INTEGRATING ENERGY SIMULATION INTO THE DESIGN PROCESS OF HIGH PERFORMANCE BUILDINGS: A CASE STUDY OF THE ALDO LEOPOLD LEGACY CENTER

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ABSTRACT

The Aldo Leopold Legacy Center is designed to be a net-zero energy building. This paper explains how simulation modelling was integrated into the design process to achieve the design goals. Simulation was used to evaluate the building shell, including natural ventilation potential as well as evaluate individual HVAC components. The simulation model was also used to size HVAC equipment and evaluate control strategies. The simulation model underestimated actual energy use. Differences between model and actual energy use are discussed.

INTRODUCTION

Building energy use is a significant fraction of the energy consumed by society, according to the US Department of Energy, 36% of the US energy consumption takes place in buildings. Most of the energy consumed in buildings is the result of fossil fuel combustion, either directly or in the generation of electricty. The carbon dioxide released by global consumption of fossil fuels is the primary human forcing function of climate change and global warming. One major path to reduce human impact on global warming is to design buildings and building renovations that have minimal energy demands and meet those demands with renewable energy rather than fossil fuels. This paper describes a high performance building (in terms of energy demand) that at least matches its annual energy requirements with renewable energy generated annually on site. This balance of energy demand and site based renewable generation defines a net zero-energy building (Torcellini, et al., 2006). To achieve net zero-energy building performance, energy simulation is required to compare design strategies, test control strategies and estimate energy use patterns. This paper describes the integration of simulation modeling into the design of the Aldo Leopold Foundation's new headquarters.

PERFORMANCE GOALS

The Aldo Leopold Foundation promotes an ethical approach to land use by society with an emphasis on stewardship and conservation. When the foundation outgrew its facility in Baraboo, Wisconsin, USA, the board decided to build a new facility representative of their mission. The design process was initiated with a goal setting meeting attended by representatives of the foundation board, the foundation's commissioning agent and design team, including architect, mechanical, electrical and structural engineers, environmental consultant and energy simulation engineer. Prior to this meeting the architect and environmental consultant had developed the spatial program and researched existing high performance buildings. At the meeting, the board stated that the building should be carbon neutral to reflect the environmental mission of the foundation. The board and design team decided that data on the carbon emission cost of the construction was not readily available, especially for manufactured products, so the boundary for carbon neutrality would be operation of the building. Operation was broadly defined to include employee commuting as well as all foundation activities that generated emissions on the site. In addition, the design would produce a net zero-energy building. Annual renewable energy production on site would be equal or greater than annual building energy demand. Electricity and bio-fuels (wood) would be the only energy sources for building operation.

Target goals for the annual energy utilization intensity (EUI) were set at the meeting. A solar photovoltaic system was sized to meet the building demand goals. The design team had studied the energy performance of their previous buildings as well as published EUI values for a number of high performance buildings (Fig. 1). Median energy consumption in US offices buildings is compared with the EUI of four high performance buildings. Energy values for the Chesapeake Bay Foundation in Maryland and the Lewis Center at Oberlin College in Ohio were published by the National Renewable Energy Laboratory (Torcellini, et al., 2005). Energy consumption of the Ordway Campus of the Woods Hole Research Center in Massachusetts was published on the Center web site (Woods Hole Research Center, 2006). The Schlitz Audubon Nature Center, a building designed previously by the architect and environmental consultant, was measured by the author. Based on these measured building performances, the team established 54 kWh per m^2 per year as the energy utilization intensity goal for the Aldo Leopold Legacy Center. For the 930 m^2 of program space, that goal would result in a 50,000 kWh annual energy demand. A 270 m^2 photovoltaic array (polycrystalline silicon) was assumed large enough to provide 50,000 kWh of electricity per year.

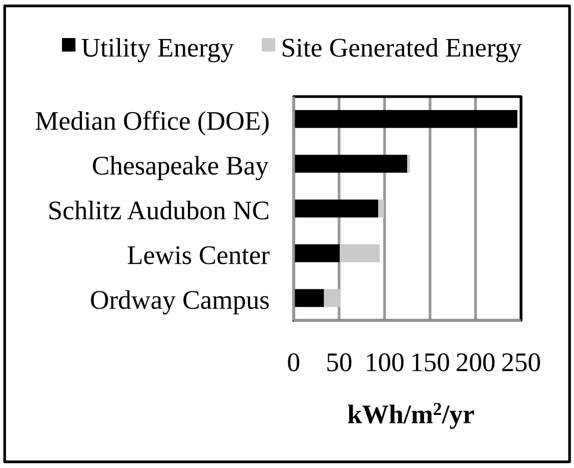

Figure 1 Energy Utilization of High Performance Buildings

Finally, the meeting set more specific design goals for the building:

- All occupied spaces shall be daylit and naturally ventilated.
- HVAC systems shall be off when the building is in natural ventilation mode during mild weather.
- Enclosure insulation levels shall be twice code mandated values.
- Passive solar heating strategies shall be employed.
- Shading shall be designed to permit winter direct sun while blocking direct sun during summer.
- Sensible heating and cooling loads shall be meet by radiantly heated and cooled floors.
- Ground source water-to-water heat pumps shall provide hot water during the heating season and chilled water during the cooling season.
- Ventilation shall be 100% outdoor air with the rate set by code (ASHRAE, 2004). Spaces with variable occupancies shall employ demand controls based on CO_2 concentration.
- Displacement ventilation shall be employed in all occupied spaces.
- Design shall minimize flow friction in ducts and pipes, maximizing fan and pump efficiencies.

INTEGRATING SIMULATION AND DESIGN

Simulation provides design teams with feedback on the expected performance of building designs. The current trend is to develop simulation programs that integrate with 3D CAD and BIM models. The trend often presents simulation as a simple add-on program that attaches to the design program and provides rapid feedback on the energy implications of design decisions. This approach works well for evaluation of building shell thermal loads and daylighting performance. However, integrating HVAC systems into high performance building designs requires the ability to model complex control strategies (e.g., integrating natural ventilation decisions controlled by the occupant). In addition, new technologies proposed for a design may require modification of or development in the simulation program. Therefore, significant additional time in the design process should be budgeted for development and running of multiple design simulations. The simulation program TRNSYS (Klein, et al., 2005) allows time steps in the range of control feedback and permits integration of component models as required. For this building, the simulation program's macroscopic multizone air flow model was modified to model control of natural ventilation systems. In addition, a previously developed component modelling earth tube heat exchangers (Hullmuler, 1998) and a previously developed model of a heat pipe (Thornton, 2004) were integrated into the simulation program.

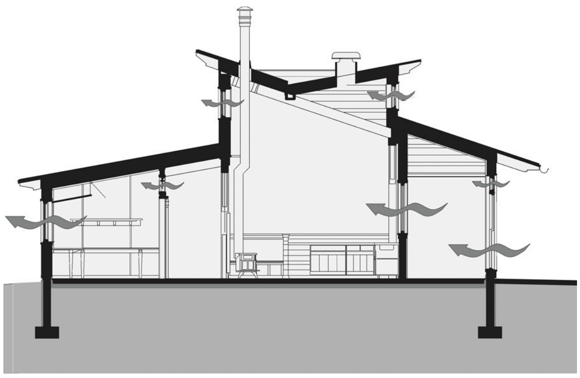

Figure 2 Building Cross-section at Offices

As the design began, the simulation program was used to model shell thermal loads and natural ventilation. An energy rate control model was used to determine the hourly heating or cooling load based on minimum and maximum space temperatures. Based on an experiment comparing measured and modelled natural ventilation at the Schlitz Audubon Nature Center (Bradley, et al. 2006), the simulation engineer modified CONTAMW, a multi-node bulk flow pollution transport model (Dols, et al. 2002), to be a natural ventilation component of the simulation program. The web based program CpGenerator (Heijmans, et al. 2003) was employed to develop a table of exterior wind pressure coefficients for the building surfaces. The cross-section of the office spaces in the building (Fig. 2) shows provision of cross-flow and clerestory ventilation strategies. The simulation model indicated that the clerestory windows were not as effective for air flow. As a result of the natural ventilation analysis, the number of operable windows in the clerestory was reduced by half.

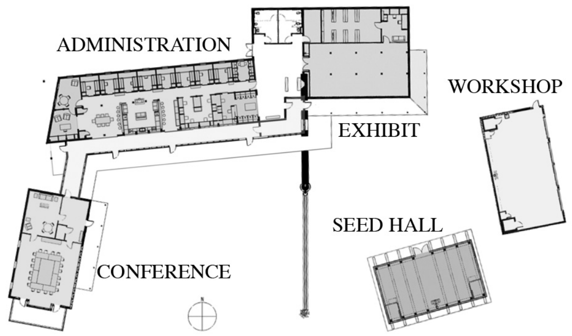

Figure 3 Aldo Leopold Legacy Center Plan

The building program grew during design from 930 m^2 to 1240 m^2. The plan (Fig. 3) illustrates the for main components of the program: an unconditioned garage/workshop; an unconditioned three season classroom (Seed Hall); a conditioned conference wing; and conditioned offices, exhibit and archive spaces. The conditioned spaces total 830 m^2. The HVAC system for the offices, exhibit and archives is described below.

While the design team recommended radiant floor slabs for the conference wing the foundation board wanted an insulated wood floor. The conference space uses a water-to-water heat pump with fin-tube convectors located around the exterior of the space for heating and a cooling coil located in the ventilation air stream for space cooling. Ventilation is provided by an enthalpy ventilator that is only operated when the conference wing is occupied (once per week in the simulation model). The system is designed to maintain 13°C in the space during the winter with a wood burning stove used to bring temperatures into comfort when the space is occupied.

The Seed Hall is somewhat unique as an occupied space without HVAC system. The Aldo Leopold Foundation offers classes to land owners in conservation, prairie restoration and forest management. Classes are typically offered during spring, summer and fall. The Seed Hall is provided with removable storm windows and screens and has operable clerestory windows. A wood-burning stove provides heating as required during spring and fall. The space is closed during winter. While the Seed Hall and the workshop did not have HVAC systems, an estimate of plug and light loads in those buildings was included in the simulation model.

Simulation models were used to compare differing HVAC strategies for the main building. The Wisconsin climate has a six to seven month heating season with an average January temperature of -9.4°C. As the building was designed for 100% outdoor air ventilation, tempering the outdoor supply air would be required. Enthalpy heat recovery ventilators were compared with earth tube heat exchangers. Simulation models of each component were constructed with Madison, Wisconsin TMY2 weather data and programmed ventilation rates set as inputs. The results indicated that enthalpy recovery ventilators worked much better during heating and earth tubes worked much better during cooling. On an annual basis, enthalpy ventilators saved more energy than earth tubes if fan power was neglected. However, when fan power was included, earth tubes resulted in lower annual energy expenditures. Earth tubes were installed between the outdoor air intake and the air handling unit. The details of this analysis as well as comparison of modelled and measured data is presented elsewhere (Bradley, 2009).

The design concept for the HVAC system was to use radiant slabs to provide sensible heating and cooling. During the cooling season, entering ventilation air would be dehumidified to 10°C and reheated to 18°C. During the heating season, ventilation air was tempered to 20°C. The system was designed to operate in either heating or cooling mode, but not both. Natural ventilation was assumed to be the controlling mode of operation during spring and fall. The load side of the HVAC system (fig. 4) illustrates the multiple zones for both radiant slab and ventilation. A 1,900 liter storage tank serves as a thermal capacitor between the ground source heat pumps and the load. The storage tank is maintained between 40°C and 45°C during the heating season and 5°C and 10°C during the cooling season. The tank temperature dead band is appropriate for the coil in the air handling unit. A mixing valve on the radiant slab return permits slab temperature control. Variable frequency drive fans and pumps allow the system to respond to energy demands in any zone or the whole building. Placing a storage tank between the ground source heat pumps and space loads isolates the heat pumps from the loads. The heat pumps can operate at design load to charge the storage tank with hot or chilled water. The HVAC system model was constructed separately from the building shell. Components were added and tested. The simulation results for the shell and components of the HVAC system were shared with the design team via e-mail providing ongoing feedback throughout the design process. When the model was complete, it was integrated with the building shell model.

The full building simulation also included models of the photovoltaic panels and the solar thermal panels used to provide service hot water. Temperature level controls were modelled for all HVAC systems, meaning that the building model did not calculate energy loads and then impose them on a system but simply reacted to the conditions of the liquid and air streams introduced into the zones by the HVAC system and controls. A time step of 5 minutes was

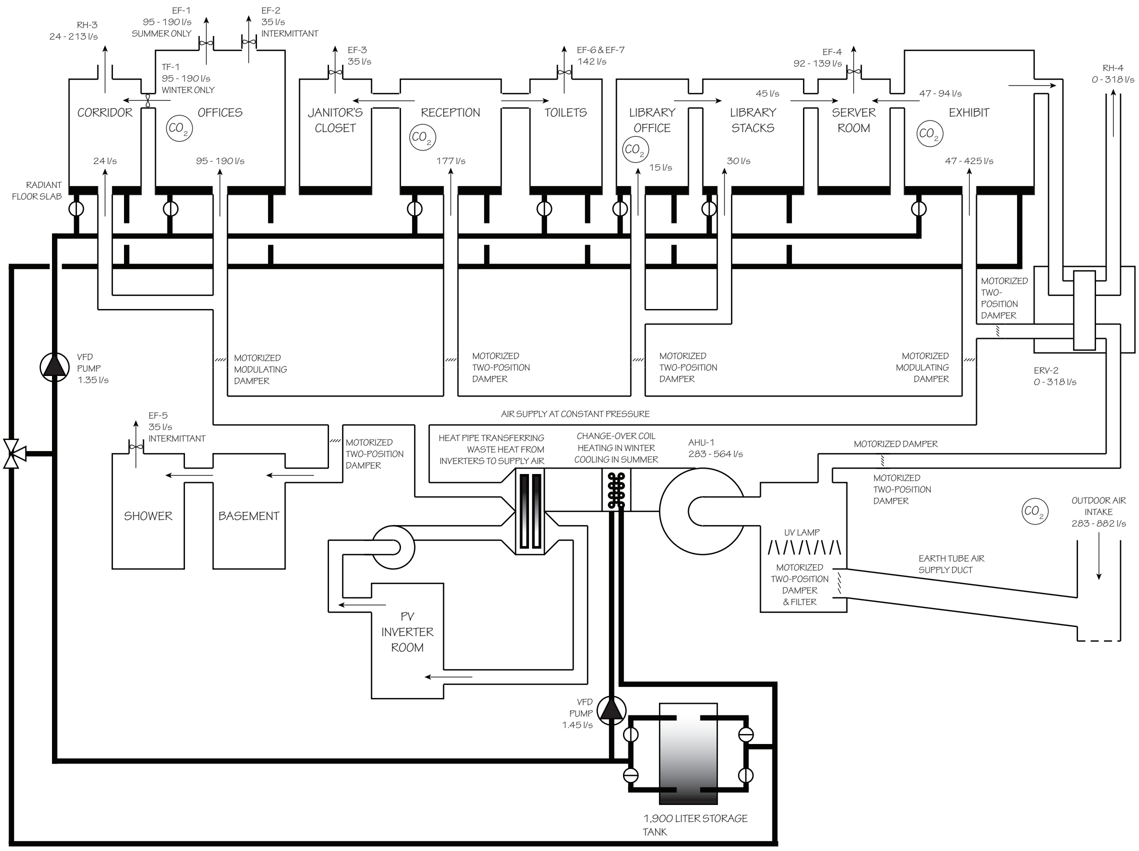

Figure 4 HVAC System Schematic, Load Side

used for the simulation. Decisions made by building occupants had to be considered as well. Occupants controlled lights, the decision to move into or out of natural ventilation mode and the decision to use a wood burning stove or fireplace. The design team decided not to model the wood burning stoves or the fireplace. Rather, the actual wood use would be monitored as a part of the total building energy use.

Rather than use automatic dimming controls, lights in the building would be switched on and off by the occupants. Observation of occupant control of lights at a Milwaukee, Wisconsin nature center (Sanati, 2009) was used to develop an empirical control for illumination levels in the building simulation. The percentage of lights modelled as on during occupancy was set as a step function of exterior solar radiation level as indicated in Table 1.

Table 1

Light Usage Model

Global Solar Radiation Intensity	Light Level during Occupancy
0 to 200 Watt per m^2	100% On
200 to 400 Watt per m^2	67% On
400 to 600 Watt per m^2	34% On
Above 600 Watt per m^2	All Off

The natural ventilation control model was developed from observations of natural ventilation in two nature centers located in Milwaukee, Wisconsin (Utzinger, 2009). Occupants tended to open all available windows when outdoor air temperatures exceeded 20°C and would open windows minimally when outdoor air temperatures dropped below 13°C. An additional control required for this building was the need to avoid condensation on the cool slabs during the cooling season. The building was assumed to be in natural ventilation mode when the ambient dry bulb temperature was between 13°C and 27°C and the absolute humidity ratio was less than 0.014. This constraint was programmed into the operator interface to the building controls system. "Conditions favourable for Natural Ventilation" was posted on the main screen of the operator controls interface when dry bulb temperature and humidity conditions were met and the statement "Conditions Not favourable for Natural Ventilation" was posted otherwise. Operable window opening area was assumed to vary linearly from 0% at 13°C to 100% at 21°C. When the building was in natural ventilation mode, the simulation model assumed the HVAC system was shut down. The actual building control system was programmed to shut down the HVAC system when the operator switched the building to natural ventilation mode. The entire hybrid ventilation simulation model has been described elsewhere (Bradley, 2007).

Finally, the shell simulation model was used to size the mechanical systems. TMY2 meteorological data for Madison, Wisconsin, a location 50 miles from the building site, was used to drive the simulation. The hottest and coldest conditions in the TMY2 file exceeded the design values for heating dry bulb and cooling dry bulb plus coincident wet bulb. The simulation was structured to match the largest expected occupancy load with the hottest summer weather. Heat pumps were sized to meet the largest expected load from the simulation model. Using the shell simulation model to size HVAC equipment is not a normal approach to system sizing and was not entirely supported by the simulation engineer. However, experience from a number of building system designs suggests that standard equipment sizing algorithms generate larger heating and cooling equipment capacities than the peak loads observed in annual simulations. The design team did not want to over size equipment and so used simulation results (with owner approval) to size equipment. On the cooling side, over-sizing equipment leads to cool, but moist conditions as the equipment cycles on and off under the design load and dehumidification is reduced. On the heating side, the design team and owners felt the wood burning stoves provided a backup to extremely cold weather. Never the less, the simulation engineer was concerned over liability associated with sizing equipment from the simulation. Had the equipment been sized using standard procedures, the heat pumps would have been larger. Details of simulation modelling of the earth tubes, the conference wing HVAC system and heat pipes for waste heat recovery from the photovoltaic inverters are described elsewhere at this conference (Bradley, 2009).

MODELLED AND MEASURED PERFORMANCE

The simulation model provided the design team and building owner with feedback on building operation and whether the goal of net zero-energy use was attainable. The simulation was also used to provide energy use requirements for LEED™ version 2.1 certification.

The United States Green Building Council provides LEED™ rating procedures as a means of certifying the environmental performance of building designs. As a part of that certification, energy savings is estimated by comparing energy requirements estimated by the building simulation (referred to as the Design Energy Case or DEC model) with the energy required if the building were designed to code requirements only (referred to as the Energy Cost Budget or ECB model). The simulation engineer developed a complete model of the building with code levels of insulation and glazing parameters, a boiler for heating and cooling tower with water-to-air heat pumps for cooling. In addition, as part of a LEED™ Innovation and Design credit for carbon neutral operation, a third model, the Carbon Neutral Case (CNC) was simulated.

Energy consumed as part of the plug loads, referred to as unregulated loads, (computers, copiers, etc.) is modelled, but not included in the DEC and ECB comparison. Energy used for lights, heating and cooling, ventilation, hot water, pumps and fans are considered to be regulated loads and are the loads USGBC compares between the DEC and ECB. Occupant control of lights is not permitted in the DEC model. Lights were assumed to be 100% on during occupancy. Original electricity generation estimates were based on 180 1.5 m^2 panels with a rated output of 165 watt peak per panel. The final installation was 198 1.5 m^2 panels with a rated output of 200 watt peak per panel. The entire array was rated 39.6 kW peak. The CNC model included the occupant lighting control model described above. The CNC model compared total modeled energy demand to energy supplied from the photovoltaic array. Wood consumed in the fireplace and three wood stoves was ignorred in the simultions.

Table 2

LEED™ DEC and ECB Model Comparisons with CNC Model - Values in kWh

	ECB Model	DEC Model	CNC Model
Total Energy	131,040	62,100	54,230
Unregulated Energy	11,680	11,680	11,680
Total Regulated Energy	119,360	50,420	42,550
Illumination	26,370	21,820	13,400
Space Heating	75,330	16,922	18,260
Space Cooling	4,340	3,150	2,320
Pumps	4,760	2,870	2,890
Fans	6,150	4,930	4,930
Service Water Heating	2,420	710	730
Renewable Energy	0	61,250	61,250
Net Regulated Energy Demand	119,360	-10,830	-18,700
Net Energy Demand	131,040	850	-7,020

The modelled energy requirements for the LEED™ submission are listed in Table 2. The LEED™ DEC model total energy demand is 47.4% of the code based ECB energy demand. The CNC model, which includes occupant control of the lights, has a total energy demand equal to 41.4% of the ECB energy demand. The CNC model predicts occupant control of lights will reduce building energy demand by 12.7% (CNC model compared with DEC model). Energy consumed by lighting drops 8,420 kWh, a reduction of 38.6% of the DEC model illumination energy. The CNC model predicts annual electricity produced by solar energy on site to exceed annual building energy demand by 7,020 kWh (12.9% of the annual energy demand). These results gave the design team confidence that the design would meet the goals.

Too estimate the impact of natural ventilation and the earth tubes used to pre-treat ventilation supply air, Natural ventilation reduced energy demand by 1,160 kWh per year, 1.9% of the total building energy demand and 4.9% of the total heating and cooling energy requirements. The earth tubes reduced total energy demand by 1,110 kWh per year, 1.8% of the total energy demand and 4.8% of the total heating and cooling requirements.

To provide detailed performance data permitting analysis of actual building performance, the building controls system was structured to archive data from the control points; sub-meters for lights, plug loads and some of the HVAC equipment; photovoltaic panels and weather data. The local utility metered electricity flowing from the grid to the building and from the building to the grid. Wood use for space heating was not modelled in the simulation. To account for actual usage, the foundation staff set out two cords of wood for spacing heating use in the winter of 2007-2008. One cord of white oak fire wood has a mass of roughly 1.54 metric tons, and an energy content of roughly 8,500 kWh. The energy content of the two cords is 31% of the annual estimated energy demand of the CNC model.

Monthly modelled and measured electric energy consumption are presented (Fig. 5). Negative values indicate net flow of electricity from the grid to the building for the month. Positive values indicate net flow of site generated solar electricity to the grid. Wood combustion is not included in the figure. The Carbon Neutral Case and Energy Cost Budget simulation results are compared with utility net-metered data. While actual energy use is reasonably similar to the Net Zero model from May through October, the building consumed more energy during winter than expected. The net zero simulation estimated a net flow of 7,570 kWh from the building to the grid. The actual metered data indicate a net flow of 20,900 kWh from the grid to the building, a difference of 28,470 kWh. There are a number of reasons for the differences between model and actual performance. First, the winter was colder than normal and included the largest winter snowfall on record, over three meters. The photovoltaic panels were covered in snow for most of December, January and February. The local utility purchased over 1,000 kWh of solar generated electricity in November and over 2,000 kWh in March. The total purchased in December, January and February was 120 kWh. While this level of snow is extreme, the average winter snowfall is roughly 1.3 meters, it should be accounted in modelling (it wasn't). This winter the contract for snow removal from the walks and parking included removing snow from the solar panels. Another potential issue with the photovoltaic system is a difference between the modelled production of 1,550 kWh per year per kW peak installed and the

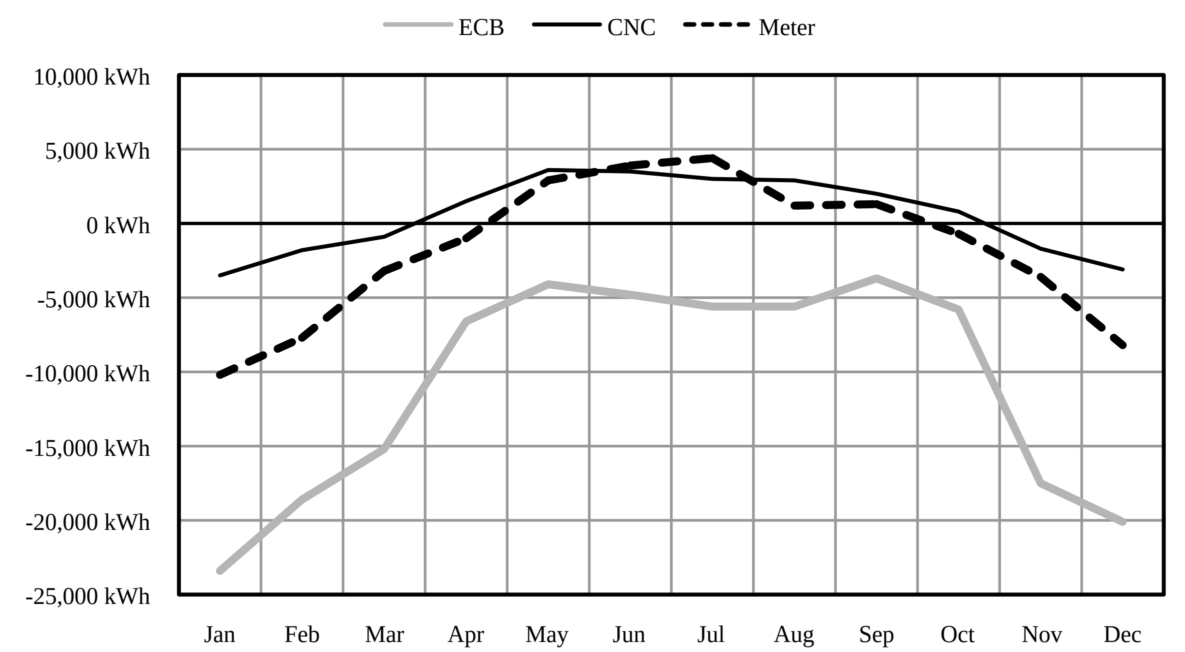

Figure 5 Modelled and Measured Monthly Energy Demand

rule of thumb of 1,200 kWh produced per kW peak installed suggested by Wisconsin Focus on Energy. For the Aldo Leopold Legacy Center, this difference amounts to a difference of 13,790 kWh in annual production. The authors have compared the TRNSYS photovoltaic model with measured data from another building (Utzinger, 2005) and found that the inverters had a built-in maximum power limit. Actual solar power available was 15% to 25% greater than AC electricity produced. The authors intend to look at the actual performance data of the Aldo Leopold Foundation photovoltaic system with the simulation model in detail.

Second, the conference wing HVAC system did not perform as designed. The original specification was that the HVAC system would maintain 13°C during winter and the wood-burning stove would be used to bring the room up to 20°C when the space was occupied. The wood stove that was installed did not have a high heat output and could not bring the room up to temperature. The heat pump/convectors were not able to maintain 20°C (there was no excess capacity in the design). As a result, the heat pump ran constantly during winter. During the past summer, the wood stove was replaced with a stove of larger capacity. During winter 2008-2009, the HVAC system has returned to maintaining 13°C and is functioning as intended. When meetings take place, the new wood stove is stoked two hours prior to the meetings and warms the room satisfactorily.

Finally, sub-meters monitoring lights and plug loads indicated differences between modelled and actual usage. The plug loads in the building and electric use in the workshop and seed hall were estimated in the simulation model to be 11,680 kWh per year. The measured use was 21,760 kWh the difference is 35% of the total difference between model and measurement. Actual light usage was 7,030 kWh compared to 13,400 kWh estimated in the net zero model and 21,820 kWh in the DEC model, which assumed all lights on during occupancy. Measurements indicate lights were used less than one third of the occupied hours. The 6,370 kWh difference between measurement and model would indicate a reduction of actual energy use rather than the increase measured over the model. Variation between model and measurement for occupant switched light loads and plug loads point to the uncertainty modellers face estimating these energy flows. The difference of 10,070 kWh in the plug loads is 19% of the total estimated energy demand. The 6,370 kWh difference in lighting use estimates is 12% of the total estimated demand.

The original goal for the building was an energy utilization intensity (EUI) of 54 kWh per m^2 per year. That goal is compared with measured and modelled EUI in Table 4. The CNC simulation model exceeds the design goal by 20% (43.7 kWh/m^2/yr). The measured EUI is less than 10% higher than the original goal when wood use is neglected. Wood use should be included in any overall energy balance. Actual wood use was 2.75 cords and represents 24% of the total measured energy demand. The measured EUI with wood use neglected is 36% greater than the modelled CNC EUI (which also neglected wood use). While this number may be larger than desired, it may be a reasonable reflection of climate variation, uncertainties in plug load estimates, uncertainties in occupant behavior, and actual system operation falling short of specification. The Aldo Leopold Foundation has replaced the poorly functioning wood stove. This winter is closer to a typical winter and wood use is expected to be half of the first year's usage.

Table 3

Comparison of Measured and Modelled EUI

	EUI
Design Goal	54.0 kWh/m^2/yr
Median US Office	246.0 kWh/m^2/yr
Energy Cost Budget (ECB)	105.7 kWh/m^2/yr
Net-Zero Energy (CNC) Model	43.7 kWh/m^2/yr
Measured w/o Wood	58.6 kWh/m^2/yr
Measured with Wood	77.5 kWh/m^2/yr
Measured net Grid EUI	16.2 kWh/m^2/yr

CONCLUSION

This paper presents a detailed case study of simulation modelling supporting the design of a high performance building. Modelled energy demand was 36% less than measured energy demand. Although the variation is higher than the design team would like, the simulation process did provide valuable information to the designers that helped shape the final design. The building was not net zero in its first year of operation, 16.2 kWh/m^2/yr net flowed from the utility grid to the building. While this demand on the grid is very low for buildings, the design team and the Aldo Leopold Foundation continue to modify the building operations and are hopeful of achieving a net zero-energy building by the 2nd or 3rd year of operation.

Simulation of building performance is a requirement for LEED™ certification by the USGBC. Recent studies suggesting LEED™ buildings perform 33% better than typical building stock (Turner, 2008) have been challenged (Malin, 2008). The study of LEED™ buildings compared their performance to average performance of buildings constructed over the past 30 years. Since the LEED™ buildings were primarily constructed since 2000, the critique suggested that the comparison should be against recent code compliant buildings (compare the difference between the median office EUI in Table 4 and the ECB model for the Aldo

Leopold Foundation). If this criticism is valid, many building simulations are not assisting design teams in the production of high performance buildings.

The authors believe that high-performance buildings are characterized by complex HVAC systems that handle multiple zones, varying loads, and the potential of occupant interaction to initiate natural ventilation, lighting, and other responses to maintain thermal, visual and acoustic comfort. This requires simulation models that can integrate control strategies, combine new models of new components and a process of evaluating building parts as well as the whole system during the design. To increase confidence in the simulation models, designers and simulators must collect measured data on the actual performance of the building permitting validation or modification of the simulation models. The Aldo Leopold Legacy Center represents an example of simulation integration into the design process from schematic design to post occupancy evaluation.

ACKNOWLEDGEMENT

The author served as environmental consultant and the co-author served as simulation engineer for the Aldo Leopold Legacy Center. The Aldo Leopold Foundation kindly provided building performance data.

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