Zero Energy: Designing and Monitoring a Zero Energy Building that Works: The Science House in Minnesota

Jason Steinbock, David Eijadi, Tom McDougall, Prasad Vaidya, and Jeff Weier
The Weidt Group

ABSTRACT

Recognized at European Council for an Energy-Efficient Economy (ECEEE) 2005 for innovation, the challenge of the Science House at the Science Museum of Minnesota was to create habitable, cold climate architecture that was a net zero energy building and to get it built in a "low bid" environment. The team used science to resolve design integration conflicts between functionality, aesthetics and performance. The team significantly reduced annual energy consumption beginning with expectations of use by the owner and architectural form and then adding a renewable energy source. The defining question became "how much building and power generation can we build with the given budget?" The resulting building uses passive solar design, daylighting, ground source heat pumps and photovoltaic (PV) panels as the major design strategies.

This paper documents the predicted energy use, the actual monitored performance and compares back to a calibrated DOE-2 model. It shows the extent of load reduction achieved with passive solar design. A challenge for getting to 'real zero' is the difference between expected performance and actual building performance. This paper illustrates how measured data is used to trace the causes to unexpected equipment performance, heat pump behavior and off-line PV panels. Assumptions regarding occupancy and building use during the design phase often differ from their actual use; this makes operating a building for zero energy an additional challenge beyond just designing one. Overall, the actual building is exceeding the goals, using on average 6.6 kWh/ sf annually and generating 9.1 kWh/sf to actually become a building that generates more energy than it uses.

Introduction

Science House was designed and built to serve as an interpretive center for environmental programming in the Big Back Yard, the Science Museum of Minnesota's 1.75 acre outdoor science park. Designed to produce as much energy on-site via renewable energy sources as it consumed, it thus was to become a zero energy building. The Science Museum, an organization committed to propagation of science among the masses, and its energy design consultants, committed to monitoring the building's performance to prove that it had met and would continue to meet the zero energy goal. The paper shows how during the programming and design process energy conservation and load reduction strategies were evaluated to form one side of a balanced consumption - production equation. Performance monitoring was designed to prove the building's performance. Along the way it has helped to solve problems related to the building systems. The monitoring system has also confirmed the performance of the passive solar design of the building. The paper shows how a calibrated model is used to predict the impact of changing the building use schedule and how the goals for this building could still be met.

This paper is organized as follows. First, we discuss the programming effort that established the building size and design parameters based on the available budget and zero energy goals. Second, we discuss aspects of the building design process and the analysis that was done concurrently to inform the design. Third, we discuss the performance monitoring system installed in the building and how it has gone beyond just a validation exercise to help achieve the zero energy goal. Lastly, we provide conclusions.

Building Programming

We looked at other commercial building with zero net energy goals to determine if and how they achieved their goal. Oberlin College designed a building with the goal of being a net energy producer; however, NREL studies found that they would need more generation or more conservation to reach the goal. (S. Pless, P. Torcellini & J. Petersen 2004) Pepsi Cola Plants in Oregon installed PV systems to offset the entire building load to become zero net energy. (GreenBiz.com, 2004) Here the building was not designed to be zero net energy, it was achieved by installing PV to offset the existing load. Even with residential buildings, zero net energy goals have not been easily met. In 1998 the Florida Solar Energy Center had a goal of building a zero energy house. In the end the house used 92% less energy than a standard home, but was not zero energy. (Parker et al. 1998).

During the early design stages different ways to reach this goal of creating a Zero Energy building were analyzed and compared. The original program called for a 1,500 square foot building with four-season greenhouse, outdoor and indoor classroom/laboratory and a project studio with full telecommunications and Internet capability. In addition to the desire to produce energy there was a fixed project budget. A rational process was needed to test the program against the budget. The defining question became: *"How much building can we build and generate power for with the given budget?"* The overall concept for building definition, design and operation is represented by Equation 1.

Equation 1. Energy Consumed by Building System <= Energy generated onsite

With a fixed budget for the project, the answer depended primarily on three key factors:

1. the area and volume of space to be constructed,
2. the total amount of energy it will take to operate the facility, and
3. the generating capacity per unit of installed cost of the renewable energy system.

To aid the conceptual decision-making process the energy consultant developed an interactive spreadsheet tool (Figure 1) to enable the design team to examine the impact of several key variables that included, spacetypes, hours of operation, percent of spacetypes to be conditioned, and percentage of energy efficiency to be achieved through conservation design. The spreadsheet allowed the design team to evaluate "what if" scenarios by including associated assumptions pertaining to construction cost, and the cost and capacity of installed power generation.

Figure 1. Conceptual Programming Tool

Science House Conceptual Programming Tool
Science Museum of Minnesota
Scenario 6

	Porch	Exhibits	Office/Sup	Total	% of total cost
Floor area	500	500	0	1000	
Energy kBtu/sf					
Heating	30	30	18		
Cooling	9	9	10		
Fan/pump	13	13	12		
Lights	10	24	18		
Plugs	3	5	16		
DHW	2	2	2		
Total kBtu/sf	67	83	76		
Total "Conditioned" kWh/sf	19.6	24.3	22.3		
% Conditioned Space	0%	0%	100%		
Total kWh/sf	4.4	9.1	22.3		
Total kWh	2,197	4,541	-	6,739	
Conservation Level	70%	70%	30%		
Annual kWh/sf	1.3	2.7	15.6		
Annual Total kWh	659	1,362	-	2,022	
Annual Energy Cost	$ 46	$ 95	$ -	142	0.14
Conservation First Cost $/sf	$ 1.08	$ 2.23	$ 2.34		
Total Cost of Conservation	$ 538	$ 1,113	$ -	**$ 1,651**	**1%**
PV area required SF	51	105	-	**156**	
Total Cost of PV installation	$ 6,592	$ 13,624	$ -	**$ 20,217**	**12%**
Base Building Cost per SF	**$ 100**	**$ 200**	**$ 250**		
Total Cost of Base Building	$ 50,000	$ 100,000	$ -	**$ 150,000**	**87%**
Total Building Cost	$ 57,131	$ 114,737	$ -	**$ 171,868**	
				1.3	
			Total Project Cost	**223,428**	
				$ 223,000	Goal
				$ 428	over / under
				0%	over / under

Presented for conceptual purposes only, the data does not reflect final project design, cost or performance

The extremes were a large area with no space conditioning and only daylight hours of operation versus a very small, totally conditioned space without an energy conserving design and with very long operating hours. Using this tool, the team identified a realistic space program with acceptable operating hours, an achievable level of energy efficiency and affordable integrated power generation. Table 1 shows the final building program.

Table 1.

Space Type	Area	% of total area
Classroom	580 sf	61%
Office	140 sf	15%
Vestibule	108 sf	11%
Restroom	128 sf	13%
Total	**956 sf**	**100%**

Building Design Process

The building area / project budget scenario studies targeted a PV capacity with an annual generation capacity of 10,000 kWh as a budget for the amount of energy the building could use. The overall conceptual approach agreed upon by the team in response to the program area, conservation, efficiency and budget constraints is shown in Figure 2. The building design was optimized in a 2 step process. First the building and form, fenestration, envelope and lighting systems were optimized to reduce the building loads. Second additional conservation and efficiency strategies were comparatively analyzed in the form of mechanical system alternatives and controls.

Figure 2. Schematic Design Floor Plan

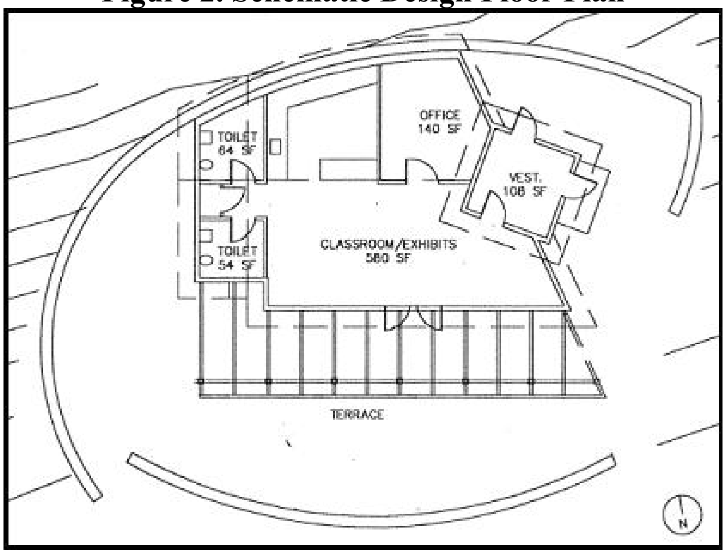
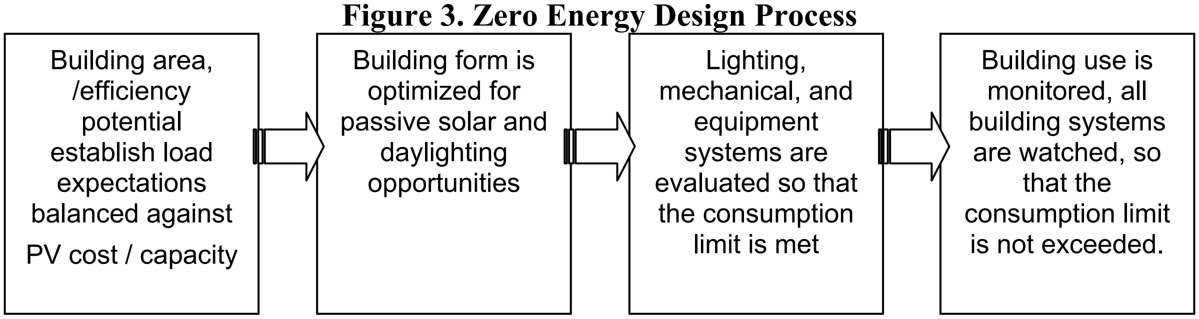


Figure 3. Zero Energy Design Process



Building Form

A key driver for the building orientation was a solar access scheme; the longer sides of the building were designed to face north and south, to effectively integrate passive heating, daylight and photovoltaic electrical generation. A balanced approach to these three strategies reduced loads while increasing electrical generation capacity. The south façade is mostly glass. Other façades are mostly unglazed. Clerestory windows daylight from north and south to reduce contrast and improve uniformity. To reduce heat loss, the north façade of the building was tucked into the gently sloping site. The landscaping around the building acts as a buffer from the north winds and shades the south plaza in summer.

The decision to install photovoltaic panels on the roof of the building influenced the slope and orientation of the roof to capture an optimal amount of solar radiation during the day while minimizing architectural volume.

Figure 4. Photographs of the Building

South Elevation North Elevation

Energy Analysis During Design

During design, computer simulation models using DOE2.1E were used to determine strategies that helped reduce load and improve performance. If the building was going to meet its zero energy goal, then the building has to consume less than 10,000 kWh per year. The evaluation process during the design phase included:

- Developing a baseline energy code model of the schematic design – this allowed us to determine the affects of the load reduction and how much conservation would be needed.
- Identifying a range of isolated energy efficiency strategies for all building system categories, architectural, mechanical, electrical and plumbing.
- Simulating the energy performance of each isolated energy efficiency strategy.
- Identifying the cost-effectiveness for each isolated energy efficiency strategy.
- Design workshop with design team and owner to create bundled sets of the most promising isolated strategies.
- Simulating the energy performance of the bundled strategy sets.
- Select a final bundle to implement.

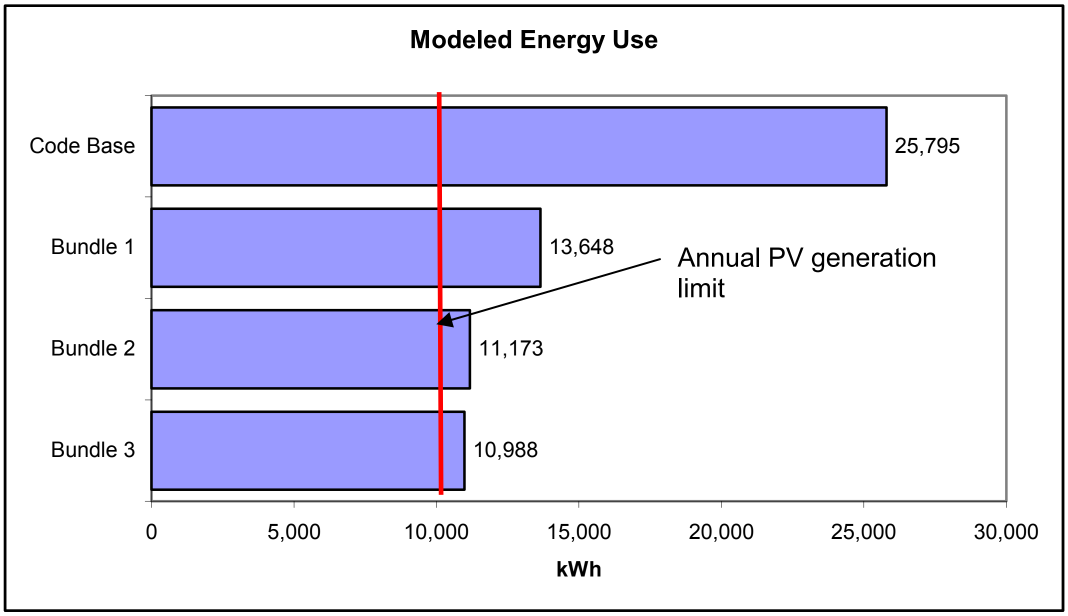
Baseline energy code schematic design results. A DOE-2.1E code base model was built based on setting all schematic design parameters for envelope, lighting, and HVAC systems (including the geothermal heat pump system) to the minimum requirements of the Minnesota Energy Code. Based on detailed discussions with owners occupancy patterns and equipment (plug loads) were assumed and input into the model. The use of the building was a key component in the overall energy use. The better and more detailed these assumptions the better the model and the better the chance of achieving zero energy.

Bundle modeling. Upon review of the results of the isolated strategy analysis, the design team created three bundles (groups) of strategies for final modeling. Figure 5 shows the three different bundles of strategies ultimately analyzed for the project. The team chose Bundle 3 for construction with some small variations. Figure 6 shows the initial estimate for the bundles' performances. The energy analysis showed Bundle 3's estimated performance to be closest to the building's budgeted generation capacity of 10,000 kWh. Along with choosing Bundle 3 the equipment (plug load) use in the building was decreased to get to the 10,000 kWh goal. During construction of Science House, a few of the energy conservation strategies were changed. Since the pumps are only 1/3 of a horsepower, a constant volume pump pack was used. These pumps only operate when the heat pump calls for heating or cooling. Due to first cost and control issues with the heat pump the installed thermostat is not programmable, thus there is no nighttime temperature setback.

Figure 5.

Strategy Description	Bundle		
	1	2	3
Envelope			
Daylight dimming controls w/ Andersen HP windows	●	●	●
North clerestory glazing	●	●	●
4 foot overhang on south side	●	●	●
R-40 roof insulation - icyenene	●	●	●
R-28 wall insulation - icyenene	●	●	●
Lighting			
Occupancy sensor control of all interior lighting systems	●	●	●
Dual level or manual dimming switching in the classroom and office	●	●	●
Classroom direct lighting system at 50 foot candles	●	●	●
Office task/ambient lighting system at 25 to 30 foot candles	●	●	●
Storage, Vestibule and Restroom lighting at 15% better than code	●	●	●
HVAC			
High efficiency ground source heat pumps with variable pumping	●	●	
Premium efficiency ground source heat pumps with variable pumping			●
Unoccupied temperature control 55F heating / 85F cooling	●	●	●
CO2 control of outside air – interlocked with bathroom exhaust	●	●	●
Total ventilation energy recovery	●	●	●
Domestic hot water			
Electric resistance only	●		
Heat pump assisted DHW w/ electric resistance back-up		●	●

Figure 6. Energy Modeling Results: The Vertical Line Marks the Annual PV Generation



On-Site Electrical Generation

Integrated Photovoltaic roof systems of Flat Plate Polycrystalline Silicon panels with an efficiency of 6% to 8% were installed at Science House. The PV array connects to four invertors located on the west façade of the building. The invertors convert direct current to alternating current and supply it first to Science House and then back to the main Science Museum building.

Performance Monitoring

In this section of the paper, we describe the monitoring system installed in the building and how it has been used to verify building performance. We describe specific issues resolved for the PV system, the heat pump system, along with performance verification of the passive solar design and the overall building performance. We also discuss the use of a calibrated model in a zero energy building.

Monitoring System

The performance monitoring system was designed and installed to validate the zero energy use of the building. While this could be done with a simple net-metering type system that tracked the grid energy in and out of the building, the decision to install a more elaborate monitoring system was made. The intent was to be able to track the performance of individual building systems and equipment and determine if they were operating as expected. This monitoring system was designed with the help of researchers from the National Renewable Energy Laboratory (NREL). A Campbell Scientific data acquisition system, that is relatively simple to install, and where the logger, modem, and power supply all fit in one location, was used. This system helps to record environmental conditions for use in system debugging as it is compatible with current transducers, temperature and humidity sensors, pyronometers, and pulse devices (WattNodes for measuring kWh consumption). The system enables downloading the data via a modem.

The monitoring scheme included recording AC power produced by the PV system[1], all energy end uses and environmental conditions. Environmental variables inside the building such as supply and return air temperatures help identify the cooling or heating mode of the HVAC system, and allow trouble shooting. Exterior environmental variables such as solar radiation, outside air temperature and humidity help in calculating the instantaneous expected efficiency of the PV system; these also help in monitoring the effectiveness of the passive solar design of the building. See Table 2 for a list of monitoring points. The datalogging equipment is typically WattNodes except where energy use was very small or rare (such as the electric resistance heater); in those exceptional cases current transducers (CTs) were used.

Table 2. Monitoring System Points

End-Use Category	Meter Type	Units
Occupancy	Wattstopper dual technology occupancy sensor	1= occupied
Total, buy	Watt node 1	kwh/15 minute
total, sell	Watt node 2	kwh/15 minute
PV	Watt node 3	kwh/15 minute
Lights, daylight cntrl	Watt node 4	kwh/15 minute
Lights, other	Watt node 5	kwh/15 minute
Plugs	Watt node 6	kwh/15 minute
HVAC	Watt node 7	kwh/15 minute
DHW Heater	Watt node 8	kwh/15 minute
Blower	Watt node 9	kwh/15 minute
ERV	Watt node 10	kwh/15 minute
Shed	Watt node 11	kwh/15 minute
Ground water from ground field	Type T thermocouple	degree C
Ground water to ground field	Type T thermocouple	degree C
Outside air temperature	Type T thermocouple	degree C
Outdoor relative humidity	Temperature / relative humidity sensor	RH
Temperature of PV panel	Type T thermocouple	degree C
Inside Temperature	Type T thermocouple	degree C
Indoor relative humidity	Temperature / relative humidity sensor	RH
Supply air temperature	Type T thermocouple	degree C
Return air temperature	Type T thermocouple	degree C
Back-up electric resistance duct heater	CT	Amps
Mezzanine lights	CT	Amps
Ground water loop pump	CT	Amps
Service hot water usage	Flow Meter	1 gallon/pulse
Horizontal solar radiation	Pyranometer 1	w/m2
Tilt solar radiation	Pyranometer 2	w/m2

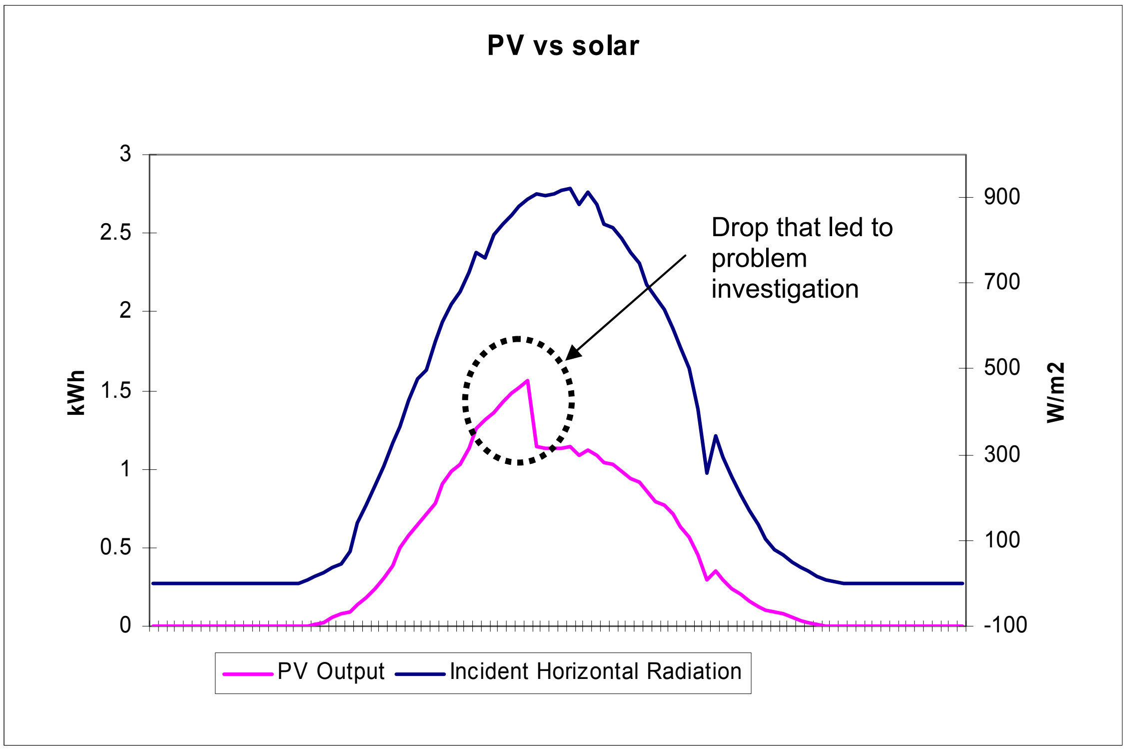
[1] The DC side of the PV system is not monitored. Originally, this was going to be monitored using inexpensive voltage and current shunts that are not subject to temperature variation. However, this did not work with the inverter system installed at Science House; if the inverters go into ground fault mode, ground "floats," causing excessive current through the shunts. DC current and voltage sensors are temperature dependent and could not be used. As a result the PV system is monitored only through its AC output and the incident solar radiation.

PV System Performance

The PV system was designed with the expectation that it would generate about 10,000 kWh annually. The building has now been in operation for two full years. The first year of operation (2004) the PV system had an average efficiency of 4.5% and generated about 7900 kWh. The second year of operation (2005) the system had an average efficiency of 5% and generated about 9000 kWh.

In 2004, the monitoring system showed the drop off in PV production (Figure 7). Note that the solar radiation level did not change, while the PV production dropped by 25% starting at Noon on this June day in 2004. This led to investigation of the problem, which was ground fault, and it was discovered that the PV panels slid on the roof thus pinching the wire against the metal roof to cause a ground fault. The physical displacement of the panels on the roof was not enough to have been noticeable in a visual inspection.

Figure 7. PV Performance Over One Day



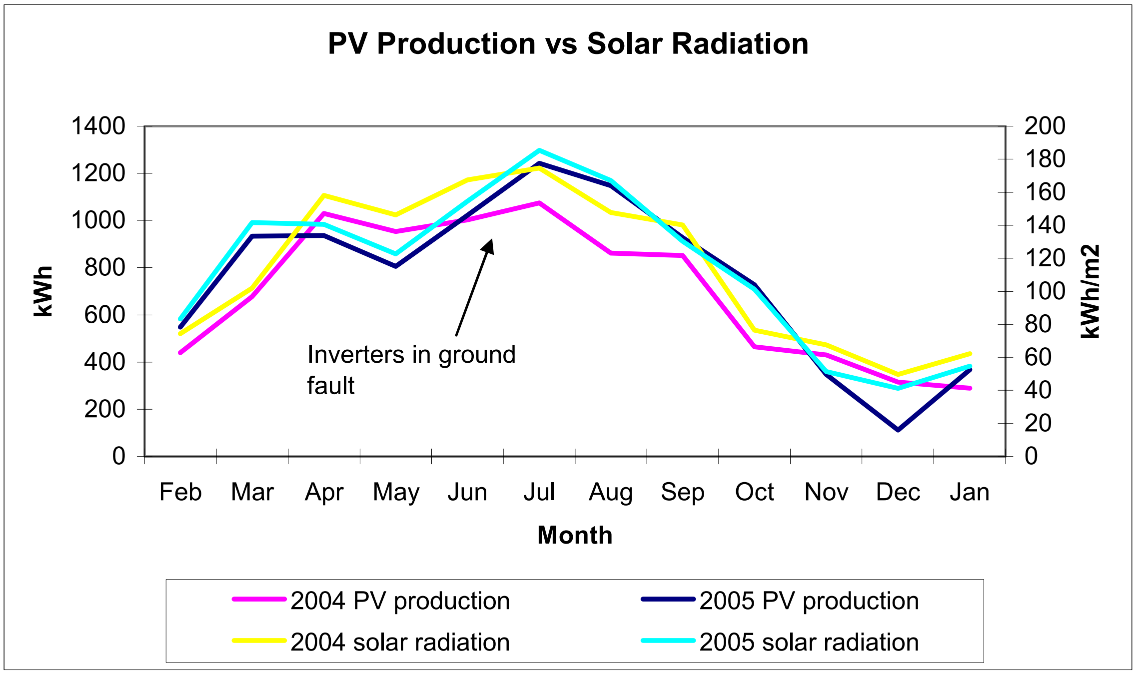
The reason the panels slid appears to be a result of the adhesion process.[2] Pushing the PV panels back up the roof remedied the problem. It is unlikely that this problem would have been discovered by the Science Museum staff through normal building maintenance. The presence of the monitoring system and weekly inspection of the data allowed the problem to be identified

[2] The PV material was applied to the roof panels indoors at the Science Museum during the winter by staff and volunteers. The solvent recommended to clean the roof surface prior to applying the PV panels was not environmentally friendly. The PV supplier told the Science Museum it would be okay to use regular soap and water instead of the solvent. This eliminated the VOCs, but did not get the panels as clean enough. Thus the glue pulled away causing the panels to slide.

and recognized quickly. Although it took some time to fix, the roof was repaired and the inverters were brought back on line.

Figure 8 shows the total monthly solar radiation and corresponding PV production for both 2004 and 2005. It further illustrates the reduction in generation due to the ground fault in the summer of 2004. In 2005 the PV system worked without faults and produced more kWh, an increase of 13% that would have been lost without a good monitoring system.

Figure 8. Comparison of Annual PV Production and Solar Radiation

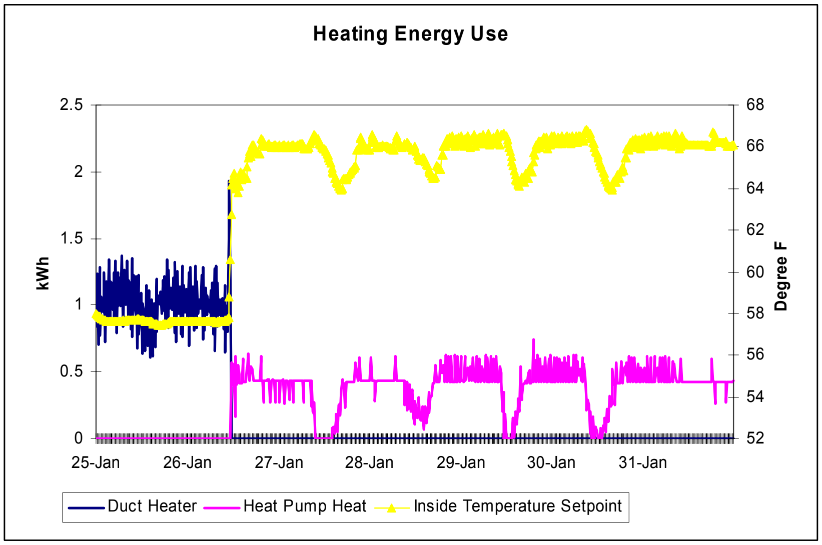


Heat Pump System Performance

The heat pump system provides heating and cooling by exchanging heat with the ground loop, and an electric resistance heater provides backup heat. During the first few weeks of building operation, the monitoring system showed that the electric resistance heater was functioning and the heating temperature setpoint was not being maintained. This indicated that the heat pump was not functioning as expected. The problem was revealed during a site visit, the heat pump pack had frozen.

Figure 9 shows the electric resistance heater (duct heater) and not the heat pump operating during January 25 and part of January 26, 2004. The middle of January 26, the heat pump was repaired and it began to heat the building. If the monitoring system were not installed this problem would likely not have been discovered until spring when the building needed cooling. Even without maintaining the desired heating temperature setpoint, Figure 9 shows that the heater uses more energy than the heat pump. If the building had used the electric resistance heater all winter, the energy goals for the building would not have been met in the first year.

Figure 9. Heating Energy Use



Passive Solar Design Performance

The climate in St Paul Minnesota, 7876 Heating Degree Days (base 65) and only 682 cooling degree days (base 65) requires that the passive solar design of the building work if zero net energy is to be achieved. The monitoring system proved that the passive solar aspects of the building are working well. Figures 10 and 11 show January 5 2005, where the heat pump system does not operate during the day yet the building temperature setpoint is maintained. On this day, the outside air temperature is at or below zero, and while the sun is out, the building does not use any heating energy. The building was unoccupied on this day and the space temperature setpoint of 65 degrees is maintained.

Figure 10. Solar Radiation vs. Heating Energy in the Building

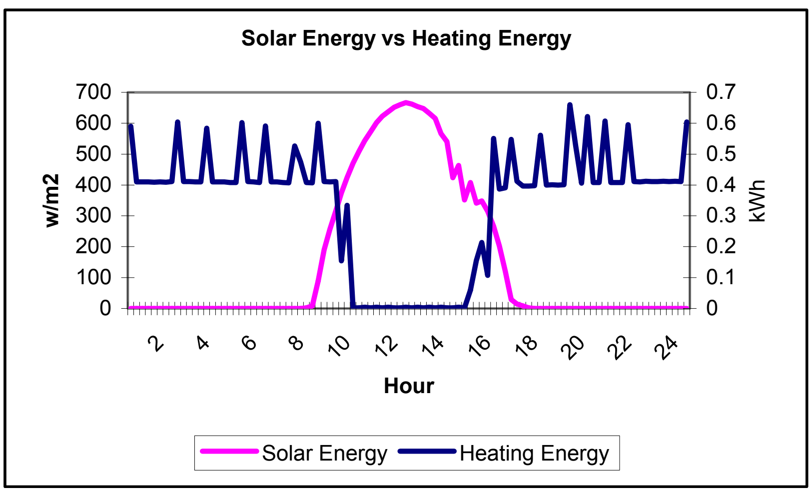
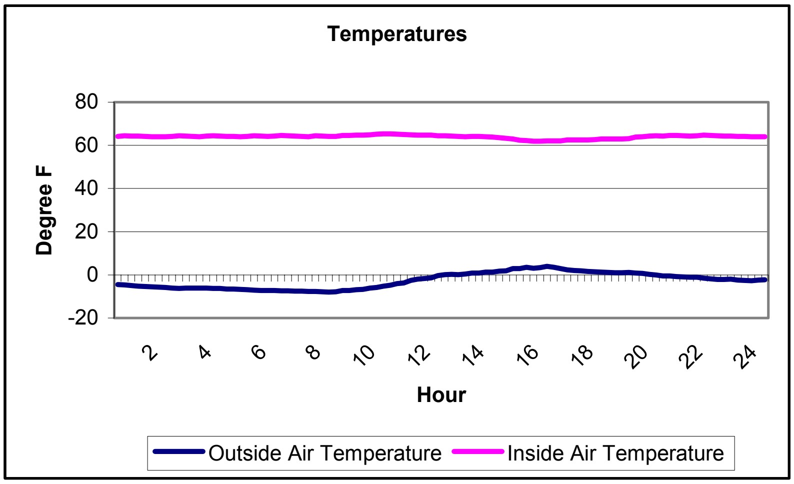


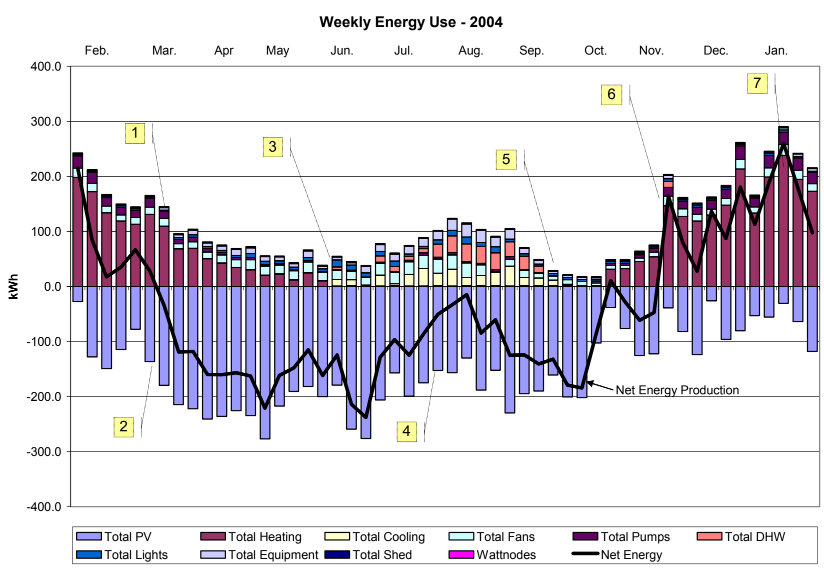
Figure 11. Temperatures During the Time Corresponding to Figure 9



Overall Building Performance

For the past 2 years the Science House has produced more energy than it has consumed. The monitoring system has been used to plot the weekly energy use of the building by end-use in Figures 12 and 13, where the PV generation is shown as negative energy use. During both years the building uses more energy than it generates in the cold winter months, however during the

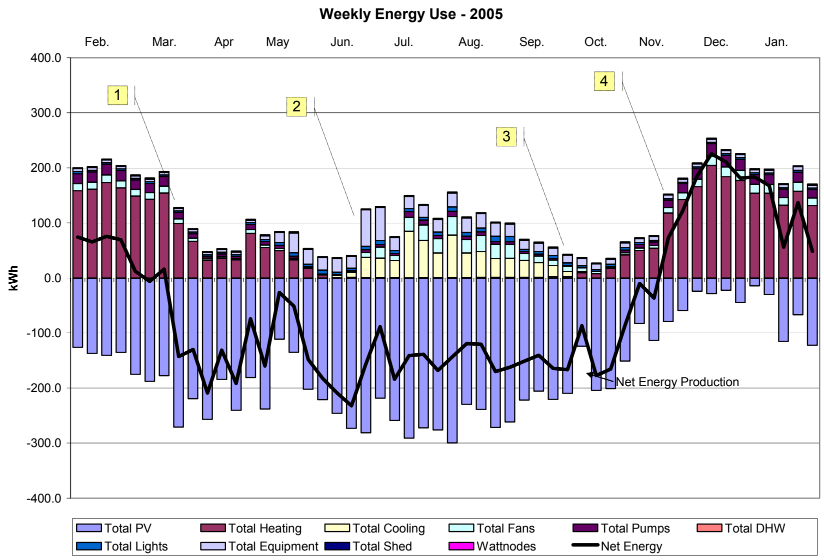
Figure 12. Weekly Energy Balance - 2004



1) Science House used as job trailer as construction is finished on Big Back Yard 2) Science House becomes energy producer 3) Science House opens to the public 4) PV panels slide and inverter goes off line 5) Science house becomes unoccupied and equipment is turned off 6) Science house becomes energy user 7) Electric resistance heat kicked on briefly as thermostat set point was increased

spring, summer, and fall months more energy is generated than is used. Overall each year the building has generated a surplus of energy. Generally in March the building begins to generate more energy than it consumes and this lasts until the end of October or early November. This is represented with the black line on the figures. The summer of 2005 was warmer than 2004 and thus the building used more cooling energy.

Figure 13. Weekly Energy Balance - 2005



1) Science house changes from energy user to energy producer 2) A new piece of equipment was accidentally plugged into Science House and left on 24 hours a day 3) Science House goes into unoccupied mode, equipment except for card reader is turned off 4) Science House becomes net energy user

Calibrated Energy Model

Calibrated models are recommended by the International Performance Measurement and Verification Protocol (IPMVP) for calculating real savings for new buildings when the baseline can only be a hypothetical model. When the goal is zero net energy, there is no need for a hypothetical baseline since the objective is to maintain the energy balance of Equation 1. In the case of Science House, since the annual energy generation is likely to remain more or less constant at about 10,000 kWh, an upper limit on building energy consumption exists. A calibrated model then helps to simulate “what if” scenarios for building occupancy and equipment usage. Different forms of building use patterns through the year can be simulated in advance to check if the energy balance equation will hold true; if not, the building uses can be modified and planned to satisfy the equation.

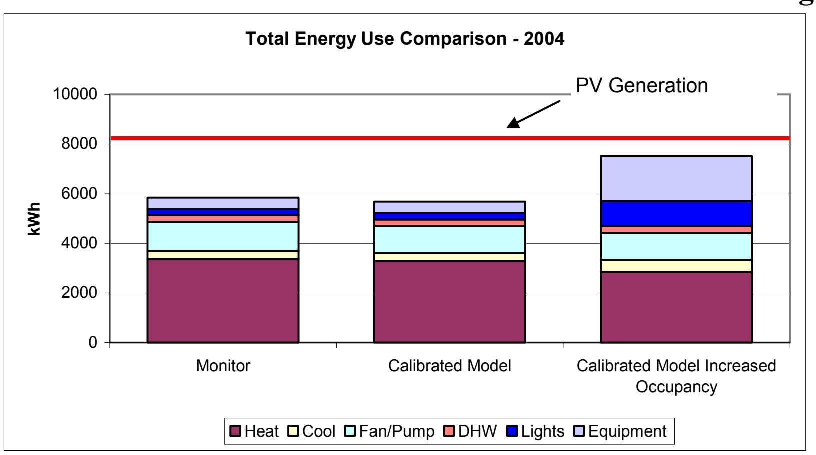
During the first two years of building operation the building has been a net energy producer rather than a zero energy building. Two main reasons for this are that the building has a lower connected plug load than designed for and that it has been occupied less than planned. Both of these variances are common in newly occupied buildings. Over time both plug loads and occupancy will increase to design levels as building operation matures toward original projections. The impact on building consumption from the reduced occupancy is minimal and may be less than expected, since the thermostat does not have a setback mode, thus even when unoccupied the building is still conditioned to occupied temperatures.

In January 2004, the building was occupied sporadically, and mainly in summer. In 2005 too, it was used as expected only during the summer months. Other than those times it is currently used only for special events. During design, the museum staff thought science house would be used year round with reduced occupancy in the fall and winter. This is a significant difference in occupancy. For 2004, the monitoring system showed the building occupied for 1285 hours, the original prediction by the design team for building use was for 2963 hours, a 43% difference. In addition, the connected plug load is lower than assumed during design. The design model used 3,264 kWh per year for plug load operation. In 2004 the actual building used 364 kWh and in 2005 738 kWh were used. All of the equipment, except for the card reader is currently turned off when the building becomes unoccupied. The actual connected plugs loads in the building use 10% of the energy that was assumed in design.

These differences in occupancy and plug load use in the building illustrate the issue with predicting actual building energy use with energy models. The users estimated plug loads and operation based on their past experiences with Science Museum operation and exhibits. Exhibits in the Science House need less energy than they originally expected and the building is not yet occupied during winter. The reduced occupancy plays a smaller role in the reduced energy use than the reduced plug loads.

The calibrated DOE-2 model was made to reflect the building loads as they currently exist and to match the resulting monthly energy use. The monitored data helped to calibrate for existing connected plug load, lighting load, and occupancy schedule for 2004. This calibrated model allows building operators to predict what would happen to the building's energy use if occupancy or plug loads were to change. Figure 14 shows the result of using the calibrated model to predict the energy use if the building were to be operated year round as originally assumed during design, but with the actual connected plug load and temperature setpoints. The increased occupancy bar shows that even in that case the overall energy use of the building would be below the annual energy generated, thus satisfying the energy balance equation.

Figure 14. Calibrated Model Predictions for Increased Building Use



The assumed occupied hours were made during the design phase (2963 hours of use) of the project. If the Calibrated Model is run with these original assumptions, but still using the actual weather and connected plug load, the building would use 7400 kWh for 2004. With this the building would meet the energy goal as 8385 kWh were generated by the PV system in 2004.

Conclusions

The building is meeting its goals of generating more energy than it consumes. The Science Museum is learning how to use the building with a calibrated model so that the generation meets the energy needs of the Science House. The design of a zero energy building requires an energy budget be established early on. The building design and use from there on need to strive to meet that energy budget. The monitoring system helped to identify problems with the building systems at an early stage and avoid energy waste as a result. Without the monitoring system, it would have been difficult to prove the zero energy goal and even more difficult to realize it. In addition, the monitoring system helped while making a calibrated DOE-2 model which allows us to anticipate how changes in the building's operation will affect the energy use. With good integrated design and attention to detail, a zero energy building is in fact possible, but a commitment to zero net energy is required throughout the process and into the building operation.

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