative office building budget. The building celebrated a grand opening in June 2000.

The IAMU Office Building and Training Complex consists of a 12,500 square foot association headquarters office building; maintenance and shop buildings; a 12 acre training field; and parking and drives situated on a 24 acre site. The building, as shown in Figure 1, is exemplary in its resource efficiency. Designed and built within a modest budget of $116 per square foot, the actual metered site energy averages 28,325 BTU/ft^2-yr with an average annual energy cost of $0.52/ft^2.

Figure 1. IAMU Office Building - Partial Southwest Elevation

The project design pre-dates the U.S. Green Buildings Council's LEED™ rating system for new construction and other similar best practice design guidelines available today. The building ranks in the top 10% with a rating score of 93 evaluated through the Energy Star Target Energy Performance Results evaluation tool. The project has received national recognition for sustainable design and has been documented in previous studies (McDougall, et al. 2006).

Design Process

The design process was driven by commitment to a low energy use goal and the application of computer simulation tools to evaluate building options supporting that goal. Early in the process a building committee consisting of staff members with a strong interest in the success of the project was created to represent the owner in the design and construction process. Design professionals selected for their qualifications in energy efficient design practices and sustainable design principles were engaged. This project team was expanded to draw in the expertise of member utilities, Iowa Energy Center, Polk County Conservation Board, Polk County Soil and Water Conservation District, Prairie Restoration specialists, Dark Sky Association members and local materials suppliers.

Design goals. A series of twelve full day design charrettes were conducted with the expanded project team. Five project goals were developed to guide the design process:

- Reduce Building Energy Consumption: The IAMU facility should serve as an example of innovative energy efficient techniques adapted to commercial buildings. A low energy use target was set at 40% less energy than a comparable new energy code compliant building.
- Create a Healthy and Productive Environment: Create as many daylit spaces as possible, provide adequate controlled thermal zones and ventilation air. Give occupants control of their environment with operable windows, blinds and task lighting control. Minimize the use of materials emitting volatile organic compounds (VOCs).

- Other Sustainable design goals included: selecting appropriate building materials; reducing the amount of building materials; and improving the ecology of the site.

Design response. Solar orientation, water runoff, prevailing breezes and topographic conditions directed the location of buildings, parking, drives, training fields and wetlands. Figure 2 shows these elements on a site plan. The office building was sited and optimally oriented along an east-west axis to maximize the view and the availability of natural lighting while simplifying solar control. The program for the office building required private, semi-private and more flexible open office space along with small and large group training areas and support space. A schematic floor plan and building section were developed and formed the basis for the initial evaluation of energy strategies. The final layout of the office building is shown in Figure 3.

Figure 2. Site Plan

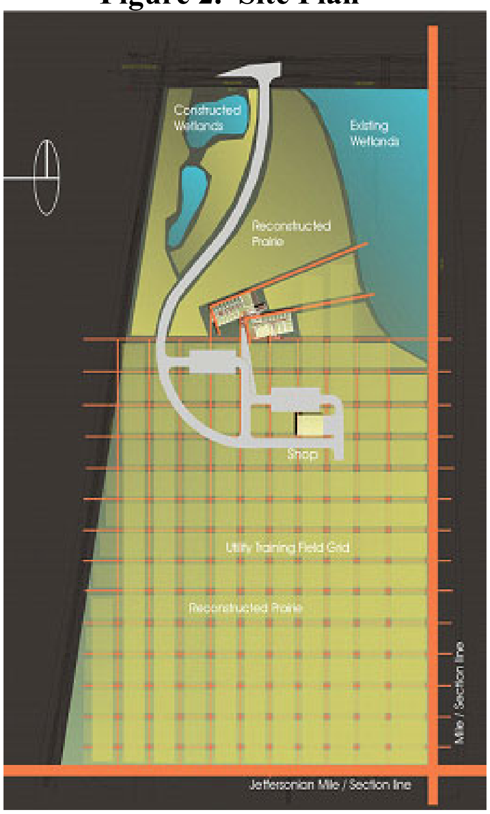
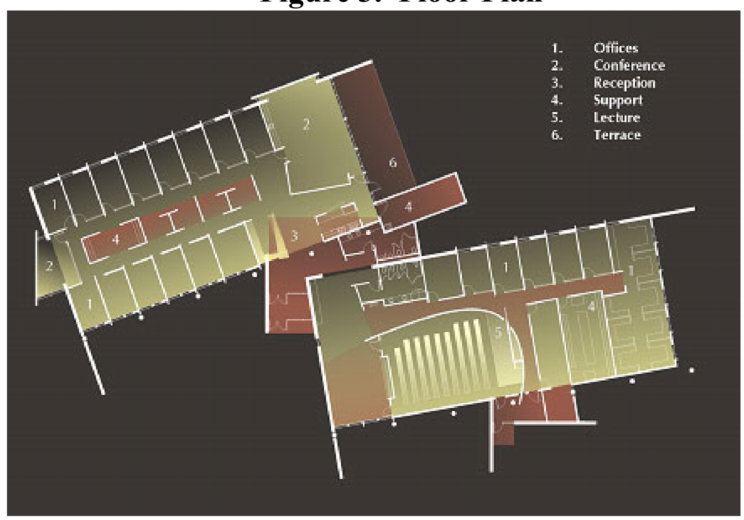


Figure 3. Floor Plan



Design integration and evaluation of energy strategies. To meet the goal of minimizing energy consumption it was necessary for the project team to evaluate energy strategies from the perspective of building systems integrated by design. The design integrated building energy strategies were evaluated using various tools and methods including:

- Modeling the building to determine energy use, energy cost and savings using the DOE-2.1E building energy simulation software program (Winkelman et al. 1993).
- Incremental construction cost estimating for various component and system alternatives.
- Life cycle cost analysis of HVAC alternatives to address the economic impact of ongoing equipment operation, maintenance, repair and replacement costs over the building life.

- Incorporation of MidAmerican Energy Company's Commercial New Construction Program which provided financial incentives determined by both the quantity and the percentage of energy savings compared to the energy use profile of a base case building.

Whole building energy modeling was conducted in several phases. A base case building was modeled initially to establish an energy benchmark. The base case model quantified the building energy performance assuming a conventional building with standard building envelope systems, HVAC equipment and lighting systems in compliance with the energy code in effect at the time of design (ASHRAE 90.1 1989). The energy use of the base case code compliant building was estimated at a nominal 65,000 BTU/ft^2-yr.

The next phase of energy modeling evaluated the energy performance results of 70 independent energy efficiency strategies identifying a range of alternatives for building envelope systems; window glazing type, area, orientation and design; lighting design and control; heating and cooling system types and equipment efficiencies; conditioning of outside air for ventilation; and adjusting HVAC system capacity to respond to lower building envelope and lighting loads.

Results from the second phase analysis were compiled to create three alternative bundles of energy strategies for further evaluation as integrated design solutions. Final DOE-2 simulations were performed to model the integrated effect of all selected strategies at the completion of the project design phase. The annual energy consumption was conservatively predicted at 34,000 BTU/ft^2-yr. This represented an energy use reduction of almost 48% compared to the base case code compliant building while exceeding the project design target goal of 40% less energy.

Design Features

The final project design integrates a number of energy efficient strategies that are innovative, straightforward, functional and cost-effective. The major design features include:

Daylighting via an Integrated Building Section.

- Daylighting based design with natural daylight as the primary illumination for the building.
- A 48 foot deep building section that provides multiple daylight sources, reduces daylight contrast and glare, establishes a visual connection to the outdoors and contributes to a more people productive environment.
- High mounted daylight transom windows on the south elevation allow daylight penetration to the center interior areas – reducing the need for electric lights by 30%.
- External shading devices, overhangs and seasonal banners effectively prevent direct sunlight from striking the work surface and reduce air conditioning loads.
- Exposed roof structure and metal deck ceiling with high reflectivity painted surfaces distribute daylight effectively and contribute toward a utilitarian appearance.
- Daylight control system using light sensors and dimming electronic ballasts reduces lighting energy by 35% at an installed cost of $0.70 per square foot.
- Integrated design solutions reducing air conditioning equipment capacity by over 10% and reducing combined lighting and air conditioning electrical demand by 24%.

High Performance Building Envelope

- Window visible light transmittance (VT) and solar heat gain coefficient (SHGC) that are varied by orientation to optimize thermal and daylighting performance (Table 1).
- Low-E, triple pane, wood frame window U-Values of 0.25 to 0.35 BTU/hr-ft^2-°F (Table 1).
- Window to wall area optimized to balance daylighting, passive winter solar gain and summer air conditioning load (Table 1).
- R-24 walls with airtight, low density sprayed foam insulation system expanded between metal studs, exterior sheathing and interior drywall.
- R-30 roof insulation sandwich panel with metal roof and metal deck.
- Operable windows allowing natural ventilation.

Table 1. Window Summary

Orientation	VT	SHGC	U-Value BTU/hr-ft^2-°F	Window to Wall %	Window to Floor Area %
North	0.67	0.44	0.35	13%	2.4%
South	0.67	0.44	0.35	25%	7.5%
East	0.60	0.35	0.25	25%	2.9%
West	0.60	0.35	0.25	6%	0.7%
Building	-	-	-	19%	13.6%

Lighting System

- Electric lighting that is used only as a supplement to daylight.
- Indirect lighting system with high reflectance painted ceiling to achieve a design illuminance of 30 to 35 footcandles on the work plane in the office areas.
- Ambient / Task lighting for individual control of lighting level.
- Inverted industrial strip lights contribute to the utilitarian appearance while providing an indirect light source with high efficiency T-8 lamps and dimming electronic ballasts.
- Occupancy sensors used in most enclosed spaces further reduce lighting energy.
- Total connected lighting power density of 1.1 watts per square foot (including parking and drive lighting) – 35% less than applicable energy code.
- Light sensors, time clocks and exit override switches control the bi-level driveway and parking lot lighting staging the lamps from 150 watts to 50 watts to correspond with the site lighting needs while reducing nighttime light pollution.

HVAC System

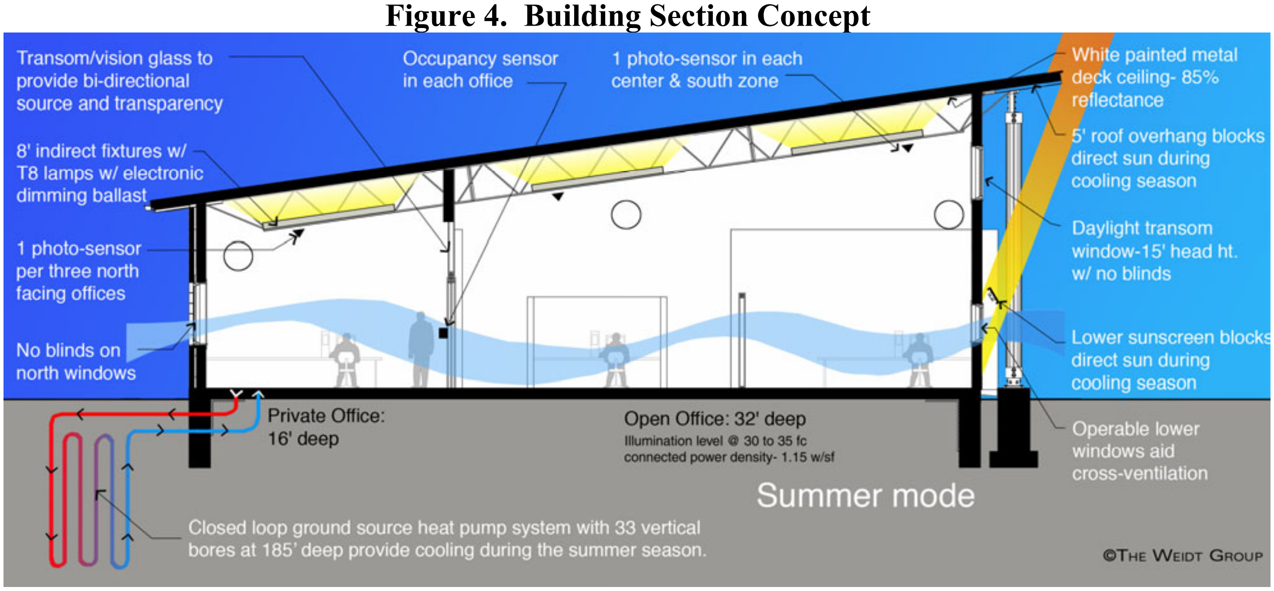
- Geothermal heat pump system rated at average 3.4 heating COP and 16.3 cooling EER.
- Building heat transferred with the ground through a vertical closed loop ground source heat exchanger using a total of 33 bores at 185 feet deep.

- Eight heat pumps match up with unique thermal zones by occupancy and envelope conditions for cost effective zone temperature control.
- Total capacity sized for the heating load requirement of 360,000 BTU per hour.
- Geothermal heat pump system cost premium of $3.10 per square foot compared to the installed cost of a conventional DX rooftop system.
- Lowest life cycle cost, lowest energy and lowest maintenance costs – meeting simple and functional project goals.
- Seven day programmable thermostats control heat pumps simply and effectively.
- Energy recovery enthalpy wheel preheats and precools outside ventilation air with energy recovered from restroom exhaust air.
- Two speed operation of energy recovery ventilation air unit as controlled by an occupancy sensor to match increased ventilation needs when the auditorium is occupied.

Building Section Energy Concept

Key energy strategies are identified on the building section concept shown in Figure 4. Many of the office building energy strategies and energy efficient design features are rooted in the integrated function of this building section. Daylight penetration into a building is generally considered to be twice the head height of the window. Daylight simulation models confirmed that the south daylight transom window with a 15 foot head height would effectively cover the central interior office zone with natural daylighting. The single pitch roof slope is defined by the 18 foot high south wall and the 10 foot high north wall. The average exterior wall height of 14 feet compares with the parapet wall height typically found on conventional single story office structures.

Figure 4. Building Section Concept



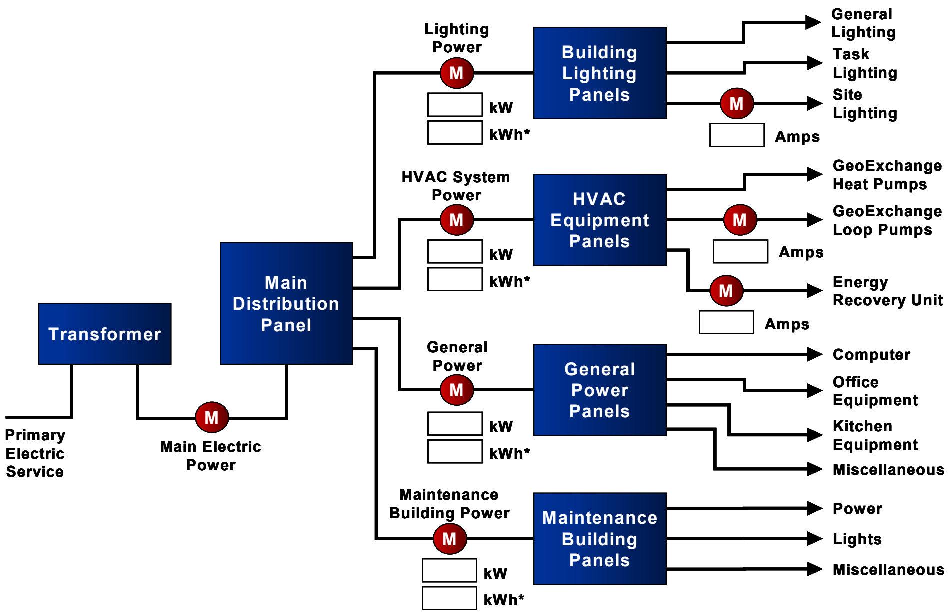
During the spring, summer and fall, the five foot roof overhang and view window exterior shading devices effectively prevent direct sun from entering the space. During the lower sun angle winter months the direct solar radiation is allowed to enter the building to offset heating loads. However, to control direct sunlight from striking work areas in the core and the north offices, the occupants mount a simple interior seasonal banner to diffuse the sunlight.

The building section energy concept equally divides the area into a north perimeter zone, an interior zone and a south perimeter zone. Each of these zones makes up a logical thermal zone under control of one heat pump. Daylight control zones follow the same configuration with the exception that the north perimeter zone private offices are controlled by two light sensors. Occupancy sensors in enclosed offices turn lights off when the sensor detects the office is vacant.

Energy Systems Measured Results

The building has been monitored over a period of five years providing a detailed energy history. The utility company meter measures total site electrical power for the office building and the maintenance and shop buildings. Four submeters segregate the electrical power for the office building lighting panels, HVAC panels, general plug loads and the power service to the maintenance and shop buildings as shown in Figure 5. The total of the four submeters reconcile with the utility premises meter to an average difference of 1.5%. Additional electrical current meters are also used to monitor the energy consumption of the geothermal loop circulating pumps, energy recovery unit and site lighting.

Figure 5. Electric Meter Diagram



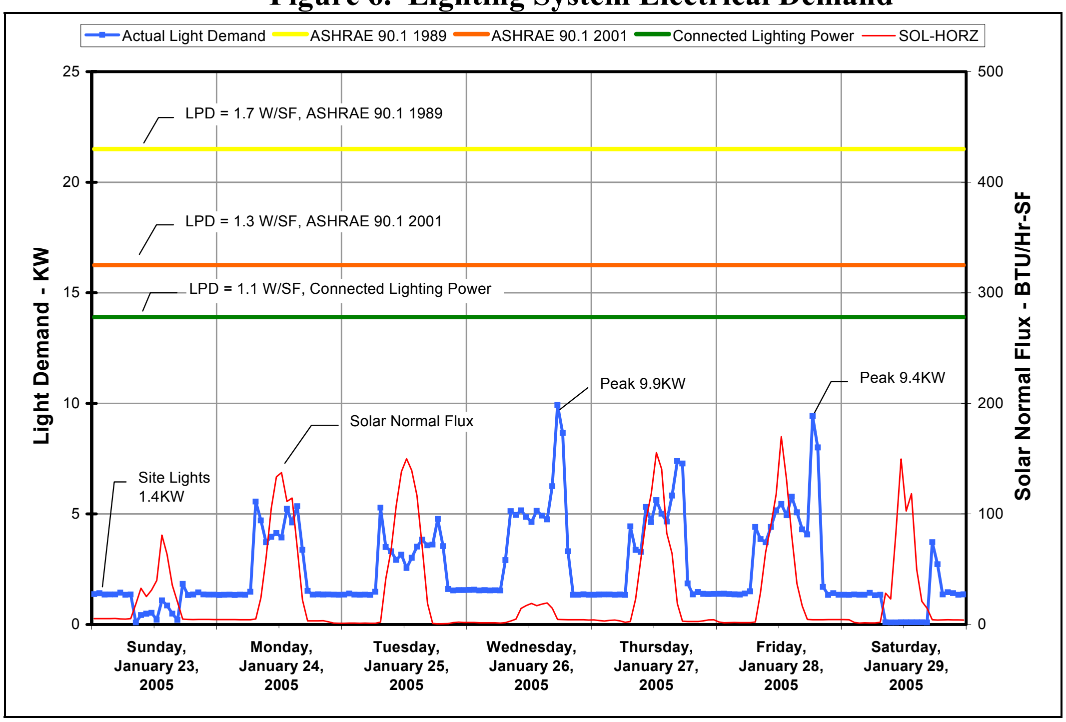
The monthly metered data for 2005 indicates the office building used a total of 103,188 kWh for the year which translates to 28,174 BTU/ft^2. Of this total annual energy, lighting energy consumption is 19,422 kWh or 19%, general plug loads are 33,116 kWh or 32%, with HVAC at 50,650 kWh or 49%of the office building total. The total annual office building energy cost of $6,537 results in an annual energy cost of $0.523/ft^2 and includes all charges, fees and taxes associated with the purchase of energy.

Lighting systems electrical demand. The lighting system electrical demand for a one week period that includes the annual peak lighting demand is shown in Figure 6. The peak demand of nearly 10 kW is the result of shorter days, and in some cases heavily overcast days, activating the site lighting at high stage while the building is still occupied and requiring interior light levels be maintained. The site lighting demand on low stage is consistent at 1.4 kW during the entire evening period and represents a significant portion of the total lighting energy.

The building is typically occupied from 8 am until 5 pm weekdays is generally not used during the weekends. The measured lighting demand predictably drops significantly during the weekend days. The solar normal flux line is indicative of ambient light intensity. The solar flux level on Tuesday registers very strong and even, indicating a bright, clear, sunny day. The corresponding lighting demand is minimal, dropping to about 3 kW midday demonstrating the effectiveness of the lighting controls. In contrast, the solar flux level on Wednesday is exceptionally low resulting in a higher and steady lighting demand of 5 kW for most of the day.

The horizontal lines in Figure 6 indicate the equivalent lighting power density levels stipulated by ASHRAE 90.1-1989, ASHRAE 90.1-2001 and the actual connected lighting power density for the building. The area between the connected lighting power density line and the actual measured lighting demand represents energy saved for the period that the lighting is on. The integrated daylight approach and lighting control system significantly reduce the lighting demand to levels that are one-third of the connected lighting power and reduce lighting energy by 68% compared to the code compliant base building.

Figure 6. Lighting System Electrical Demand



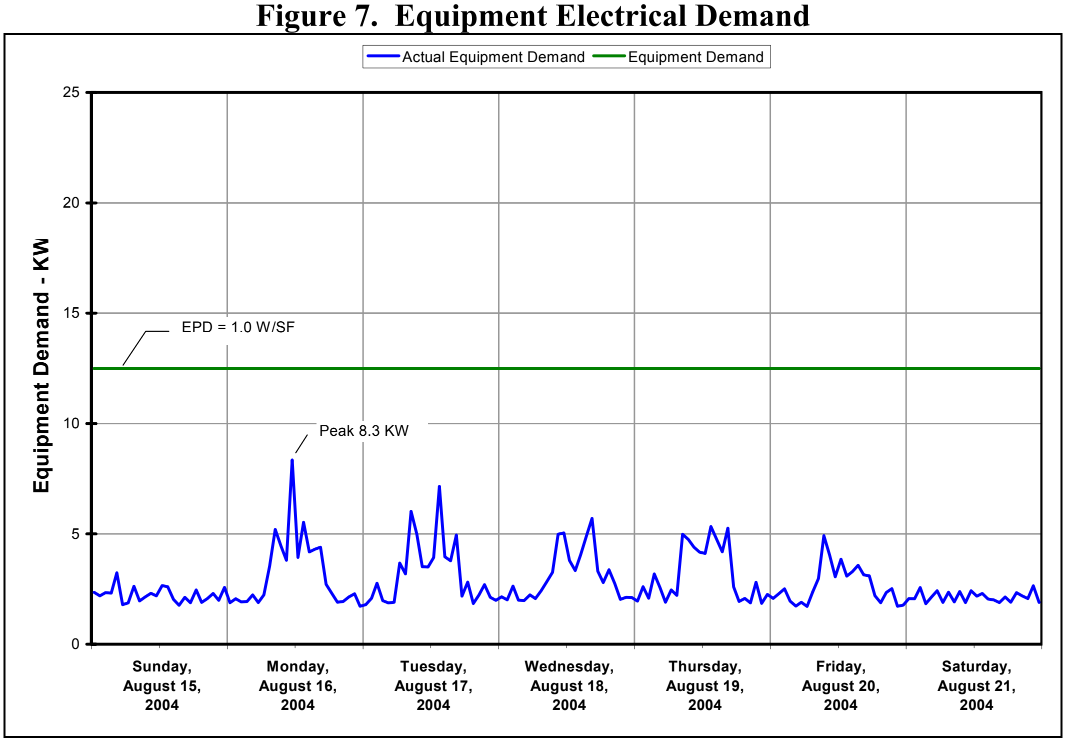
Equipment electrical demand. The major energy consumers on the general plug load meter include: computers, office equipment, domestic water heaters, kitchenette range, refrigerator and microwave, electric water coolers, and entrance vestibule and auxiliary heaters. The general plug load electrical demand is shown for a typical summer week on Figure 7. The demand peak of over 8kW is coincident with a training event and attributed to food preparation activities and hot water use during the event noon break.

A steady residual load of 2 to 3 kW during unoccupied times represents half of the typical occupied demand. It is possible to speculate on the nature of this residual electric load, however, additional investigation is necessary to identify the load and evaluate energy strategies.

The measured equipment electrical demand is significantly lower than the design equipment power density level of 1.0 watt per square foot anticipated for the cooling and electrical load calculations. The actual operating diversity of the equipment is a factor and was partially addressed by the energy simulation modeling. Another contributing factor is estimating the peak demand of general plug loads by assigning a conservative demand load of 180 watts or more for a computer and monitor at every workstation as part of the design process. In reality, the trend toward more flat panel displays has driven the average demand down to about 90 watts for a continuously active workstation. Furthermore, several desktop units have been displaced by laptop computers which operate at 50 watts or less.

An important part of the decrease in equipment demand and energy is due to IAMU personnel extending their concerns for energy efficiency and sustainability to the procurement of office equipment, water heaters, refrigerators and other appliances. For example, the vending machines are controlled by an occupancy based sensor specifically designed to deactivate the vending machine lighting and power when the sensor detects nobody in the area. These items result in equipment electrical energy consumption at over 16% less than anticipated through the building energy simulation model.

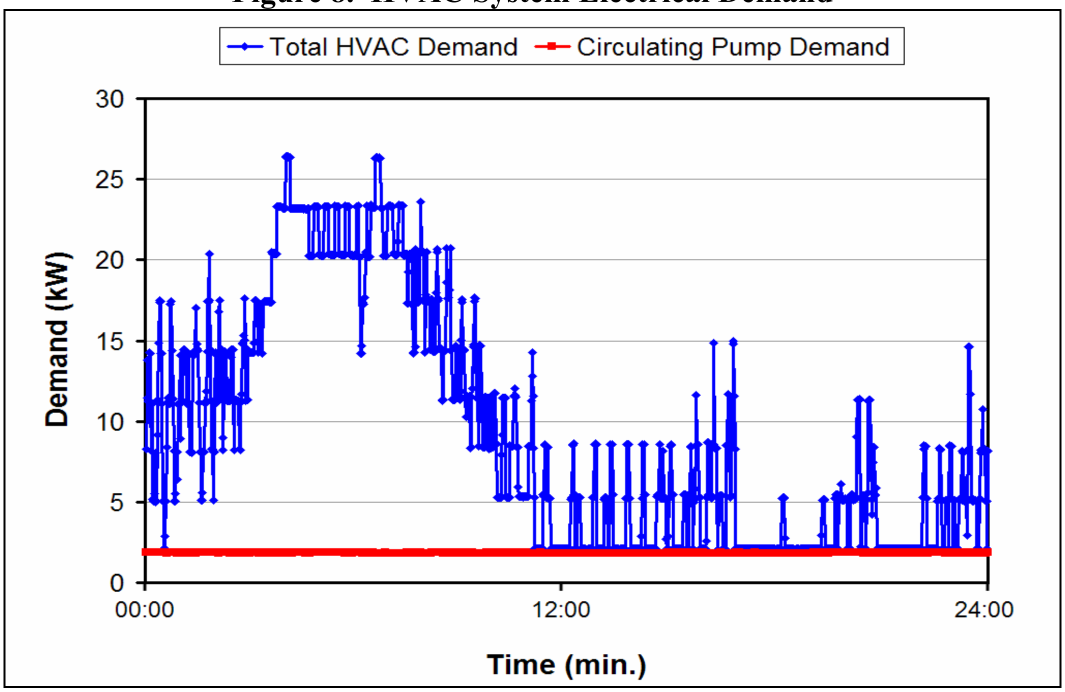
Figure 7. Equipment Electrical Demand



HVAC system electrical demand. The electrical demand of the geothermal heat pumps and the loop circulating pump is shown in Figure 8. The time period covers one winter day with a temperature range of 5°F to 22°F. A characteristic 'on' signature of 3 kW can be resolved for each heat pump that is in operation. Based on the rated capacity of the heat pumps, the data indicates a maximum nominal heating load of about 315,000 BTU/Hr with a corresponding electrical demand of 26 kW occurring in the early morning hours as the building recovers from night setback and all eight heat pumps are operating. The heating demand falls off as the building becomes occupied and internal heat gains and solar gains offset building heat loss. The lowest demand occurs at the end of the day when night setback is introduced and none of the heat pumps are in operation for a 2.5 hour period.

The loop circulating pump operates continuously as indicated by the lower limit demand line recorded at 2 kW. This pump represents only 8% of the HVAC measured system demand. However, on an annual basis the circulating pump consumes 36% of the HVAC system measured kWh energy consumption and is responsible for 18% of the total building energy costs. This disproportionate consumption is due to the 24/7 continuous operation of the loop pump. In a low energy building this otherwise minor load becomes prominent.

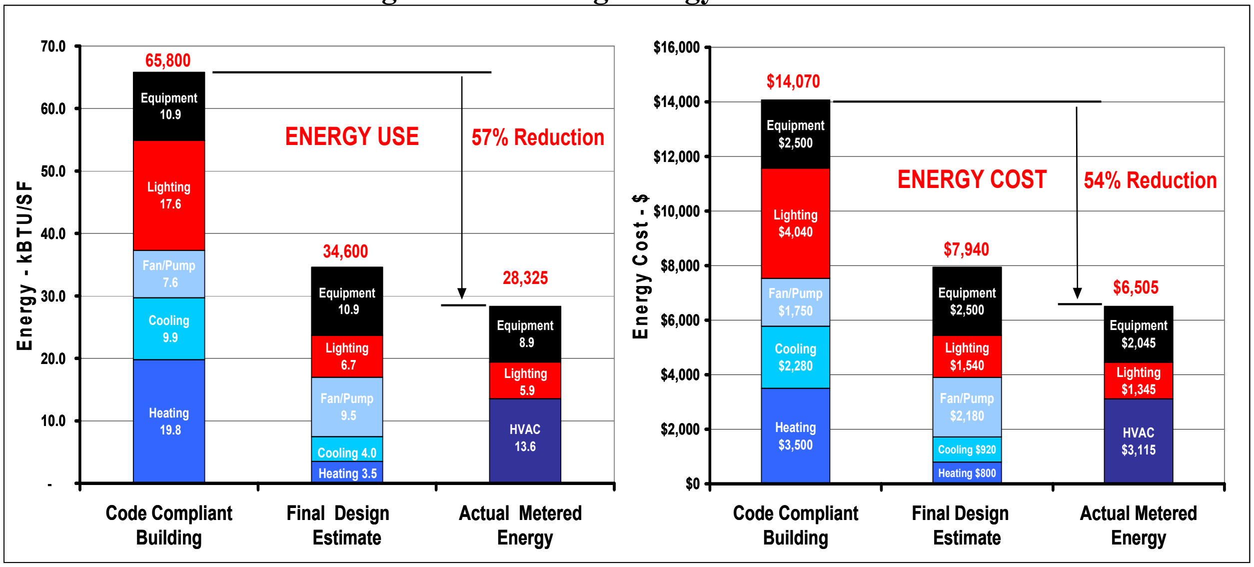
Figure 8. HVAC System Electrical Demand



Total building energy performance. The energy performance for the base case, code compliant building model, the final design simulation estimate and the actual metered energy use are summarized on Figure 9 which shows both energy and energy cost performance. The three year average energy use index of 28,325 BTU/ft^2-yr represents a 57% reduction in energy use compared to the base case, code compliant building benchmark. The actual three year average energy cost of $6,506 results in an annual energy cost index of $0.52/ft^2.

The energy performance for a typical Midwest region office/professional building is 126,120 BTU/ft^2-yr at an annual energy cost of $1.53/ft^2 according to data from the Commercial Buildings Energy Consumption Survey (CBECS 1999). In comparison, the IAMU Office Building uses only 25% of the energy and operates at one-third of the energy cost against this benchmark of similar use buildings.

Figure 9. Building Energy Performance



Conclusions

This facility creates a meaningful place that provides more than basic administrative offices, conference and training rooms and paved parking lots that are status quo with strip mall office developments. It demonstrates that a high performance, energy efficient, environmentally responsible small office building is possible on a speculative office building budget. The integrated design process coupled with an extended project team allowed the team to capture energy performance that is not possible with conventional project design approaches. The project energy efficiency design goals were met or exceeded. Measured energy performance results confirm that the energy goals were achieved and are sustainable over time.

No plan is perfect – there is always room for improvement through lessons learned during the design and implementation of any building. Experience with the project from conceptual design through five years of post occupancy monitoring offers several prominent lessons learned:

- Windows may easily become a cost and thermal liability. Use simulation tools to optimize window to wall areas by orientation. Due to low sun angles, East and West windows are least effective for daylight since blinds or shades need to be drawn and are typically left drawn even on overcast days.
- Dueling controls are problematic. The lighting for the north side private offices was zoned with one closed loop light sensor installed to control three adjacent offices. Since north daylighting does not require sun control, blinds were not installed and control problems were not anticipated. However, the office lights are also controlled by an occupancy sensor. When the occupancy sensor in the same office as a zone light sensor detects a vacant office, the lights turn off and the office goes dark. The light sensor reacts by attempting to increase light level but can only do so in the adjacent offices. While this phenomenon is not frequent, it causes the adjacent offices to quickly become brighter and the change is noticeable by the occupants. The application of an open loop light sensor would eliminate the problem.

- Geothermal heat pump systems are intrinsically energy efficient. However, pumping energy can be significant. Further evaluation of the pumping system to cost effectively include two stage pumping, variable speed pumping, or control options allowing night standby pump operation would offer additional potential for energy efficiency.
- Simpler is better – and sustainable. The energy efficient techniques applied to the building are passive, simple and straightforward. Exotic and elaborate energy solutions such as active window blinds, networked lighting controls, and direct digital HVAC control systems were avoided. The five year energy consumption track record substantiates this – the energy use index has been less than 30,000 BTU per square foot per year since the building opened.

The integral design process and fundamental energy performance techniques that make the IAMU Office Building and Training Complex exemplary may easily be replicated in the design of other small office buildings. This case study building serves as an example ready to convince other building owners and design professionals that a low energy and sustainable design are possible on a modest construction budget.

While the IAMU Office Building does not possess the renewable energy features necessary to function as a zero energy building, it is necessary for a practical zero energy building to possess the energy performance features of the IAMU Office Building.

Acknowledgements

The monitoring and evaluation of the IAMU Office Building is sponsored by the Iowa Energy Center. The administration and staff of IAMU are recognized for their commitment to energy efficiency and sustainability that make this project possible and their continuing support in allowing the facility to be used as a case study example.

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