Low Energy Building Case Study: Toward Net Zero Energy

Joel Logan, Iowa Association of Municipal Utilities
Curtis J. Klaassen, Iowa Energy Center

ABSTRACT

The Iowa Association of Municipal Utilities (IAMU) office building has demonstrated that it is a low energy building through six years of energy monitoring. Over this time period, the building had a site energy use index 55% lower than an equivalent energy code compliant building. This low energy use was achieved through a commitment to energy efficiency beginning in the design of the building, continuing through the construction, and into the occupancy of the building. However, energy monitoring also revealed several areas where the building's energy consumption could be significantly reduced through cost effective measures.

This case study will examine how the performance of the low energy IAMU building was enhanced through a retrofit to variable speed pumping for the ground source heat pump system; retro-commissioning of the energy recovery ventilator; and behavior modification to reduce plug loads during unoccupied hours. Energy monitoring documents a 15% decline in weather adjusted site energy consumption for a building operating at a level of 26,100 Btu/ft^2 after the improvements were made.

The feasibility of the energy efficiency upgrades is also cross examined for net energy, economic, and carbon reduction merits against on-site renewable energy sources as the building moves toward net zero energy.

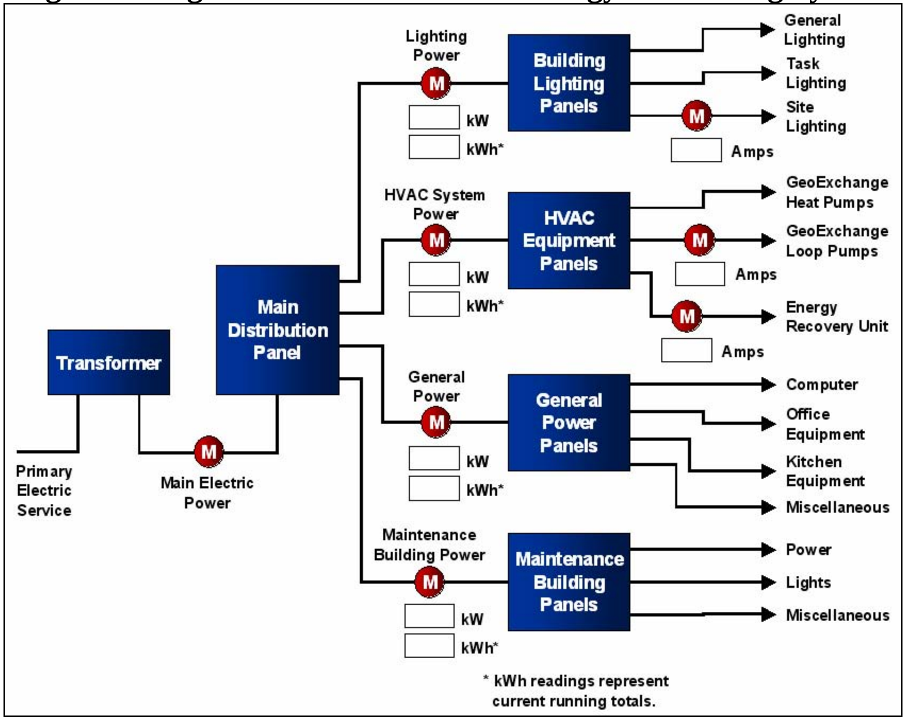
Introduction

The Iowa Association of Municipal Utilities' (IAMU) administrative headquarters in Ankeny is a showcase for energy efficiency and environmental sustainable design. The purpose of the IAMU is to support and strengthen Iowa's municipal utilities, and the association made it a top priority, from the inception of the building design in 1997, to demonstrate to their members how an energy efficiency and environmentally sound facility could be economically built. To achieve the owner's commitment to constructing an energy efficient building, an expanded design team was assembled and met during twelve full day design charettes. Through this process, five project goals were developed, including the goal of reducing the building's energy consumption 40% below the energy code requirement. Energy modeling of alternate building systems with varying energy savings was key in determining the final design. By modeling many different energy savings systems, the owner was able to choose a bundle of efficiency measures that matched the construction budget and the energy savings goal. Among the design features that make the IAMU building energy efficient are a high performance building envelope, the use of daylighting with dimmable fluorescent lights as supplemental lighting, occupancy controls on light fixtures, a ground source heat pump HVAC system, and an energy recovery ventilator. In keeping with its roots in the utilities industry, the building was built using utilitarian design features, but use of an open floor plan, abundant daylighting, views to the outside and natural wood finishes provide a pleasant work environment. All this was accomplished within an economical construction budget of \$116/ft^2 (2000 dollars). The design process and final building design are outlined in detail by McDougall et. al (2006).

Figure 1. Southwestern Elevation of the IAMU Building

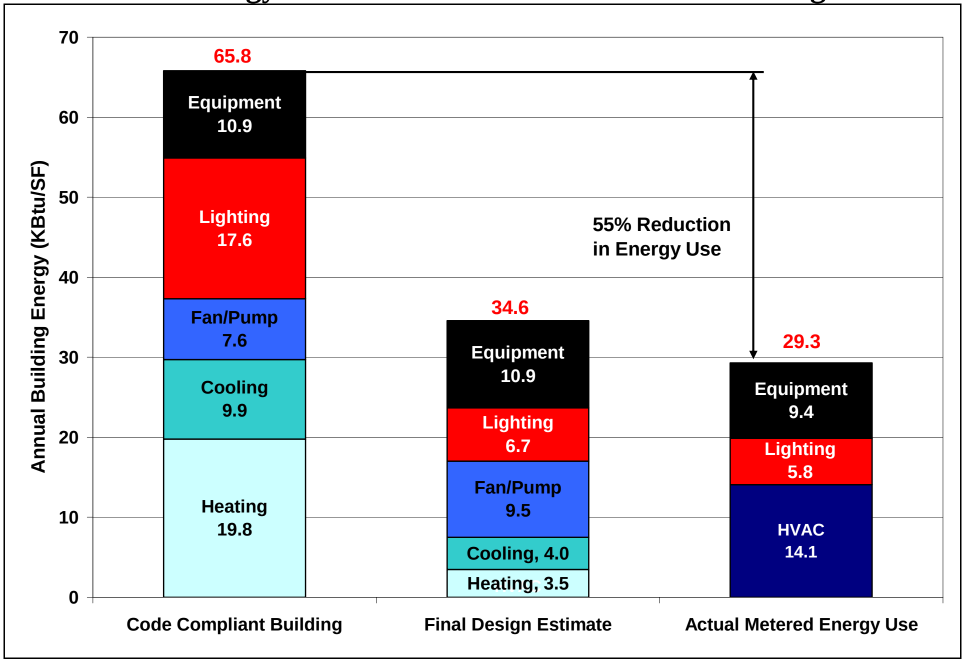
Besides housing office space for 30 employees, the 12,500 ft^2 office building contains a board room seating 30 people and an auditorium seating 76 people for educational sessions. A twelve acre field on the grounds is used for training utility workers in the service of electric, gas, water, and telecommunication infrastructure, and a maintenance building is used for additional indoor training. The landscaping surrounding the building and training field consist of native Iowa tall grass prairie, oak trees, and marshland. Figure 1 shows a partial southwestern elevation of the IAMU building

Figure 2. Organization of the IAMU Energy Monitoring System



The energy use and indoor environment of the IAMU office building has been monitored for the past nine years. This has provided valuable insight into how the building operates and where it can be improved. Figure 2 shows the organization of the building energy monitoring system (the building is all electric). The electric utility meter provides an overall measure of the energy used by the office building and two maintenance buildings. The energy use is then monitored by four sub power meters: office lighting and site lighting, heating ventilation and air conditioning (HVAC), general equipment, and the maintenance buildings. Current transducers provide sub metering for three end uses: the site lighting, the ground source heat pump system circulating pump, and the energy recovery ventilator. This combination of power meters and current transducers provides sufficient detail on the energy use of the building to evaluate the performance of the subsystems and the building as a whole. In addition to energy monitoring, indoor environmental indices and light levels are monitored throughout the building.

Figure 3. Comparison of IAMU Energy Use to Code Compliant Building, and Design Estimate Energy Use. Metered Data is from 2001 through 2007



The average annual energy use of the IAMU office building from 2002 through 2007 was 366,000 kBtu, which is equivalent to an energy use index (EUI) of 29,300 Btu/ft^2. Thus, the building used nearly 55% less energy than it would if it had been built to the Iowa energy code in effect during building design: ANSI/ASHRAE/IESA 90.1-1989 (ASHRAE 1989). Over this time period lighting made up 20% of the annual energy use, general equipment made up 32%, and HVAC energy made up 48%. Figure 3 contains a comparison of the average EUI of the IAMU building to an equivalent code compliant building and the predicted EUI of the building from the final design. The energy use of the equivalent code compliant building and the as-designed building were determined by modeling the building using the building energy simulation software DOE-2. The building's actual EUI was 29,300 Btu/ft^2, while the modeled EUI of an equivalent minimally code compliant building was 65,800 Btu/ft^2, and the design estimate was 34,600 Btu/ft^2. The building shows similar reduction in energy cost; the building had an average annual energy cost of $6,700 over the period 2002 through 2007, while the annual energy cost of the modeled code compliant building was $14,000. Klaassen, et al.

provide detailed descriptions of the energy consumption of each of the three major end use categories: lighting, HVAC, and general equipment (2006).

According to the 2003 Commercial Buildings Energy Consumption Survey (CBECS), office buildings in the U.S. have an average EUI of 92,900 Btu/ft^2, and office buildings in climate zone 2 have an average EUI of 114,900 Btu/ft^2 (EIA, 2006). The IAMU building, thus, uses 68% less energy than the average U.S. office building, and 74% less energy than the average office building in climate zone 2. The building received an Energy Star rating of 93, which places it among the top 10% most energy efficient buildings in the United States.

Making the Best Better

The monitoring of the IAMU building, has verified that it is indeed a low energy high performance building. A cursory look at the energy use index (Btu/ft^2) of the building and the successful operation of the building for several years may initially cause one to believe that all possible energy efficiency measures have been taken in the building. However, looking closely at the energy data collected on the building, aberrations were found that indicated that there were areas to significantly reduce the energy consumption the building. Based on end use monitoring of the building, three energy uses were targeted for reduction to make this exemplary building even better.

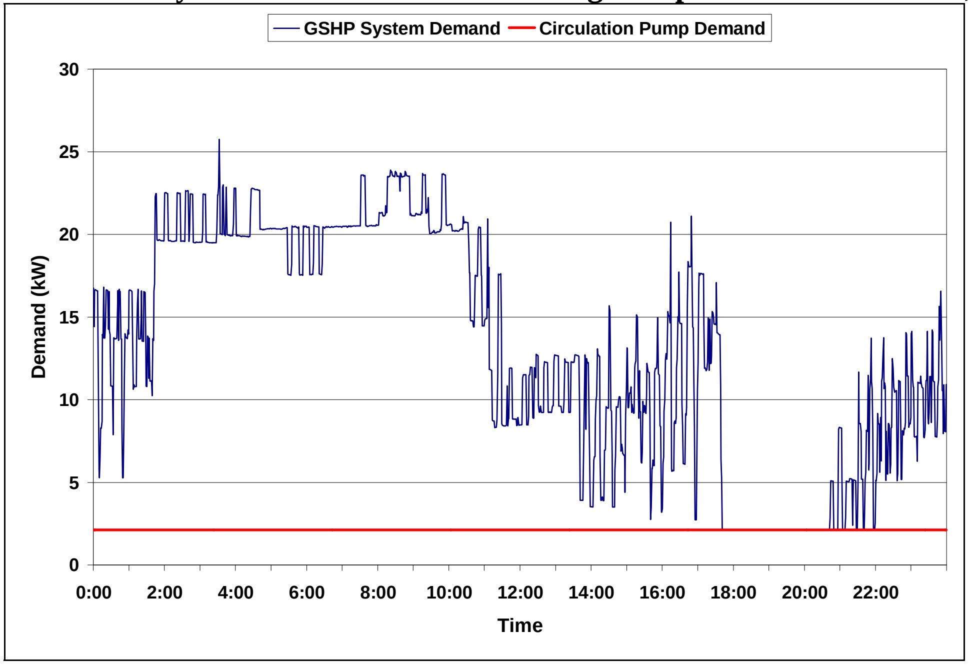
The monitoring of the IAMU building reveled areas where excess energy was being consumed. These excesses could be traced to decisions made and actions taken during the design, construction and commissioning, and occupancy phases of the building. In 2007 three areas with excess energy consumption were chosen for in depth analysis and improvement. The first area identified for improvement was the pumping system for the ground source heat pump system. During the design of the system, a constant speed continuous pump arrangement with a wet standby pump was specified to circulate working fluid between the ground heat exchanger and the heat pumps in the building. While this pump is only 3 HP, unnecessary continuous constant speed operation resulted in energy waste. The second area chosen to improve the building’s energy performance, was retro-commissioning the energy recovery ventilator’s (ERV) defrost heater. This electric resistance heater was set to an unnecessarily high temperature when the unit was installed, and was thus wasting energy. The final area chosen for energy performance improvements was the general equipment energy use when the building is unoccupied. Monitoring revealed that general equipment energy use when the building is unoccupied accounted for a significant portion, 16%, of the IAMU building’s energy use.

Ground Source Heat Pump System Circulating Pump

The ground source heat pump (GSHP) system, used to provide heating and cooling in the IAMU building, consists of eight four ton heat pump units connected to a ground heat exchanger. The heat pumps are water to air units, and each unit provides 1600 cfm of conditioned air to the eight thermal zones in the building. Each zone contains a programmable thermostat that allows the user to program up to four different set points for each day of the week. The thermostats have been programmed for temperature setbacks at night and on the weekends. A 3 HP pump circulates a glycol-water heat transfer fluid, at a nominal rate of 90 GPM, between the heat pumps and the closed loop ground heat exchanger.

The electrical demand of the ground source heat pumps and the loop circulating pump on a winter day, when the outdoor temperature ranged from -8°F to 7°F, is shown in Figure 4. A characteristic 'on' signature of 3 kW can be resolved for each heat pump that is in operation, with a system peak demand of 26 kW occurring when the system is recovering from night setback. 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.

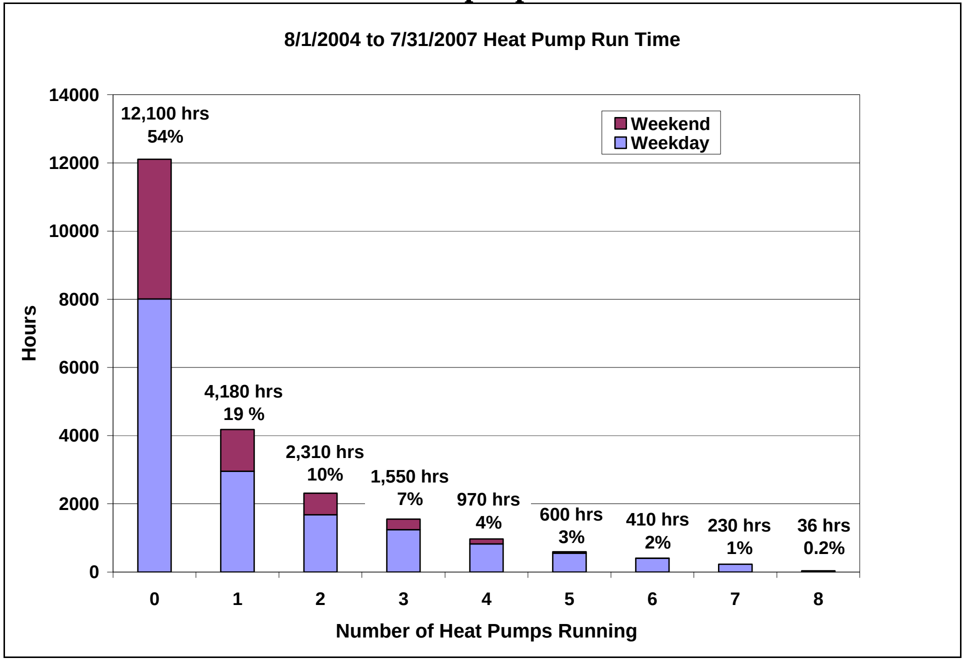
Figure 4. GSHP System Demand and Circulating Pump Demand for Feb 15, 2007



The circulating pump operated continuously as indicated by the lower limit demand line recorded at 2 kW. The circulating pump provided a nominal 11.25 GPM to each heat pump regardless if it was operating or not. The loop circulating pump represents only 8% of the maximum HVAC measured system demand. However, on an annual basis the circulating pump consumes 35% of the HVAC system measured energy consumption and is responsible for 17% of the total building energy consumption. 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.

To determine the magnitude of potential energy savings that would result from altering the control system of the circulating pumping system, further investigation was done to determine the amount of time reduced flow could be provided to the system. Figure 5 shows the amount of time zero, one, two, three, four, five, six, seven, and eight heat pumps operated concurrently over a 35 month period from August 1, 2004 through July 31, 2007. The figure clearly shows that there was a significant amount of time when zero or only a few heat pumps operated. For over half of the analysis period no heat pumps ran, and for a full 94% of the time four or fewer heat pumps ran. All eight heat pumps ran at the same time for only 36 hours or 0.2% of the analysis period. The graph gives compelling evidence that a new control strategy for the circulating pump would save significant energy.

Figure 5. Hours of Concurrent Heat Pump Operation Between 8/1/2004 and 7/31/2007



To achieve energy savings by only providing flow to the heat pumps in operation, a variable frequency drive (VFD) was installed on the circulating pump motor, and shutoff valves were installed on seven of the eight heat pumps. The VFD is controlled by a differential pressure transducer installed within the piping system. The VFD is programmed to maintain a constant pressure differential, as sensed by the transducer, as heat pump shutoff valves open and close throughout the system. As heat pumps turn on and off their associated shutoff valves open and close, and the VFD speeds up and slows down the pump.

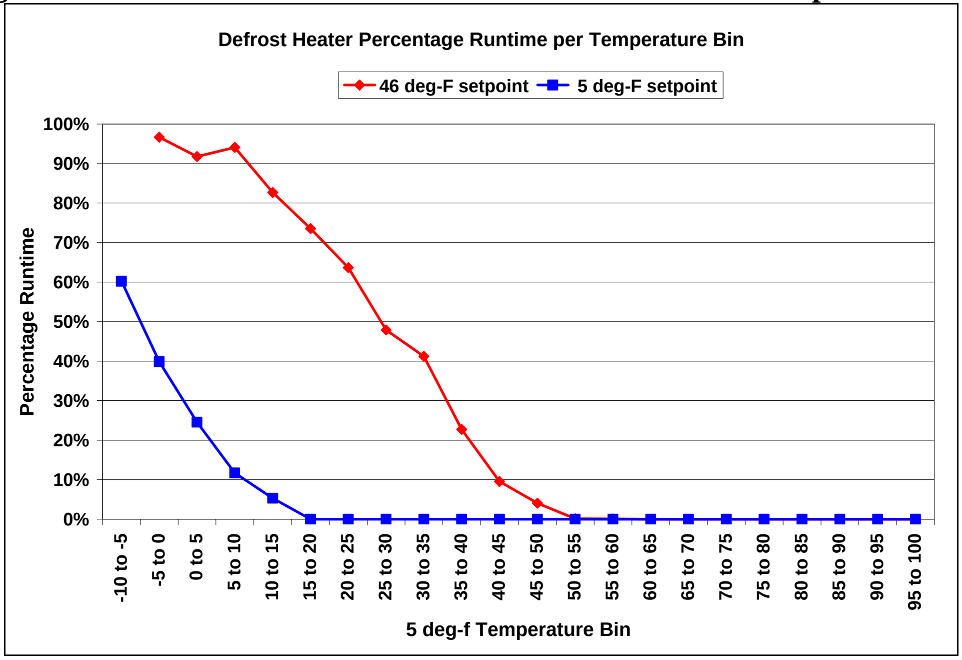
The circulating pump energy was analyzed for 70 days following the installation of the VFD. Over this time period the VFD/circulating pump consumed 965 kWh. If the pump had operated at constant speed, it would have consumed 3300 kWh; therefore the VFD saved 71% of the pumping energy compared to constant speed pumping during this time. Even though the monitoring period occurred during the harsh winter months of December, January, and February, and the daily average outdoor air temperature was around 0^{o}F on four days, significant energy savings were obtained throughout the monitoring period. During milder months, with small heating and cooling loads, the savings resulting from the VFD are even greater. The VFD decreased the circulating pump annual energy consumption from 18,200 kWh to 4,100 kWh, and provided an annual cost savings of $900.

Energy Recovery Ventilator Defrost Heater

The second area examined for energy savings potential was the energy recovery ventilator's defrost heater. When the energy recovery ventilator (ERV) was installed, the thermostat controlling the unit's defrost heater was set unnecessarily high. This simple error in commissioning the system resulted in the heater using excessive amounts of energy.

The IAMU building uses an enthalpy wheel ERV to precondition outside ventilation air by transferring both sensible and latent heat between the outside air and the building exhaust air when the building is occupied. When the outdoor air temperature is very low, it is possible for frost to form in the enthalpy wheel. This would restrict the flow of air through the unit and could damage the enthalpy wheel. To prevent frost formation, a 12.2 kW electric resistance heater is installed in the outside ventilation air inlet and controlled by a thermostat in the airstream. Examining the data from the current transducer that monitors the ERV, it was found that the defrost heater operated for significant amounts of time when the outside air temperature was below 50°F. When the outside temperature was near 0°F, the defrost heater operated nearly continuously. Further investigation revealed that the thermostat controlling the defrost heater was set unnecessarily high to 46°F.

Figure 7. Annual Runtime of ERV Defrost Heater in 5°F Temperature Bins



Because of the transient nature of the heat and moisture transfer in the ERV, frost will not start to form immediately when the temperature of the ventilation air falls below 32°F. According to the ERV's operation and maintenance manual, with exhaust air at 72°F and 40% relative humidity, frost will not form until the ventilation air falls to 0°F. Therefore, the thermostat of the defrost heater needs to be set only slightly higher than 0°F to prevent frost formation. Based on the recommendations of the ERV's operation and maintenance manual, the set point of the thermostat was decreased to 5°F.

Figure 7 compares the operation of the defrost heater now that it is set to 5°F to when it was set to 46°F. It can be seen that reducing the defrost heater thermostat has significantly reduced its operation. When the heater was set to 46°F, it operated for 420 hours per year and accounted for 4.8% of the building's annual energy consumption. At the new set point of 5°F, the heater operates for 30 hours per year, and accounts for 0.3% of the building's annual energy consumption. The heater's annual energy consumption decreased from 5100 kWh to 360 kWh, and the annual energy cost decreased from $278 to $20.

Besides consuming unnecessary energy, the high set point of the defrost heater greatly reduced the effectiveness of the ERV at transferring sensible heat from the exhaust air to the outside ventilation air. As an example of the increased effectiveness of the ERV when the defrost heater was set to 5°F, two days, before and after the resetting of the thermostat were compared. On both days the average outside air temperature was around 0°F. When the defrost heater was set to 46°F, the average temperature rise of the ventilation air was 51°F across the heater and 18°F across the enthalpy wheel. In contrast, when the defrost heater was set to 5°F, the average temperature rise was 14°F across the heater and 49°F across the enthalpy wheel. Therefore, assuming constant air properties, the ERV recovered 170% more sensible heat from the exhaust air when the defrost heater was set to 5°F than when it was set to 46°F.

General Equipment Loads during Unoccupied Periods

The third area that was examined for potential energy savings was the general equipment loads during periods when the building is unoccupied. While the previous two energy use categories were determined during the design and construction of the building, the general equipment loads are highly dependent on the occupants of the building. The IAMU building contains a variety of general equipment ranging from computers and office equipment, to electrical appliances in the kitchen, to the building energy monitoring system and fire alarm system. The building energy monitoring system has revealed a significant residual general equipment energy demand when the building is unoccupied. The IAMU building has typical office hours from 8:00 am to 5:00 pm Monday through Friday. While employees may come in early or stay late, the building is generally unoccupied outside of these hours, as well as eight work holidays throughout the year. In total, the building is unoccupied for approximately 6588 hours, or 75% of the hours in a year.

Figure 8. Summer General Load Meter Power Profile

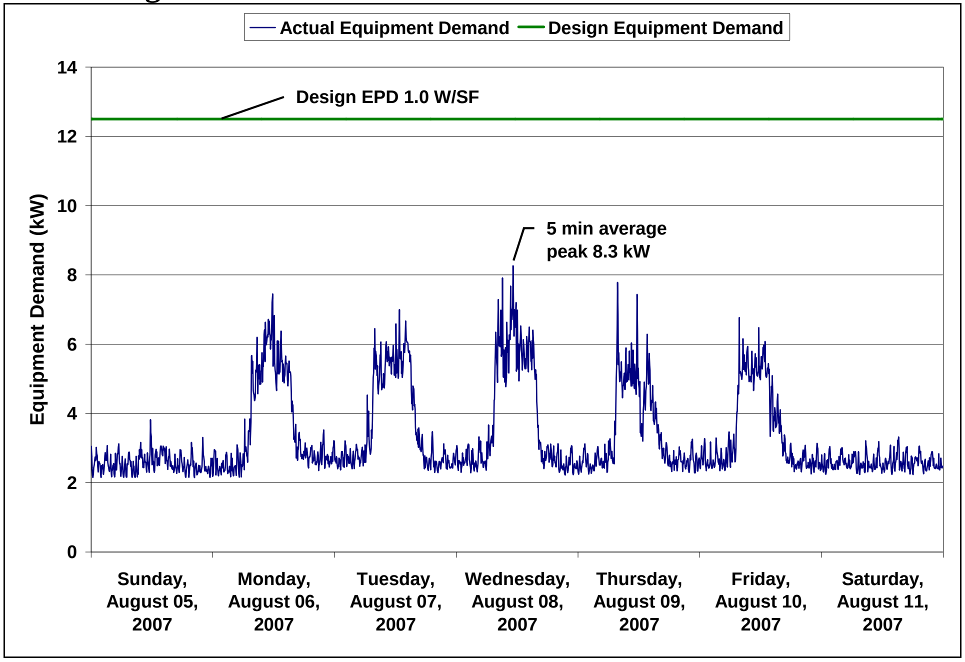


Figure 8 shows the typical energy consumption of the general equipment during a week in the summer of 2007. This figure revels the daily variation in general equipment energy consumption when the building is occupied, as well as the residual energy consumption when the building is unoccupied at night and on the weekends. On a typical weekday the energy demand rises sharply to between 5 and 7 kW between 7:00 and 8:00 am as the building becomes occupied and then falls back to the residual level when the building becomes unoccupied between 5:00 and 6:00 pm. For the week shown in Figure 8, the residual energy consumption was 2.7 kW, and is nearly half of the general equipment load when the building was occupied.

The 2.7 kW residual general equipment load when the office building is unoccupied represents a significant amount of the general equipment's annual energy use. To determine what equipment was making up the plug load, and assess if there was any opportunity to decrease the general equipment load during unoccupied hours, a complete inventory of the general equipment was made. First, in the evening when the building was unoccupied, a handheld power meter was used to measure the instantaneous power of each circuit breaker monitored by the general load meter. The sum of the loads on the general equipment circuit breakers totaled 2.6 kW. This was within 4% of the average load recorded by the data acquisition system during the same period. The bottom row of Table 2 summarizes the energy usage and cost of the general load power during unoccupied periods. A 2.6 kW load during the 6588 unoccupied hours will consume approximately 17,000 kWh of electricity annually. This makes up 53% of the total annual general load and 16% of all the energy used by the building in a year. Based on a historical energy rate of $0.065/kWh, this would cost $1,100 annually.

Second, using the building's wiring schematics, an inventory was taken of each piece of equipment connected to each circuit breaker. The equipment was then divided into three categories: nondiscretionary (N), discretionary communal (DC), and discretionary personal (DP). Nondiscretionary equipment is equipment that must remain on when the building is unoccupied. This includes, among others, a computer server. Discretionary communal equipment is equipment that is used communally by the office staff, such as the copy machines, but can be turned off when the building is unoccupied. Discretionary personal equipment is equipment used by individuals in their own office space and can be turned off when the office is unoccupied. Table 2 summarizes the energy use and energy cost of the three categories of general equipment loads. Nondiscretionary loads account for 47% of the unoccupied general equipment load, while discretionary communal and discretionary personal loads each account for 27% of the load. If all of the discretionary loads are turned off when the building is unoccupied, it is possible to save 9400 kWh and $600 a year. This would reduce the entire building's annual energy use by 9%.

Table 2. Unoccupied Hours General Equipment Energy Use

Unoccupied General Equipment Load Type	**Power** (W)	**Unoccupied Gen. Power** (kW)	**Annual Energy** (kWh)	**Annual Energy Cost**	**% Annual General Meter Energy**	**% Annual Building Energy**
Nondiscretionary Loads	1,200	47%	8,100	$530	25%	7.6%
Discretionary Common Loads	710	27%	4,700	$300	14%	4.3%
Discretionary Personal Loads	710	27%	4,700	$300	14%	4.4%
Total Unoccupied General Load	2,600	100%	17,000	$1,100	53%	16%

The IAMU staff has taken efforts to reduced the unoccupied hours general equipment energy use. Employee awareness of the issue has been increased through discussions on the subject and the impact that they can have on the building's energy consumption through their daily actions, such as turning off all unnecessary equipment in their offices when they leave for the day and to use the power management features of their computers. In some cases, a technological solution has been implemented. As an example, the office has a coffee maker that maintains a tank of hot water at all times. To eliminate the energy use of the heating element when the building is unoccupied, an inexpensive time clock was installed. This provided an annual savings of 800 kWh and $52.

On the Road to Net Zero: Comparison to Renewable Energy

In 2008, the U.S. Department of Energy launched the Net-Zero Energy Commercial Building Initiative, with the goal of making net-zero energy buildings marketable by 2025. Torcellini et al. lay out four definitions of a net zero energy buildings, including net zero site energy (2006). According to their definition, a net zero site energy building produces as much energy onsite through renewable sources as it uses in one year. Because the cost of renewable energy sources are typically high, effectively incorporating energy efficiency into a building is important to reduce the size of the renewable energy system required to achieve net-zero energy. The IAMU building was designed with the efficiency components necessary for a net-zero building. However, before installing such a renewable energy system, it is important to compare the economics of renewable energy to the economics of implementing additional efficiency enhancements.

To compare the cost of implementing the energy efficiency improvements discussed above to the cost of installing an onsite photovoltaic system, values from an actual PV installation in central Iowa will be used. This photovoltaic project has a bid installed cost of $7.99 per Watt. This includes all costs to make the photovoltaic system operational. The design calls for a 2,574 ft^2 solar array with a capacity of 28.8 kW. Based on the performance characteristics of the system and the average annual incident solar radiation in central Iowa, the array is expected to produce 36,069 kWh/year. Stated another way, this photovoltaic panel is expected to produce 1.25 kWh of energy annually per 1 Watt of installed capacity.

Table 3. Cost Comparison of Energy Efficiency Measures to Installing Photovoltaic System

Energy Efficiency Project	kWh Savings	Est. Cost	Avoided PV Watts	Avoided PV Cost	Reduced Annual CO^2 (lb)
VFD Retrofit	14,100	$ 10,000	11,280	$ 90,200	30,600
Defrost Heater Retro Commission	4,740	$ 540	3,792	$ 30,336	10,300
General Equipment Turned off when Building is Unoccupied	9,300	No Estimate	7,440	$ 59,520	20,200

Using the cost and performance data of this photovoltaic system, Table 3 compares the cost of implementing the three energy efficiency projects to the cost of installing a photovoltaic system that would reduce the amount of purchased energy by the same amount. The VFD retrofit on the circulating pump of the ground source heat pump system has an annual energy savings of 14,100 kWh and an implementation cost of $10,000. Because the design work and commissioning of the system was performed by a graduate student, the labor costs for these components of the project were estimated. A photovoltaic system with equivalent energy production would need to have a capacity of 11,280 Watts, and would have an installed cost of $90,000. Therefore, the VFD saved roughly $80,000 in first costs compared to an equivalent photovoltaic system as the building moves toward net zero energy. Retro commissioning of the defrost heater resulted savings of 4,740 kWh annually and had an estimated cost of $540 (again a graduate student performed this work and the labor cost is estimated). This project avoided the need for 3,792 Watts of photovoltaic system, that would have cost over $30,000. By eliminating all discretionary general equipment loads when the building is unoccupied there is the potential to save 9,300 kWh annually. Because eliminating these loads is an ongoing project, there are no specific cost estimates for this project. However, if these loads could be eliminated, the need for 7,440 Watts of photovoltaic system at a cost of nearly $60,000 would be also be eliminated.

Beside reducing the energy consumption of the building, the energy efficiency projects also reduce the greenhouse gas emissions associated with the energy consumed by the building. According to the Emissions and Generation Resource Integrated Database (eGRID), the greenhouse gas emissions associated with baseload electricity generation, in the region where the IAMU office is located, is 1.83 lb CO_2 equivalents/kWh (EPA 2009). Given the building's average energy consumption of 29,300 Btu/ft^2 before any improvements were made, the building had an annual greenhouse gas footprint of 15.6 lb CO_2 equivalent/ft^2, or a total annual footprint of 195,000 lb CO_2 equivalent. Table 3 shows the carbon emissions reduction from each of the efficiency improvements. When calculating reductions in greenhouse gas emissions due to energy efficiency projects, a non-baseload emissions factor is used (EPA 2009). For the IAMU building the non-baseload factor is 2.1712 lb CO_2 equivalent/kWh (EPA 2009). The total potential reduction in annual greenhouse gas emissions from the three efficiency projects is 61,100 lb CO_2.

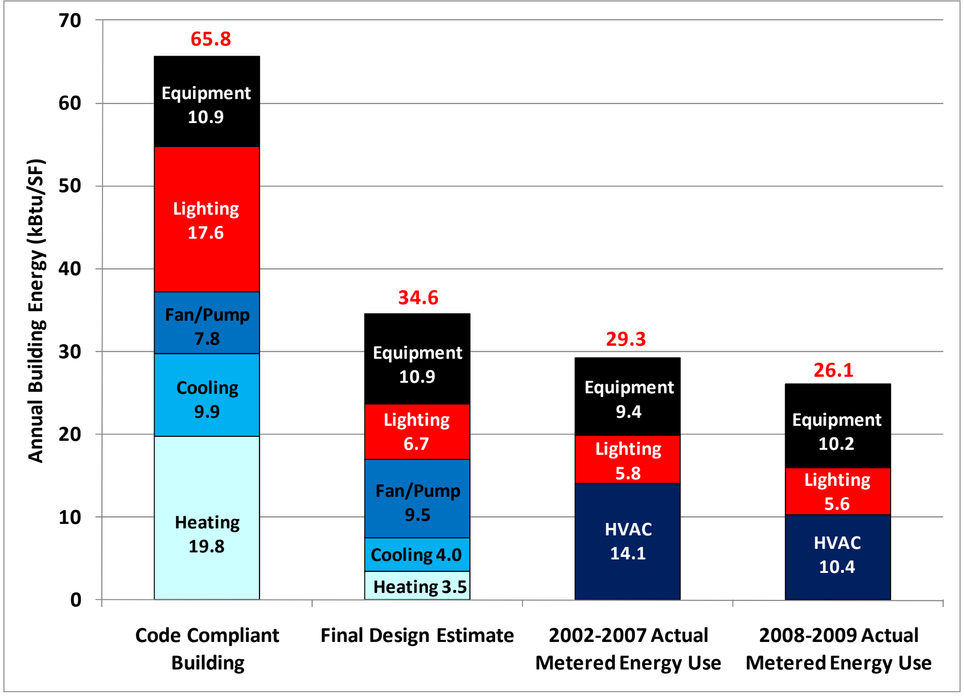
Results of Efficiency Enhancements

Monitoring of the IAMU building over its first seven years of operation demonstrated that it is indeed a high performance low energy building, however the monitoring revealed areas where significant reductions in energy consumption could be made. The installation of the VFD on the circulating pump, the retro-commissioning of the defrost heater's thermostat to the correct set point, and initial efforts to reduce the general equipment load were undertaken in the fall of 2007. Since then two more years of building energy data has been collected, and a significant reduction in building energy consumption has been noted. Figure 9 shows the building's new average annual EUI of 26.1 kBtu/ft^2 over the years 2008 and 2009. This is an 11% reduction in energy use compared to the previous average annual EUI of 29.3 kBtu/ft^2 over the years 2002 through 2007. When the new EUI from 2008 and 2009 is compared to the EUI from just 2006 and 2007, the building has shown a 15% reduction in energy consumption. Weather normalization of the EUI maintains a 15% reduction of building energy consumption between the periods of 2006-2007 (4.23 Btu/ft$^{2}\cdot$DD$\cdot$yr) and 2008-2009 (3.59 Btu/ft$^{2}\cdot$DD$\cdot$yr).

Conclusion

The energy efficiency improvements made to the IAMU building were a cost-effective method to reduce the net site energy consumption of the building. Compared to installing a photovoltaic system to achieve the same results, the VFD retrofit and defrost heater retro-commissioning incurred 91% less cost. Sub-metering of end energy uses and review of the data collected was key to reveling these significant, yet simple, areas where the building's energy consumption could be reduced through energy efficiency measures. Without the energy sub-metering, it would have been difficult to know that additional energy efficiency measures existed. This case study serves as an example to building managers, design professionals and policy makers, that energy efficiency is highly cost effective compared to installing renewable energy sources.

Figure 9. Comparison on of Energy Usage of Building after the Efficiency Improvements



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