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Early Performance of a Green Academic Building[*]

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ABSTRACT

The energy performance for the first 24 months of occupancy of Oberlin College's Adam Joseph Lewis Center, a recently constructed, 13,600 ft^2 (1,263 m^2) green academic building in NE Ohio is described. The building, advertised as a model of sustainable construction, boasts an impressive list of green technologies including a 4,700 ft^2 (435 m^2) rooftop photovoltaic (PV) array. Data are presented for building energy consumption and for energy generation by the PV array. The annual energy consumption is shown to be 3 times higher than originally projected and 3-4 times the amount produced by the PV array. The building's combined on-and off-site energy consumption is no better than that for a comparable, conventional building. Details of the building design are presented and examined. Results of heating and ventilation simulations based on these details are presented which are consistent with performance data. Major HVAC problems are identified and changes proposed which simulations suggest will significantly lower energy consumption. Various lessons learned are discussed.

INTRODUCTION

The construction and operation of buildings is responsible for a large portion of the energy consumed in this country. Most of this energy is supplied directly or indirectly through the burning of fossil fuels. With dwindling oil and natural gas supplies and growing concern for the atmospheric effects of the CO_2 produced in their combustion there is increasing interest in green buildings – buildings that are designed and constructed so as to reduce their environmental impact. One of the most important considerations for such a building is its energy consumption.

Increasing interest in green design is evidenced by the growth in *Environmental Studies* and *Environmental Science* programs at colleges and universities around the U. S. In the last few years many such programs have either constructed or initiated a design process to construct *Environmental Studies Centers* (ESC), academic buildings that provide both facilities and a visible focal point for these programs. These buildings are intended either to showcase energy-efficient and renewable technologies or, by their very construction and operation, to embody green ideas, providing working examples of the green design process [Perrin, 2001].

This paper considers one such building, the *Adam Joseph Lewis Center*, on the Oberlin College campus in NE Ohio. Building construction was completed in January 2000 and the building has been in operation for just over two years. In addition to showcasing energy-efficient technologies this building also includes a photovoltaic (PV) array and an on-site, organic waste-water-treatment system. The waste-water system is intended to process all the building's waste and the PV array is intended to produce more energy annually than the building consumes, making the building a "net-energy exporter" [Gabrielli, 1995].

Here the author describes the building, its thermal envelope and HVAC systems, and presents energy-consumption and PV-production data for the first 24 months of occupancy. Energy consumption, largely associated with winter heating, is found to greatly exceed original projections for the building. To understand this energy simulations are performed for the "as-built" structure. The resulting projection for heating and ventilation energy-use is consistent with actual building performance and greatly exceeds earlier projections. A variety of problem areas are identified and specific changes to the HVAC systems are proposed.

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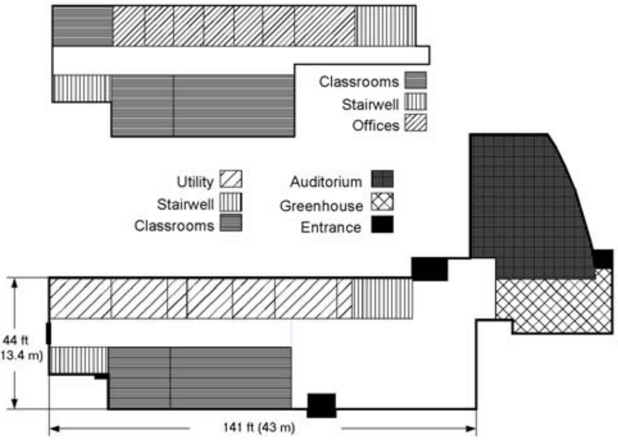

Figure 1. *Floor layout for the ESC.*

BUILDING DESCRIPTION

The *Environmental Studies Center* (ESC) under study is a recently constructed, all-electric, 2-story, 13,600 ft^2 (1,263 m^2) college/university classroom building located in NE Ohio. The building, whose design received two 1999 architectural awards, was conceived to be a showcase of green construction and a model of sustainable architecture [Gabrielli, 1995]. Groundbreaking was in September 1998 and construction was completed in January 2000. The total project is budgeted at $7.0M, which includes $5.0M for construction, furniture, and equipment, $1.5M for fees and expenses, and a $0.5M endowment.

The floor plan for the building is shown in Figure 1. The building contains 7 offices, 4 classrooms[2], a conference room, a 100-seat auditorium, a large, open atrium, and an attached greenhouse, home of the organic waste-water-treatment system. Both 1st and 2nd floor hallways open to the atrium. 1st and 2nd floor classrooms (west end), the atrium, and green house (east end) have southern exposure as shown in Figure 2. Offices and the conference room are located on the north side of the 2nd floor. The auditorium, utility rooms, kitchen and restrooms are located on the north side of the 1st floor where they receive little or no natural lighting. A north view of the building is shown in Figure 3.

Technologies

The building incorporates a variety of old and new energy-efficient design strategies. It is oriented so as to receive maximum solar exposure. Bountiful glazing, mostly on the south and east sides, captures natural lighting and solar heat gain and provides natural lighting for all occupied spaces with the exception of the auditorium where windows are not desirable. Concrete floors and block walls provide thermal mass for storing heat energy. A roof overhang on the south side limits direct sunlight through windows in the summer months. While not yet installed, a vine trellis is planned for the south atrium wall to provide summer shading.

Figure 2. *A south-eastern view of the building showing the on-site waste processing system (on right), atrium (center) and 1st and 2nd floor classroom windows (left).*

Figure 3. *A north view of the building showing the auditorium (left), 2nd floor office windows, and upper windows that light the 2nd floor hallway.*

Exterior walls are roughly a foot thick consisting (from outside to inside) of brick facade, insulation/air space, and cement blocks. Walls and floors have considerable heat capacity. Expanded and extruded polystyrene panels provide R-30 roof and R-21 wall insulation. Structural support is provided by steel I-beams. Atrium windows are low-e coated, triple-pane, argon filled units with a glazing R-value of 8.3 (not accounting for metal frames). Other windows are double-pane units with glazing R-values of 3.3. Heating and cooling for offices, classrooms, and the auditorium is provided by water-source heat pumps connected to a closed-loop ground well system. The two primary (atrium) entrances incorporate double-door vestibules for limiting infiltration. The atrium includes automated windows that open under computer control to provide convective cooling when appropriate.

Most rooms have occupancy sensors to minimize energy for artificial lighting and many incorporate CO_2 sensors that are monitored by an HVAC computer control system for limiting make-up air as required.[3] All occupied rooms are zoned separately. The control system monitors and controls individual room temperatures with

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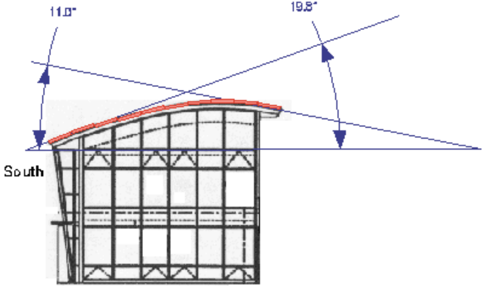
[2] The second floor small classroom is being used for a library/reading room.

[3] While CO_2 sensors have been installed, a demand-driven ventilation strategy has not been implemented in part due to the fact that all fans are fixed speed.

a complicated building schedule to minimize energy use. Outside air intake and exhaust are controlled through two central locations where energy recovery ventilators (ERV) extract energy from return air with up to 78% efficiency.

Rooftop Photovoltaic (PV) Array

The main roof of the ESC supports a 4,680 ft^2 (435 m^2), 45 kW, crystalline silicon PV-array consisting of 690, 85 W modules. The modules are mounted on the curved roof in 10 rows, each row with a fixed tilt angle, as shown in Figure 4. The tilt angles range from 20°S for Row 1 to nearly 10°N for Row 10. The modules are grouped into three identical sub-arrays, each connected to its own 15 kW inverter and isolation transformer. The 208 V, three phase secondaries of the three transformers are connected in parallel, then fed through a billing meter to the building power distribution system.



row	tilt angle
1	20
2	19
3	17
4	16
5	14
6	9
7	4
8	0
9	-4
10	-10

Figure 4. Drawing for ESC atrium east wall showing angles for curved main roof. (Taken from construction drawings.)

The author has performed simulations using hour-by-hour TMY2 (typical meteorological year) data for the region. These simulations use manufacturer's specifications to account for losses due to heating, inverter efficiency, and transformers, and also account for Fresnel scattering at large incident angles. Calculations show that annual energy output of the PV-System (array/inverters/transformers) should average 67,500 kW-hr [Scofield, 2002]. This figure does not account for nighttime transformer losses. The projected monthly output is represented by the crosshatched bars in Figure 5. As the graph clearly shows most of the energy production will occur during summer months.

The PV-Array was installed and tested in Fall 2000 and became operational in mid-November. Energy production for the calendar year 2001 is represented by the solid bars in Figure 5. Some of the December through February deficit is associated with un-melted snow sitting on the array. May 2000 output is reduced because the array was inadvertently turned-off for three days. Deficits for other months are not yet understood. The total energy production for 2001 was 59,166 kW-hr, 12% below projections.

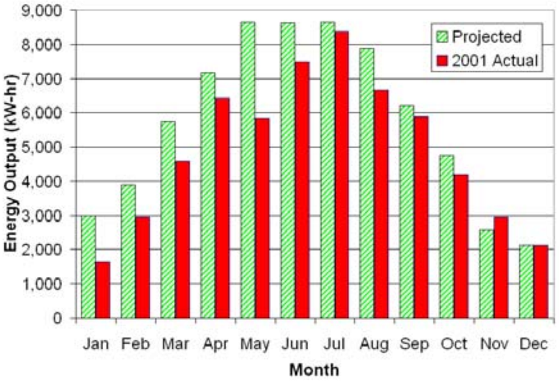


Figure 5. Projected (cross-hatched) and measured (solid) month-by-month AC energy output for PV-array system at the secondary of the isolation transformers.

Including the effects of snow and assuming that the inverter performance may be improved, the projected annual energy production for the PV-array then is about 65,000 kW-hr. This corresponds to a monthly energy contribution of 5,400 kW-hr and an average power of 7.4 kW. If the building is to achieve its goal of becoming a "net-energy exporter" these numbers establish the target level for the annual building energy consumption.

TWO YEAR BUILDING ENERGY USE

In contrast to the typical campus building, the ESC is not connected to a central plant nor does it use natural gas. The only non-solar energy imported into the building is electricity from the grid through a 500-kVA power transformer. A billing meter connected to the transformer primary measures energy flow in one direction only, into the building. The transformer and meter are shown in Figure 6.

Figure 6. Photograph of electric enclosures on west end of ESC showing meter (foreground) and 500 kVA building transformer (background).

Monthly electric meter readings have been recorded since October 1999 and meter readings have been logged on 15-minute intervals since construction was completed in January 2000. A second meter was added in November 2000 to record energy output from the PV isolation transformers. Both meters record energy flow in just one direction only. The monthly readings for the grid and PV meters are listed in Table 1 (1 MW = 1000 kW).

In 2000 and 2001 the building purchased 339,886 kW-hr of energy from the grid, of which an estimated 17,000 kW-hr went to its parking lot lights[4] and another 19,000 kW-hr to transformer losses.[5] In the same 24-month period the rooftop PV-array produced a total of 60,803 kW-hr of energy, some of this being exported to the grid.

Before the PV array became operational the building energy consumption was simply equal to the energy purchased from the grid. With the PV array in operation things are more complicated, since neither meter records energy exported to the grid. Upper- and lower-bounds for building energy consumption are calculated from data logged from both meters on 15-minute intervals.[6] The monthly energy consumption E is estimated to be the average of these two numbers with an uncertainty ΔE given by half the difference; both are listed in Table 1. Cumulated values for the 12-preceding months are listed in Table 1 along with their uncertainties. Shaded rows are affected by energy associated with construction.

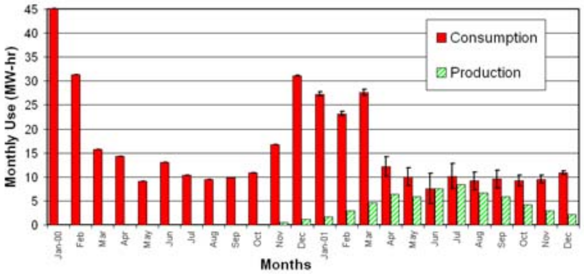


Figure 7. Monthly energy consumption (solid) and production (cross-hatched) data. Error bars on consumption figures represent upper- and lower-bounds calculated from billing meters (see text).

TABLE 1

Meter readings and calculated building energy consumption (1 MW-hr ≡ 1000 kW-hr). For

Month	Grid (kWh)	PV (kWh)	E (MWh)	ΔE (MWh)	12-mos (MWh)	(MWh)
Oct	20,460	0	20.5	0.0	avg.	uncert.
Nov	27,420	0	27.4	0.0		
Dec	26,040	0	26.0	0.0		
Jan-00	45,180	0	45.2	0.0		
Feb	31,320	0	31.3	0.0		
Mar	15,780	0	15.8	0.0		
Apr	14,340	0	14.3	0.0		
May	9,120	0	9.1	0.0		
Jun	13,020	0	13.0	0.0		
Jul	10,320	0	10.3	0.0		
Aug	9,480	0	9.5	0.0		
Sep	9,780	0	9.8	0.0	232	0
Oct	10,860	0	10.9	0.0	223	0
Nov	16,200	507	16.7	0.0	212	0
Dec	30,011	1,130	31.1	0.0	217	0
Jan-01	26,089	1,643	27.3	0.4	199	1
Feb	20,700	2,960	23.2	0.5	191	1
Mar	23,711	4,579	27.6	0.7	203	1
Apr	7,814	6,430	12.2	2.1	201	2
May	6,003	5,840	10.0	1.8	202	3
Jun	3,202	7,496	7.6	3.1	196	4
Jul	4,382	8,381	10.1	2.6	196	5
Aug	4,322	6,678	9.2	1.8	196	5
Sep	5,483	5,880	9.5	1.8	195	6
Oct	6,188	4,197	9.2	1.2	194	6
Nov	7,405	2,947	9.5	0.8	186	6
Dec	9,176	2,135	10.9	0.4	166	6
Totals	**413,806**	**60,803**	**457.2**	**5.9**		

* The building was still under construction.

Monthly energy consumption (solid) and PV energy generation (open) figures for the 24 months of occupancy are graphed in Figure 7. Error bars on the consumption figures indicate uncertainties as discussed earlier.

Annual energy consumption figures are graphed in Figure 8. The first three points are inflated because they include data from Fall 1999 while the building was still under construction. The growing PV production and decreasing building consumption for summer months makes it increasingly difficult to calculate building energy

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[4] The building parking lot lights, installed in Feb. 2000, are fed from the building electric panels. They consume 2.0 kW of continuous power.

[5] Estimated from data supplied by the manufacturer, which include continuous core losses of 0.857 kW.

[6] For any time interval for which the grid meter reads zero while the PV-meter is positive one can only say that the building energy consumption during this period lies between zero and the PV-meter reading.

use after March 2001 using just these two meters.[7] Annual energy consumption declined in November 2001 owing to operational changes combined with unusually warm weather. In round numbers, annual energy consumption has been about 200,000 kW-hr, though it has declined with system optimization.

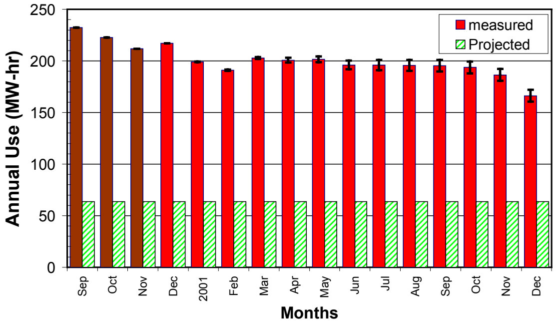

Figure 8. Annual energy consumption as measured (solid bars) and architect's projections (striped bars). First three measurements are inflated because they include construction energy.

Clearly the dominant energy use for the building occurs in the winter months and is associated with heating and ventilation. Note that excessive 1999 energy use is associated with construction.

For the first two years of occupancy the annual energy use for this building is (192,000 ± 3,000) kW-hr corresponding to an annual site energy intensity of 48,000 Btu/ft^2 (540 MJ/m^2). The projected annual energy production for the rooftop PV-Array is 65,000 kW-hr, just under 1/3 this amount. For the rooftop PV-Array to make this building a *net energy exporter* the annual building site energy must be reduced accordingly to 16,300 Btu/ft^2 (185 MJ/m^2). This corresponds to the target energy consumption that has long been used for this building [Reis, 2000].

Figure 7 shows that even in spring/fall months there is a constant energy load of about 10,000 kW-hr per month. This represents a non-seasonal load of 120,000 kW-hr for lighting, pumps, transformer losses, ventilation fans, and other equipment. Rough estimates for these loads are shown in Table 2. Estimates are based on isolated measurements, equipment data sheets, and numerical simulations.

TABLE 2

Breakdown of non-seasonal energy.

Category	Annual E (kW-hr)
HVAC fans	25-40,000
domestic hot water	4-6,000
building power transformer	10,000
PV isolation transformers	7,000
waste-water treatment	20-22,000
parking lot lights	8,800
interior lights	10-15,000

Another 72,000 kW-hr of energy is associated with heating (Oct.- Apr). Clearly heating and ventilation represent the largest component of the building energy

Comparison with Conventional Buildings

It is useful to compare this building's energy-use with that for buildings of conventional construction. Two comparisons are made, one with data from a national database and the second with other academic buildings on the same campus.

The *DOE Commercial Building Energy Consumption Survey* (CBECS) database gives estimated annual energy use for thousands of commercial buildings throughout the U. S. Two forms of energy are relevant – *site energy* and *source energy*. Site energy is simply the sum of all energy used at the building site, regardless of the energy form (gas, coal, fuel oil, electric, etc.), in some common unit, say Btu. Source energy is a similar sum, but one in which electric energy is weighted by a factor of three to account for the 30-35% efficiency of off-site electric generation. While more difficult to calculate, source energy, provides a more-appropriate comparison between two buildings for determining which has the greater operating costs and environmental impact.

As mentioned already the site energy for the ESC is 48,000 Btu/ft^2 (540 MJ/m^2). Since all of its energy is electric, this corresponds to a source energy of 144,000 Btu/ft^2 (1,630 MJ/m^2).

The 1995 CBECS database indicates that the average site and source energy for all U. S. buildings are 90,500 Btu/ft^2 (1,030 MJ/m^2) and 179,300 Btu/ft^2 (2,030 MJ/m^2) respectively. The comparison is more relevant, however, if made with other buildings of similar characteristics. Restricting the data base to 1) educational buildings, 2) built between 1993-1995 (i. e., new construction), 3) size 10,000 – 25,000 gross square footage (930 - 2,300 m^2), and 4) located in climate with 5,500-7,000 heating degree days and less than 2,000 cooling degree days, we find the average site and source energies to be 76,000 Btu/ft^2 (860 MJ/m^2) and 123,000 Btu/ft^2 (1,400 MJ/m^2) respectively.

As a second comparison consider the energy-use by 33 non-residential buildings on the same NE Ohio college

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[7] An extensive energy monitoring system has now been installed within the building which will yield more detailed energy-consumption data.

campus. Data are available for the period July 1, 1995 – June 30, 1996. These data yield average site and source energies of 76,000 Btu/ft^2 (860 MJ/m^2) and 130,000 Btu/ft^2 (1,475 MJ/m^2) respectively, in close agreement with the numbers obtained from the CBECS database. Note that some campus buildings included provide energy to nearby parking lot lights and some transformers are metered on the primary side. No attempt has been made to remove these contributions from the data.

In its first two years of occupancy the ESC used about 37% less site energy than comparable buildings both nationally and on the same college campus. But, because it is a 100% electric building the ESC actually used 11-17% more source energy than comparable buildings. Therefore, its green technologies not withstanding, the combined on- and off-site energy consumption for the ESC is not significantly lower than for conventional buildings of similar size and use. Absent the PV array, the ESC has been responsible for slightly more energy consumption, pollution, and CO_2 production than a conventional building.

BUILDING ENERGY SYSTEMS

Since the largest energy use is associated with heating and ventilation these are now considered. The goal is to understand why so much energy is being used to heat and ventilate the building and to identify necessary changes to significantly reduce energy use for these functions.

The Thermal Envelope

The *ESC* sits on an insulated concrete slab. The footprint of the building is 8,300 ft^2 (770 m^2) the perimeter is roughly 560 ft (171 m), and the interior volume is 190,000 ft^3 (5,380 m^3). The non-floor surface area of the thermal envelope totals 20,000 ft^2 (1,860 m^2), and is composed of roof panels, walls, atrium windows, and other windows. The thermal properties of these components are summarized in Table 3. As is necessarily the case for such calculations, numerous details have been ignored to obtain approximate results, expected to be accurate to about 10%. Wall R-values are dominated by 3 in (8 cm) polystyrene insulation, R = 16.8 ft^2·hr·°F/Btu (3.0 m^2·°C/W). Curved roof insulation is provided by 5.5 in (14 cm) of expanded polystyrene R = 23.9 ft^2·hr·°F/Btu (4.2 m^2·°C/W). Flat roof insulation is from 6 in (15 cm) of extruded polystyrene, R = 30 ft^2·hr·°F/Btu (5.3 m^2·°C/W).

The glazing schedule is complicated, but most glazing corresponds to one of two types. Atrium windows use triple-pane, argon-filled glazing with a U-value of 0.13 Btu/ft^2/hr/°F (0.74 W/m^2/°C). Numerical simulations that include the effects of the aluminum window frames show that the combination glazing/frame has an effective U-value of 0.24 Btu/ft^2/hr/°F (1.36 W/m^2/°C). Other windows are made from double-pane, argon-filled glazing with a U-value of 0.23 Btu/ft^2/hr/°F (1.30 W/m^2/°C). Including frames the effective window U-values range from 0.41 Btu/ft^2/hr/°F (2.3 W/m^2/°C) for the small office windows to 0.30 Btu/ft^2/hr/°F (1.70 W/m^2/°C) for the large classroom windows. All non-atrium windows are represented by standard thermal-pane units with a U-value of 0.34 Btu/ft^2/hr/°F (1.93 W/m^2/°C).

TABLE 3

Summary of properties for the AJLC thermal envelope

	R_{eff}	U	A	UA	
	ft^2 hr F/Btu	Btu/hr/F/ft^2	ft^2	Btu/hr/F	
walls	21.0	0.048	6,633	316	13%
roofs	30.0	0.033	7,876	260	11%
slab floor	35.7	0.028	8,322	233	10%
atrium windows	4.2	0.240	3,309	794	33%
other windows	2.9	0.340	2,460	837	34%
Total	11.7	0.085	28,600	2,440	

Note that 2/3 of the envelope heat loss is associated with windows. The effective R-value for the thermal envelope is roughly 12 ft^2·hr·°F/Btu (2.1 m^2·°C/W), not particularly high for a green building.

Blower-door measurements were performed in the Spring of 2000. Subsequent independent measurements confirm these results [Musser, 2001]. The lowest pressure drop that could be reached simultaneously utilizing two 5,500 cfm (2,600 L/s) blower doors was 40 Pascal. A series of measurements for different flow rates was made and used to extrapolate a CFM50 figure of 4.7 air changes per hour. The natural infiltration level is estimated then to be a factor of 20 lower, or 0.25 air changes per hour.

HVAC Systems

The heating system for the ESC is fairly complicated involving 2 large and 21 small water-to-air heat pumps, two electric boilers, various lengths of fin tube, several fan coil units, two energy recovery ventilators (ERV), three water pumps, nine exhaust-fans, and two electric air reheat coils. All HVAC systems, with the exception of the seven office heat pumps which are controlled manually by the occupants, are connected to the computer control system which, with numerous sensors and valves, maintains appropriate air flow and set temperatures in the various spaces.

The 21 small heat pumps ("motel units"), located along the perimeters of offices and classrooms, are used to offset heat losses/gains through the thermal envelope. Ventilation for all spaces, except for the auditorium, is achieved by supplying tempered fresh air from a central air handler attached to a 6.5 ton heat pump, HP-5. A 10-ton heat pump, HP-4, provides all HVAC needs for the auditorium or, alternatively, may be used to cool the atrium.

The HVAC system for the auditorium is shown in Figure 9. Outside air enters HP-4 through ERV-1 which, with supply and return flows of 1,561 cfm (741 L/s) and 1,383 cfm (653 L/s) respectively, has a rated efficiency of 76%. The supply fan for HP-4 operates at 3,500 cfm (1,650 L/s) with over 50% of the air re-circulated. All blowers operate at fixed speed.

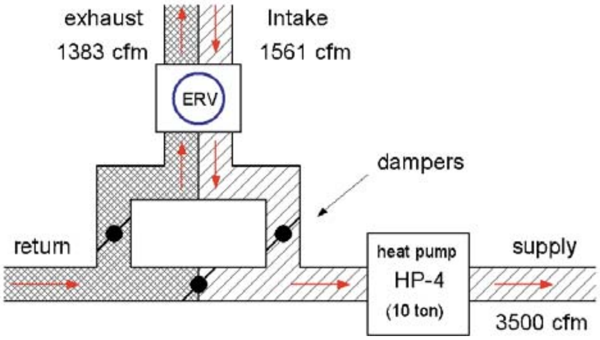

Figure 9. Schematic diagram showing the auditorium air supply and return.

The main air handler is shown in Figure 10. Outside air enters HP-5 through ERV-2 which, with supply and return flows of 2,675 cfm (1,262 L/s) and 1,415 cfm (668 L/s) respectively, has a rated efficiency of 53%. Both ERV-2 and HP-5 are commanded "ON" when the building is occupied. The system is designed to supply 100% outside air (i.e., no re-circulation). The supply fan for HP-5 operates at 2,700 cfm (1,274 L/s). Nearly 50% of its air is exhausted elsewhere and never returns for energy recovery. Auxiliary electric heaters EH-1 and EH-2 are placed either side of HP-5. EH-1 (10 kW) runs whenever the incoming air temperature falls below 30°F (-1°C). EH-2 (16 kW) is activated by the HP-5 control loop. The bypass duct around HP-5 was apparently installed so that a "demand-driven" strategy might be used for controlling supply air. It has never been used [Musser, 2001].

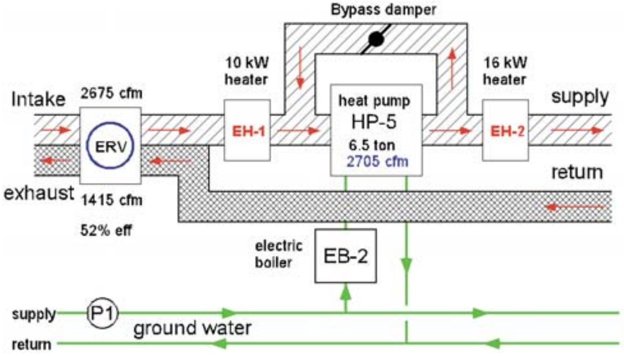

Figure 10. Schematic diagram showing the main building air supply and return.

All heat pumps are extended-range, ARI-320 rated, water-source units tied to common water supply- and water-return manifolds which are part of a closed-loop, vertical well ground system. Manufacturer specifications indicate pumps have heating COP's between 3.2 and 3.8 and, except for HP-5, operate with supply water down to 40°F (4°C). An electric boiler (EB-2) was installed in the ground water line to HP-5 to maintain its supply temperature above 60°F (16°C). Measurements since January 19, 2001 show that the ground water supply temperature has remained between 46°F (8°C) and 66°F (19°C) for the peak heating months of November – March, falling below 60°F (16°C) for 99% of this time period.[8] Ground water pump P1, driven by a variable frequency drive, continually circulates water through the system maintaining a fixed pressure drop across the two manifolds, regardless of the number of heat pumps that are operating.[9] The closed well system consists of 24, 6 in (15 cm) diameter, 240 ft (73 m) deep bore holes with 2 in (5 cm) diameter tubing.

Not all heat is supplied from heat pumps, however. Primary heat for more than 4,000 ft^2 (370 m^2) including the atrium, greenhouse, kitchen, utility rooms, restrooms, and stair wells is provided by a radiant system that is fed by 150°F (66°C) water from 112 kW electric boiler EB-1. These rooms represent 30% of the building area, but due to their extensive glazing, more than 50% of the thermal losses (i.e., UA-product). Pump P3 supplies hot water to

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[8] Very early into occupancy it was realized that EB-2 operation sent energy back into the ground. The operating protocol was subsequently changed to run EB-2 only when the ground supply water temperature fell below 40°F (4.5°C). It has not been used since.

[9] Pump P1 runs continuously, even when no heat pumps are in use because there are not controls to detect when the office heat pumps are activated.

all of the radiant units with the exception of the atrium radiant floor system, which must run at a cooler temperature. Pump P5 provides boiler water through a mixing valve to a radiant pipe system embedded in the 6 in (15 cm) concrete atrium floor. The mixing valve is used, in conjunction with cooler return water, to deliver 120°F (49°C) water to the radiant floor system at a rate of 10 gpm (0.63 L/s). The electric boiler heating system is shown in Figure 11.

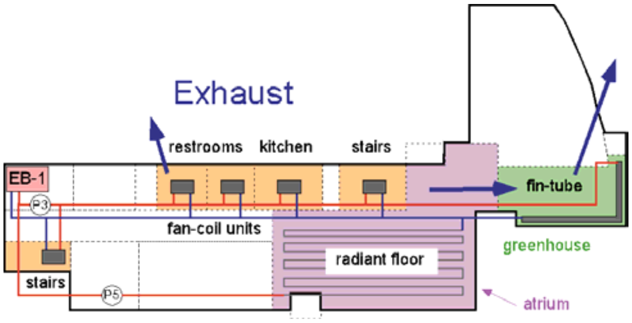

Figure 11. Schematic diagram showing the electric boiler radiant heat system.

The building contains nine exhaust fans. In the two restrooms exhaust fans are activated temporarily by occupancy sensors. In the greenhouse a 2,500 cfm (1,180 L/s) exhaust fan runs continuously at 24% capacity to maintain that space at negative pressure.

Domestic hot water is supplied by a 40 gal (151 L), 4.6 kW, 208 VAC electric hot water heater.

HEATING AND VENTILATION SIMULATIONS

Since winter heating/ventilation is the major area of concern the author restricts his analysis to understanding these. Two important questions are addressed. First, what is the projected winter heating and ventilation energy-use for the building as it was designed and constructed? And second, given the existing building envelope, what is the minimum amount of energy that might be used for these functions assuming that various HVAC systems could be changed? DOE2 simulations are performed using assumptions appropriate for each of these two situations. For these calculations the building was broken into four independent components: 1) the auditorium, 2) the greenhouse, 3) the atrium, and 4) the main building (offices/classrooms). Care was taken not to count heat flow between building sections or to double-count exhaust air.

Energy simulations require detailed schedule information regarding building occupancy, fans, infiltration, set-temperatures, etc. The assumed 24-hour occupancies (Weekday, Saturday, Sunday) are shown in Table 4. The building was assumed to be unoccupied on Sundays and holidays (standard U. S. holidays).

TABLE 4

Building occupancy used in simulations.

Time	M-F	Sat	Sun
00:00-08:00	0%	0%	0%
08:00-10:00	20%	0%	0%
10:00-12:00	60%	20%	0%
12:00-14:00	60%	40%	0%
14:00-16:00	60%	40%	0%
16:00-18:00	40%	20%	0%
18:00-20:00	20%	0%	0%
20:00-24:00	0%	0%	0%

Schedules reflecting the above table were assembled and included in the simulations. Space occupancy densities were taken to be 100 ft^2 (9.3 m^2) per occupant for offices and kitchen, no occupants in atrium, living machine, hallways, stairwells, and utility spaces, 20 ft^2 (1.9 m^2) per occupant in the auditorium, and 35 ft^2 (3.2 m^2) per occupant in the classrooms and conference room. Except for the atrium and greenhouse, set temperatures were taken to be 55°F and 70°F (13°C and 21°C) when unoccupied and occupied respectively, and the fan schedule is OFF when unoccupied and ON when occupied.

Simulations were performed for a 7-month period (October – April) with no cooling. Cooling, equipment, and lighting energy will be considered later. Information describing the building envelope was entered as software inputs. LBNL software Windows 4.1 was used to simulate glazing properties and the overall window properties (including metal frames) for atrium windows.

As-Built Heating & Ventilation (existing equipment and air supply)

The measured energy used by the ESC for the 2000-2001 heating season was roughly 135,000 kW-hr. This figure also includes energy for lights, computers, and other equipment. Also included in this figure are losses associated with the building- and PV-transformers; these combine to about 10,000 kW-hr for 7 months. But the bulk of the 7-month energy use is associated with heating and ventilation.

Input parameters for the DOE2 simulations were adjusted to capture the following important features of the as-built HVAC system and operation:

- 20 cfm (9.4 L/s) outside air per occupant
- infiltration levels of
  - 0.25 ACH for the atrium
  - 0.20 ACH for the main building
  - 0.10 ACH for the auditorium and greenhouse
- all heat from 90% efficient electric boiler (to be adjusted to reflect HP for auditorium and

main building)
- auditorium supply fan 3,500 cfm (1,650 L/s) with ERV efficiency 80%
- greenhouse has continuous exhaust of 600 cfm (283 L/s)
- main building supply, return, and exhaust fans set to 2,675, 1,400, and 1,275 cfm (1,263, 661, and 602 L/s)
- main building return air through ERV with 80% efficiency
- greenhouse and atrium heating set temperature fixed at 65°F (18°C)

The results (in kW-hr) of the as-built DOE2 simulations are summarized in Table 5.

TABLE 5

Results of DOE2 heating/ventilation simulations for as-built ESC.

Space	Heating	Pumps	Fans	Total	Actual
atrium	20,868	168	0	21,036	21,036
auditorium	4,143	68	11,028	15,239	12,477
living machine	33,206	272	3,296	36,774	36,774
main building	55,565	1,009	9,691	66,265	29,222
	73,977	1,517	24,015		99,509

For auditorium and main building actual energy-use is lower than a direct sum because the heat is supplied by HP with COP = 3. All numbers are in kW-hr.

The "heating" column in Table 5 represents the energy supplied by an electric boiler with 90% efficiency. The columns labeled "Pumps" and "Fans" are DOE2 estimates for these categories accepting default fan, motor, and pump efficiencies. Zero fan energy is used by the atrium zero outside air is assumed. The fan energy for the greenhouse is for a 600 cfm (283 L/s) exhaust fan. The "Total" column is the direct sum of the heating, pump and fan energies. For the atrium and greenhouse the "actual" column is the identical to this total. For the main building and auditorium (which employ heat pumps) the "actual" figure is the sum of the heating energy divided by the heating COP = 3, the pump energy, and the fan energy.

The last entry in the table, approximately 100,000 kW-hr, is a reasonable estimate of the site energy required to heat and ventilate the as-built ESC during the 7-month heating season. While numerous small effects were neglected in this calculation it is difficult to imagine the as-built building could use less energy for heating and ventilation given average weather and occupancy described by the above schedule.

The results of these simulations are not particularly sensitive to changes in building schedule. This is, in part, due to the fixed supply and return fan speeds. Another reason is that the main air handler uses 100% fresh air (i.e., no air re-circulation). Thus air handler energy consumption does not vary with the number of occupants. The large heat capacities of the walls and floors also contribute by limiting the amount of energy that will be saved by shutting down a room for short periods of time.

Note that the results of these as-built simulations are consistent with the observed 1st year energy use for this building and greatly exceed earlier design projections [Reis, 2000].

Minimum Heating & Ventilation

There are obvious changes to be made to the HVAC system to reduce energy use – for instance, to replace the electric boiler with a gas-fired boiler[10] or water-to-water heat pump. Such changes are feasible. It is much more difficult to significantly alter the building envelope. The question arises – what is the minimum energy that might be used to heat and ventilate this building without making changes to the building envelope but unconstrained by the current HVAC systems? Here it is assumed that infiltration may be drastically reduced without major renovation by improvements in window and door seals.

To model this case I have made the following assumptions:

- zero infiltration
- air supply at 10 cfm (4.7 L/s) per occupant
- all supply air returned to ERV with 80% efficiency
- all heat supplied with 90% efficient electric boiler (results subsequently to be adjusted for HP COP = 3)
- except for auditorium, heat supplied hydronically
- auditorium heated with existing system, but fan and ERV sized to serve only the auditorium
- greenhouse set temperature fixed at 55°F (13°C)
- heat atrium air (not floor) allowing occ./unocc. set temp of 70°F and 55°F (21°C and 13°C)

These assumptions lead to the minimum heating and ventilation energies listed in the Table 6 below (in kW-hr).

TABLE 6

Results of DOE2 heating/ventilation simulations with assumptions to minimize energy use.

Space	Heating	Pumps	Fans	Total	Actual
atrium	13,051	225	0	13,276	4,575
auditorium	6,226	65	2,474	8,765	4,614
living machine	8,199	60	108	8,367	2,901
main building	35,446	764	3,019	39,229	15,598
	20,974	1,114	5,601		27,689

This represents energy use under ideal conditions where all heat is supplied by heat pumps with COP = 3 and zero infiltration.

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[10] A gas-fired boiler would slightly increase the building site-energy but would significantly lower its source energy.

As before simulations were performed for the 7-month heating period without A/C. The "total" column is the direct sum of the heating, pump and fan energy. Assuming all the heat may be supplied by a heat pump with COP = 3 the minimum energy for this space is the sum of the heating energy divided by 3, the pump energy, and fan energy. The final entry in the right column, approximately 30,000 kW-hr is the minimum energy that might be used to supply heating and ventilation for the 7-heating months without major changes to the building envelope but with major changes to the HVAC systems.

This minimum-energy model represents a 70,000 kW-hr reduction from the as-built case -- more than the annual energy that would be generated by a second PV-array the same size as the present rooftop array! The heating component, 21,000 kW-hr, possibly achievable after significant renovation to the HVAC system, remains significantly higher than the 12,600 kW-hr heating energy previously projected by the architect for this building [Reis, 2000].

The feasibility for achieving this target heating and ventilation energy and the specific changes that will be required are now discussed.

RECOMMENDED RENOVATIONS

In both of these energy simulations a variety of simplifying assumptions were made, too many to be listed here. For instance, window frames were not considered for non-atrium windows and all doors were modeled as thermal windows. The raised floor plenums were ignored and all roofs were treated as flat. Nevertheless, the author is confident that the as-built model captures the essential thermal properties of the building. If anything the model under estimates-heating energy because it:

- does not account for energy-use by electric heaters EH-1, EH-2, or boiler EB-2
- does not include energy to run the ground-water pump, P1
- does not account for fan energies for the two ERV's
- treats restrooms, stairwells, and the kitchen as if heated by HP rather than EB-1, and
- does not account for fresh air delivered to the atrium.

Now consider the specific changes that are recommended which will significantly lower the building energy use. Suggested changes to the HVAC system are considered first followed by other energy-saving recommendations.

HVAC Systems

It is interesting to see what the important changes are in reducing the heating and ventilation energy by 70,000 kW-hr. The various improvements are listed in Table 7 below.

TABLE 7

Specific areas for improvement in reducing heating & ventilation energy from "as-built" to "minimum" DOE2 models.

Improvement		Savings
1. replace boiler EB-1 with water-to-water HP		36,049
2. balance HP-5 return/supply fans and ERV		17,048
3. reduce auditorium supply fan		4,548
4. reduce outsde air to 10 cfm/occ		9,558
5. reduce infiltration		2,403
6. heat atrium air not floor		1,167
	(kW-hr)	70,773

Clearly the largest energy savings, 36,000 kW-hr, is achieved by replacing electric boiler EB-1 with a ground-source, water-to-water heat pump. The obvious savings is due to the COP = 3 for a heat pump (as compared with the COP = 1 for electric heat). But there are barriers to making such a change. The water supplied by a water-to-water heat pump is not generally hotter than 120°F (50°C) and, while this should work with the atrium radiant floor, it may not work with the fan-coil units and fin-tube radiators that are designed for 150°F (66°C) supply water.

And more importantly, there are questions as to whether the existing well field can support the additional heat load. The increased load on the well field may cause its winter supply temperature to fall below the operating range of the existing ARI-320 rated heat pumps. In this event it will become necessary to drill additional wells or replace all 23 existing heat pumps with ARI-330 rated models designed to work with supply water down to 32°F (0°C). It is doubtful that the energy saved in annual heating will ever recover the embodied energy contained in these discarded heat pumps, let alone the cost of their replacements.

A simpler solution worthy of serious consideration would to replace EB-1 with a high-efficiency gas boiler. This would increase the building site energy but lower its source energy by nearly as much as the water-to-water heat pump alternative at far lower capital cost. Moreover, the summer cooling capability of the ground-source heat pump is not an advantage in this application. The original design decision to use an electric rather than a gas boiler for this application suggests an inappropriate emphasis on site- rather than source-energy (see below).

The next biggest savings is to capture all exhaust air and return it to the ERV to recover its energy. The savings is about 17,000 kW-hr after the electric boiler has been replace with a heat pump; if the boiler is not replaced the savings would, of course, be even higher as part of the exhaust air is currently being heated by the electric boiler. To accomplish this requires major changes in the HVAC ducts associated with HP-5 and ERV-2. ERV-2 would need to be replaced with a model that has balanced flow. Moreover, continuous make-up air for the greenhouse must come from the outside rather from the rest of the building, preferably using natural convection. The return fan for ERV-2 needs to be driven by a variable frequency drive so that its flow may be adjusted when other exhaust fans are temporarily activated.

The third change is to eliminate mechanical cooling to the atrium, thereby allowing the auditorium supply fan to be reduced to 50% of its current size of 3,500 cfm (1,650 L/s. Passive cooling of the atrium, already built into its design, seems more consistent with green design principles for this space.

A fourth change is to re-engineer the atrium heating system so as to heat the air not the floor. It turns out that the atrium heat capacity, mainly associated with its 6 in (15 cm) concrete floor, combined with the heat-loss rate yield a very long time-constant. This makes it impossible to significantly change the atrium temperature over an 8-hour period – so that attempts to save energy via nighttime setback temperatures for this space are frustrated. Much of the energy saved by shutting off the heat at night must be put back into the concrete floor the following morning when it again is asked to supply heat to the space. It takes 30X more energy to heat the atrium floor than the atrium air above it. The introduction of a perimeter radiant system or another system for heating atrium air would save about 1,000-3,000 kW-hr, again, assuming the boiler is first replaced with a heat pump.[11] Such a change is clearly not cost effective but would have been a better choice for the initial design.

Note that the above changes, estimated to save 60,000 kW-hr annually, require major re-engineering/replacement of the HVAC systems. Further energy savings can be achieved with operational changes.

One of these is to use 10 cfm (4.7 L/s) of outside air per occupant rather than the 20 cfm (9.4 L/s) originally specified.[12] This will save about 10,000 kW-hr. However, part of this savings comes in fan energy, which requires that the supply and return fans run at lower speeds. This requires drive/belt changes to the supply fan for HP-5 and supply and exhaust fans for the ERV-2.

Though not incorporated in either of the above models, energy-use can be further reduced by instituting demand-mode ventilation based on information from the CO_2 sensors. Clearly the building designers installed these sensors and supply air dampers in each room with such a strategy in mind. Simple control software changes would allow the supply air to each room to be modulated based on CO_2 information, and a bypass duct around HP-5 was installed to maintain its design flow while reducing air to the building. But ERV-2 has fixed fan speeds and cannot accommodate a change in air flow [Musser, 2001]. If such a strategy is to result in significant energy savings it will be necessary to make significant changes to the main air-handler, possibly operating all fans with variable frequency drives. The task is complicated by the close connection between heat pump performance and the rate at which air passes through it.

Another 2,500 kW-hr can be saved annually through significant reduction of infiltration. Clearly an infiltration rate of 0.25 ACH is high for a "green building." But it does not appear that simple tweaking of door and window seals can significantly lower this. It is also clear that the ADA features on the swinging atrium vestibule doors greatly reduce their effectiveness in limiting infiltration. This is particularly problematic given the highly concentrated student traffic associated with changing class periods. Replacement with revolving doors might be considered.

Another place for saving energy (not included in either DOE2 model) is to interlock ground water P1 with all heat pumps so that it may be powered off when not required. This pump now runs continuously, albeit at a minimum setting, even when no heat pumps are being used. If it runs unnecessarily 12 hours per day, all year at 20% of its rated 2.5 kW load it will waste about 2,200 kW-hr.

Non-HVAC Changes

There are other readily identifiable elements of excessive energy use that need to be addressed. The 500 kVA building transformer, made necessary by the extensive use of electric heat, has losses that come to 10,000 kW-hr annually. After eliminating electric heat this could be replaced with a smaller, more efficient model. PV isolation transformers, which remain continually connected to the grid, have nighttime core losses which are expected to total 3,500 kW-hr annually. A simple contactor circuit could be installed to disconnect these from the grid when the PV array produces no energy. Domestic hot water is supplied by an electric water heater estimated to use 5,000 kW-hr annually. This should be replaced with a gas-fired or solar hot-water heater.

Another major user of energy is the organic waste-water-treatment system. It is reported that the fans and blowers for this represent a continuous 2.5 kW load. Hence its operation accounts for roughly 20,000 kW-hr of energy use annually, over and above the energy to heat the greenhouse. To reduce energy consumption the organic waste-water-treatment system should be eliminated.

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[11] The 1,000 kW-hr figure comes from comparing the various DOE2 models. However, independent calculations suggest the savings is more like 3,000 kW-hr after changing out the boiler (or 9,000 kW-hr if the boiler remains).

[12] This has also been suggested by the architect in his October 2000 report.

DISCUSSION

The annual energy consumption of the ESC was originally projected to be 63,609 kW-hr, corresponding to an annual site-energy of 16,000 Btu/ft^2 (187MJ/m^2), roughly 1/5th that of a comparable, conventional building in NE Ohio [Reis, 2000]. The annual energy consumption during its first two years of operation is three times this amount. Moreover, simulations of the as-built structure project the winter heating and ventilation energy alone to be 100,000 kW-hr. And to this must be added the energy for lighting, summer cooling and ventilation, and an additional 40,000 kW-hr consumption by the on-site waste-treatment system, power transformer, PV isolation transformers, and electric domestic hot-water heater. When fully-optimized the author finds it inconceivable that the building, as designed and constructed, could, assuming normal weather and occupancy patterns, consume any less than 150,000 kW-hr annually, more than twice the projected output of the rooftop PV array. It would appear that there is not now and never has been any reasonable expectation that the rooftop PV-array could make the as-built structure a net-energy exporter.

Calculations presented here suggest that this figure might be optimistically reduced by as much as 70,000 kW-hr with major renovations to the HVAC system. (Few, if any of the recommended changes are expected to result in cost savings that justify their capital expense.) But even then there is no expectation that the building would consume less than 80,000 kW-hr annually, an amount that still exceeds the projected energy production of the rooftop PV-array. With such renovations the building will consume considerably less energy, but it will necessarily remain a net-energy consumer.

That is not to say that this structure cannot be sufficiently modified or additional PV generating capacity added so as to achieve this goal. Anything is possible with unlimited funding. But the reduction in annual energy consumption brought about by such major renovation will be outweighed by the increased energy consumed by the renovation process and the embodied energy lost by discarding major building components only two years into their useful lifetime.

It has been suggested that building commissioning has uncovered construction changes that are responsible for the excessive energy use [Barista, 2001]. The as-built structure described here corresponds to the final design whose construction was contracted in November 1998. The electric boilers, electric hot water heater, unbalanced ERV, and exhaust fans are all clearly shown in the October 30, 1998 mechanical drawings – all part of the contracted design. (The building transformer size was increased to 500 kVA in December 1998.) The building owner has conducted a review process that verified that the building was constructed per contract and systems are operating per specifications.

Early in the project the program called for inclusion of the on-site, organic waste-processing system. But the system's energy consumption is substantial. The DOE2 simulations indicate that the greenhouse in which the system is located consumes 40,000 kW-hr to heat and ventilate. Combine this with the estimated 20,000 kW-hr to run the fan and blowers and you find that this system consumes all the energy the PV-Array can produce! Eliminating electric boiler EB-1 will lower the heating energy considerably, but is this a sensible technology for this building in the first place? The system is designed to process 2000 gal (7600 L) of sewage daily. With 1.5 gal (5.7 L), low-flow toilets this corresponds to 1300 flushes per day, or just about 1 flush per minute from either of the two restrooms. Estimated waste production is less than 1/20th this amount.[13] And the building is literally unoccupied during academic breaks and sees little use during summer months. The energy cost per unit volume of sewage processed by the on-site system is 250 times that used by the local Municipal Sewage Processing Plant.[14] This would appear to be an inappropriate technology for an energy-efficient building.

In contrast, the designers did not wish to include a parking lot from the outset. The local zoning board insisted and the parking lot was inserted late in the process. But because it was never perceived as a part of the ESC project no attempt was made to minimize parking lot light energy use or its effect on urban heat or site drainage. The light fixtures, recycled from an earlier campus project, are not particularly efficient and send a considerable fraction of their light upwards in the form of light pollution.

The building power transformer presents another interesting case. In an earlier design (which used steam and chilled-water from the campus central heating plant) the building was to be serviced by a smaller transformer with the power company metering the secondary, thereby absorbing any transformer losses. When the transformer size was increased to 500 kVA the power company, consistent with long-standing policy, chose to meter the primary instead so that the energy delivered to the customer's transformer was billed. The transformer has no other purpose than to deliver energy to the ESC; it is not a high-efficiency transformer because no consideration was given this issue. And, had the building design not included the electric heaters and boilers it could have been much smaller in the first place. The 500 kVA transformer which serves the ESC is similar in size to that which serves a local department store nearly 6X

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[13] Until recently all supply water to the AJLC came from city water lines. Metered use shows that the total building water use was about 2000 gal per month.

[14] This calculation is based on figures supplied by Maria Wossilek, Supervisor of the Oberlin Municipal Sewage Treatement Plant.

the size of the ESC. The 500 kVA transformer is more than 10X the size of the 45 kW PV array.

Energy data provided here come directly from the power meters that serve only the ESC. These figures include energy used to light the building parking lot, energy losses in the building transformer, losses in the PV isolation transformers, energy used by exterior lights on the building, energy used by the on-site waste-treatment facility, and, of course, energy used by other equipment inside the building (including energy and air-quality monitoring equipment). Some would argue that the building energy should not include any of these. But these are either necessary features of a modern building or an integral part of this building's program and removing these contributions would render comparisons with other buildings meaningless. Other large electric building transformers on campus are metered at the primary and all parking lot lights are connected to nearby building meters. Thus the comparison data for other campus buildings includes, where applicable, similar contributions.

The building designers envisioned that one day the building would generate more electricity than it used. In this case, they supposed it would be better to have an electric rather than a gas boiler. But even if the ESC one day generates sufficient electric energy to cover the 52,000 kW-hr of heat used by EB-1 the world would be much better off if this electricity were sold back to the grid and natural gas was used to fuel EB-1, instead. Any PV electricity sold back to the grid displaces alternate peak-generating capacity – namely, electricity generated by natural gas and diesel generators. Hence every unit of electric energy sent back to the grid saves three units of chemical energy stored in fossil fuels from being consumed elsewhere. The design intent to one day become a net-energy exporter appears to have led to the regrettable choice of electric over gas heat.

It is also clear that the designers focused on site energy rather than source energy. Electric heat is 100% efficient while the best gas boilers are only about 90% efficient. Hence, using electric rather than gas heat slightly reduced the site energy while significantly increasing the building source energy. The as-built DOE2 model suggests that boiler EB-1 consumes annually 52,000 kW-hr of electric energy contributing 13,000 Btu/ft^2 and 39,000 Btu/ft^2, respectively, to building site- and source-energies (150 and 440 MJ/m^2). For a 90% efficient gas boiler the corresponding numbers are <u>both</u> 14,500 Btu/ft^2 (165 MJ/m^2). This small decrease of 1,500 Btu/ft^2 (17 MJ/m^2) in site energy comes at the expense of a 25,000 Btu/ft^2 (280 MJ/m^2) increase in source energy – an annual off-site energy consumption of 335,000,000 Btu (350,000 MJ), equivalent to the burning of 14 tons of coal.

And most importantly, it appears that no one verified that the mechanical design actually achieved the design intent. While the building owner and architect described the mechanical design as one that used geothermal heat with a small electric boiler for backup, the actual mechanical drawings show something quite different. There appears to have been a serious lack of communication between the architect and engineer. The budget includes $125k for building commissioning, but little or none of this was spent until after construction was completed. And while the architect employed numerous energy simulations to guide the design process, these simulations were based on hypothetical assumptions not actual engineering specifications. The design process ran "open-loop:" energy-simulations → architect → engineer. There was apparently no flow of information from the engineer back to the energy simulator.

Not counting the $0.5M endowment, the project budget for the ESC comes to $6.5M, which includes $5.0M for construction and another $1.5M for fees and expenses. This translates into a cost of $480/ft^2, at least double that for a conventional classroom/office building. (The fees and expenses alone come to $110/ft^2.) Roughly half of the cost, $3.25M, then is associated with the "green features" of this building, including $450k for the rooftop PV array. The additional expense certainly cannot be justified by any traditional cost/benefit analysis. For instance, the annual energy production for the PV-array, at a savings of $0.10/kW-hr, represents a benefit of only $6,500 per year, or $130,000 over the 20-year lifetime of the array. At 6% interest the annual debt service alone on the $450k investment is $27,000. Nor can doubling the project cost be justified on the projected energy savings. The difference between the annual site energy for a conventional building and the target figure for this building is 60,000 Btu/ft^2 which, for an all-electric building, corresponds to annual energy savings of 238,000 kW-hr, or $23,800. Again, at 6% interest the annual debt service on the added $3.25 M project cost is $195,000, nearly ten times the value of the energy saved. And, of course, a conventional building would not use 100% electric energy, making the comparison even worse.

Clearly, if this building were simply to provide a comfortable environment for activities that take place within, conventional cost/benefit analysis could not justify many of its "green features." But the building is not just to provide shelter for the program – <u>the building is the program</u>. If a bell tower for a church is deemed crucial to its program then it defies cost/benefit analysis. So here the PV array and other costly features of this building were deemed essential to the program. Moreover, the architect provided non-traditional services such as researching the environmental impact of the use of various materials. Yet traditional cost/benefit analysis was invoked to eliminate some energy-saving features such as automated ventilation windows in the greenhouse and a vine trellis for the south atrium windows.

The building boasts an impressive list of green technologies yet its energy-related environmental impact is little better than that for a conventional building. The specific components of the HVAC design that lead to this energy consumption have been enumerated. But what larger factors lead to these design problems?

First, the HVAC engineering resulted in systems that could not meet the design intent. This is evidenced by air handlers which are unable to fully implement a demand-mode air-supply strategy, an unbalanced energy recovery ventilator, a ground-water pump which runs continuously, and water-source heat pumps with inadequate ARI rating. Proper management of this project should have identified these problems long before construction.

Second, there was a failure to adequately address collateral issues which are inescapably part of any modern building, and which have significant impact on total energy consumption. These include the building transformer, the PV array isolation transformers, parking lot and other outside lighting, and other items (e.g., exhaust fans) mandated by building codes.

Third, and perhaps most important, is the fundamental incompatibility of key building goals, these being 1) to showcase green technologies (e.g., rooftop PV array, on-site waste-processing), 2) to be a model of energy-efficiency, and 3) to have a full cost accounting of all systems [Gabrielli, 1995]. The first of these falls in the category of a demonstration site. The last two of these fall in the category of an implementation site – that the building would, by virtue of the way it was constructed and by its performance be a concrete example of what can be accomplished by adopting green processes. Unfortunately decisions to achieve one or more of these goals defeat other purposes. The on-site waste processing system, for instance, consumes an inordinate amount of energy. And, to change out HVAC components now to improve energy-efficiency will greatly reduce the life-cycle of initial building components. The goals of being a demonstration and an implementation site are mutually incompatible.

And finally, the design process lacked integration. Rather than a design team that interacted regularly the team was assembled from geographically-scattered, highly-paid consultants with limited time to devote to this project. Each consultant focused on his/her area of specialty and paid little or no attention to the activity of others. The building owner provided inadequate technical oversight of the project, relying instead on the architect to manage the project. Clearly appropriate integration was not achieved – devastating for any building project, let alone one with such difficult goals.

There are many lessons to be learned from this case study. But it would be inaccurate to conclude that all green buildings suffer from the similar problems. Many green design features can and have been implemented in other buildings with success and without greatly inflating the cost.

CONCLUSIONS

Here the author has considered the early performance of a recently-constructed, 13,600 ft^2 (1263 m^2), all-electric, green academic building in NE Ohio. Twenty-four months of data indicate that building's energy consumption is three times the original energy projections and, similarly, three times higher than the expected energy production of its rooftop photovoltaic array. Annual site- and source-energy consumptions for the building are 48,000 Btu/ft^2 (540 MJ/m^2) and 144,000 Btu/ft^2 (1,630 MJ/m^2) respectively, and decreasing slowly with improvements. Comparison with data for other buildings on the same campus or from a national building energy data base show that, so far, this building, despite its green label, is responsible for as much energy consumption and pollution as a comparable, conventional building. The energy benefits of its rooftop PV array are no different than what would be achieved by installing such an array on any other building.

The author's energy-modeling of the "as-built" structure shows that its energy consumption is as expected given its design, with much of the consumption associated with winter heating, roughly half being supplied by an electric boiler. Simulations also suggest that significant energy savings may be achieved with major redesign and renovation of the HVAC systems.

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DISCUSSION

Ross M. Sherrill, P.E., Owner, Sherrill Engineering, San Francisco, Calif.: This symposium provided many "aspects" of the ASHRAE initiated "Design Intent" terminology, which is almost completely foreign to the owners, architects, and engineers in Northern California. We have been a Commissioning provider since 1990 and I have never seen an official published project Design Intent.

The last paper, by John H. Scofield, dealt with a project that developed an extravagant and detailed "green building" design intent that nobody, including the A&E and the commissioning authority paid any attention to. My understanding is that ASHRAE Guideline 1-1996 indicates that the commissioning authority is to verify that the HVAC systems have been furnished and installed in accordance with the contract documents and function in accordance with the Design Intent. I make a detailed HVAC system "design review" in order to perform this service.

Not one of the five (5) papers mentioned verification of the HVAC systems functioning per design intent or any design review in regard to design intent by the commissioning authority.

What good is developing a "design intent" document if it is "ignored" by the A&E and the commissioning authority?

Kevin Burke, Partner, William McDonough + Partners, Charlottesville, Va.; David W. Orr, Chair, Environmental Studies Program, Oberlin College; Ron Perkins, Supersymmetry USA; Adrian Tuluca, Steven Winter Associates, Inc.: In response to John Scofield's article, "Early Performance of a Green Academic Building," about the Oberlin College Adam Joseph Lewis Center ("AJLC") printed in this issue, we make the following points:

1. Professor Scofield analyzes data from the Lewis Center's first two years of occupancy, without qualifying the status of the project during that time. This leads to misleading conclusions about the project's energy use over the first two years, and misleading interpretations about its projected future use.
2. Professor Scofield states throughout the article that building construction was completed in January 2000. In fact, while "substantial completion" was achieved in January 2000, allowing for building occupancy, building construction, including the mechanical punch list, extended for another year. And perhaps more importantly to the project's energy use, building commissioning has been an ongoing process and is not yet complete. Significant punch list items that adversely affected energy consumption during that first year included operable windows that were not closing and sealing properly (particularly those on motor controllers) and the building lighting controls.
3. Professor Scofield is also misleading in his statement that "Energy consumption, largely associated with winter heating, is found to greatly exceed original projections for the building." By including energy use data from the first year of occupancy before completion of construction and during commissioning, he arrives at a greatly exaggerated average annual site energy intensity of 48,000 Btu/ft2.
4. A more accurate rendering of the building's performance, based upon completed construction and a significant level of commissioning, is given by the first year of data authenticated by an independent analysis (National Renewable Energy Laboratory). NREL's figures, ranging from April 2001 through April 2002, show the site energy use at 27,000 Btu/ft2, or 44% less than Professor Scofield's figure.
5. In context, the 27,000 Btu/ft total is a remarkable figure, well below the performance of standard academic buildings (estimated between 80,000 and 90,000 Btu/ft2), and roughly 25% less than the next-best comparable building (Vermont Law School Oakes Hall). Subtracting the PV production over the same period, the net energy used by the Lewis Center is approximately 12,000 Btu/ft2, or one-third of the energy of the next best comparable building on a college campus. And contrary to Professor Scofield's assertion that improved performance can be attributed to a mild winter, simulations done at NREL show that even allowing for "normal" winter, the data change only modestly.
6. In the past 12 months, the building generated 59% of its energy from direct sunlight. Professor Scofield is correct that the Lewis Center is not yet a "net energy exporter." This is a program goal that the design team assumed would not be met for ten to twelve years.
7. We believe that Professor Scofield needs to provide

more detailed data to substantiate his "source energy" comparisons. A reoccurring conclusion, the building uses more source energy than other buildings of its type" is, in fact, inconclusive, as it appears that Professor Scofield failed to include the source energy of the central utilities plant in comparisons to campus buildings. There is not mention of chilled water use, the electricity to run the chillers, coal to fire the boilers, electricity to pump water and condensate, and all of the waste energy involved in distributing steam and chilled water. When this energy is added to the typical campus building's source energy profile, we believe a more favorable rendering of the AJLC project will emerge. The Btu/gsf/year metric varies widely with occupancy, and comparisons with the AJLC should have equal use patterns and density of occupants to be valid.

8. The building's design, as well as the design process itself, was purposefully intended to be instructive about an entire range of issues associated with sustainable design. Professor Scofield's article fails to address the context of the project team's design decisions. He ignores the fact that the design of the building evolved over a period of three years. Each iteration had different energy "projections," associated with different assumptions about energy sources, and different mechanical designs. More importantly, the build- and our expectations of it were designed to evolve over a period of years, in order to model advances in energy systems and technologies. Thus, the design team's emphasis upon an "all-electric" design was based upon an assump- that fuel cells, along with photovoltaic panels, would be added to the project at a later date. In fact, significant time was spent by the design team in pursuing fuel cells for the project, and infrastructure was set in place for their eventual installation.
9. His complaint about the energy and dollar costs of the waste water system is irrelevant. The waste water system was designed to purify water and serve as a laboratory for ecological engineering. It has done both quite well.
10. Professor Scofield's cost calculations are overstated. Of the $7 million project budget that is referenced, a more accurate breakdown of the costs is as follows:
    - Construction cost, including PVs: $4,783,000
    - Photovoltaic system costs, installed: $403,000
    - Construction cost, site, landscape, and parking: $674,000
    - Construction cost, core, and shell (excluding PV, site, landscape, and parking): $3,706,000, or $272/sf
    - Living machine costs (including system costs and estimated core and shell costs): $300,000
    - Excluding the living machine from the building costs renders core and shell costs at $250/sf
11. If one wishes to make a more accurate, "apples to apples" cost assessment, the $1.377 million in anomalous costs should be subtracted, including the relocation of storm and sanitary sewers, parking lot, and the costs of the PV array and living machine. Those latter features were not included because of cost effectiveness, but because of their educational and research value. A more valid cost calculation shows that the basic building cost ~$250/sf and that a substantial fraction of that was a matter of choice not cost effectiveness. This is not out of line with construction costs at this scale in the prevailing bid environment of the late 1990s.

John H. Scofield: As Burke, Orr, Perkins, and Tuluca suggest, numerous punch list items were addressed during the first year of occupancy, and some of these resulted in reduced energy usage. During 2000, the college completed an extensive commissioning process in which it was verified that the *Lewis Center* was built per construction documents and systems were operating per specifications. The post-commissioning 2001 energy consumption was (166,000 ± 6,000) kWh, 23% lower than for the previous year (see Table 1). This corresponds to a source energy of 125,000 Btu/ft^2, similar to that of a comparable, conventional building.

But a sizable fraction of the improved energy performance for 2001 is concentrated in the months of November and December, the beginning of an unusually warm winter (see Figure 8). The lower consumption continued through the rest of the winter. For the selected 12-month period ending March 31, 2002, my measurements show that the building consumed (130,000 ± 6,000) kWh of energy. This is 22% lower than that consumed during the 2001 calendar year, but still twice the architect's projected consumption.

The April 1, 2001-March 31, 2002 period includes the warmest winter experienced by NE Ohio in half a century! For this HVAC design heating energy increases dramatically with sub-freezing cold periods due to the operation of electric heaters EH-1, EH-2, and the ground water boiler, EB-2. I am not impressed by Burke et al.'s assertion that NREL simulations show otherwise.

More importantly, a variety of factors combined to reduce building usage during this same period. Furthermore, the building was operated with insufficient heating and ventilation, documented by log files of numerous HVAC control points on 15-minute intervals. For example, the living machine was only heated to 45ºF, hardly justifying its inclusion as conditioned space at all. And, during February and March, regularly scheduled classes met in the auditorium with neither heating nor ventilation. (On more than 20 occasions $C0_2$ levels in that space rose above 1000 ppm and, on several occasions, exceeded the 2000 ppm sensor maximum.) Students wore coats in class and frequently complained of the cold. Such draconian measures could be employed to lower the energy use of any building.

Any doubt regarding the sustainability of this recent performance could be readily addressed by monitoring energy use for the next few years. Alas, this will not be possible because, in April, the college, urged by the design team, replaced boiler EB-1 with ground-source heat pumps at an estimated cost of $100k.

Burke et al. imply that their recent data, collected in a collaboration with Paul Torcellini (NREL), are somehow more accurate than my own. This reflects a naive understanding of the scientific process. A detailed comparison of the two data sets shows they are in complete agreement, except that my data includes transformer losses while their data do not (see http://energy.physics.oberlin.edu/comparison.htrn). My data begin in October 1999 while the NREL data begin in March 2001, conveniently missing the first 14 months of occupancy. (The only justification for Burke et al. beginning their "selected year" of data in April rather than March 2001 is that it lowers the use by 10% -- March 2001 was a bad month!) I note that Paul Torcellini attended my talk in Honolulu where he raised no questions, nor is his name listed with Burke et al.

The comparison between *Lewis Center* energy consumption for the selected year and energy used in earlier years by the Vermont Law School's *Oakes Hall is* skewed. No doubt *Oakes Hall* used less energy during this same "selected year" due to its mild winter. In the paper, I argue that source, rather than site energy, provides a better measure of the environmental impact of a building design. The quoted *Oakes Hall* site energy of 30,000 Btu/sf corresponds to a source energy of 61,000 Btu/sf

(for data, see

http://www.vermontlaw.edu/life/lifabooak.cfm. The 27,000 Btu/sf site energy figure offered by Burke et al. corresponds to a source energy of 81,000 Btu/ sf, 30% higher than that for *Oakes Hall.* It should be noted that the *Oakes Hall* (23,500 ft^2) achieves its performance at a reported project cost of $140/ft^2; about 1/3 that of the *Lewis Center.*

The "net-consumption" (obtained by subtracting the energy generated by the PV Array from that consumed by the building) makes for a nice sound bite but is otherwise of little comparative value. By adding a sufficiently large PV Array to any building, its "net-consumption" may be made arbitrarily small--even negative! This demonstrates the benefits of a PV Array but says nothing about building energy efficiency. Imagine its "net-energy consumption" had Oakes Hall had the same budget as the Lewis Center and the construction savings been invested in a PV Array!

Burke et al. suggest, without explanation, that the site energy for a comparable, conventional building ranges from 80,000-90,000 Btu/ft^2. This would be the third such figure put forward by the design team in four years. A figure of 75,000 Btu/ft^2 was originally asserted in the September 1998 *Performance Data Sheet,* while a range of 124,000-168,000 Btu/ft2 was asserted in their October 2000 *Energy Performance Status Report.* Clearly, site energy figures are rather soft (probably good only to 10% precision). I justify the 76,000 Btu/ft^2 in the paper and still believe the design team got this right the first time.

Burke et al. say that the design team assumed it would take 10 to 12 years to achieve the goal of being a net-energy exporter. Unfortunately this assumption was not clearly expressed in print. In the 1998 *Performance Data Sheet,* the architect wrote, "Anticipated advancements in PV efficiencies should meet or exceed the building energy demand (64,000 kWh) within five years." There was no suggestion that major HVAC components would require changing as well. As recently as April 2000, Professor Orr is quoted in *Environmental Design and Construction* magazine saying, "We believe that right off the bat, the building will generate more power than it will use."

Burke et al. raise questions regarding source energy calculations. While these concerns are valid, closer examination shows them to be of minor consequence. Correction for efficiencies of central chilled water and steam systems raise source energy for other academic buildings on the same campus by only 5% to 10%. The reason for this is that central chilled water represents only 5% of college's electrical use and central steam contributes only 35% of the total building source energy. The correction does not change the conclusion that, for the first two years of occupancy, the source energy consumption of the Lewis Center is not significantly lower than that of a conventional, comparable building.

The new cost information provided by the Burke et al. is welcome. I was not given access to such detailed cost information and, instead, provided budget figures in the paper. But the cost figures provided do not mention design fees and expenses, estimated to be about $1.5M. (Public records confirm the architect was paid at least $1.0M.) Also, neither budget figures nor these cost data include the estimated $100k value of carpet and raised flooring, provided by the manufacturer to the building at no charge.

And, finally, Burke et al. justify their "all electric" design by saying they were planning for future inclusion of a fuel cell, providing yet another example of this project's mutually incompatible goals. A fuel cell necessarily exports less energy than it imports, decreasing building efficiency. Moreover, without a natural gas line into the building, it is unclear how the anticipated fuel cell would generate sufficient electricity to justify the larger building transformer. It is clear, however, that the larger transformer introduced additional losses that harm the goal to become a net-energy exporter.