Evaluation Results for an Energy-Efficient Office New Construction Project

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ABSTRACT

As part of an energy efficiency research & development project, a major northern California utility in conjunction with the California State Automobile Association (CSAA) designed, built and analyzed the most energy efficient office building in California. The 1,419 m^2 building is located in Antioch, California and has been occupied since June 1994.

Before the utility invited CSAA to participate in the research project, the district office was to be built as specified by CSAA's corporate construction guidelines, which would have minimally satisfied California's Title-24 energy standards. However, by applying an integrated design concept, the design team reduced the building's projected energy consumption by 70% at a cost competitive with electric and gas utility supply costs.

The savings are achieved with variable-aperture daylighting; dual-fan, dual-duct HVAC; high performance glazing; energy efficient computers; and several other measures. Based upon the data collected from the end-use metering system installed by the utility, the actual energy savings are about 64%, closely matching the DOE-2 modeled energy savings projections.

Introduction

Measured data and a calibrated simulation model were used to estimate the actual savings and cost effectiveness of energy efficiency measures (EEMs) installed at the California State Automobile Association (CSAA) commercial new construction site in Antioch, California.[1] The performance of the CSAA office building was compared against a typical CSAA office design, a two-story structure with a floor area of 17,310 ft^2. The efficient design changes the structure to a single story, eliminating the need for an elevator, stairs, and a second set of bathrooms. By eliminating the extra spaces, the floor area is reduced to 15,704 ft^2. The one-story design also allows for the use of skylights for daylighting.

Cooling is provided by a 30-ton packaged variable-air-volume system, including an evaporatively-cooled condenser and a variable-speed drive to control the supply air fan. The unit includes three compressors, with a variable-speed drive on the first compressor to improve part-load performance. Ventilation air is provided with an outside air economizer.

A separate gas furnace with its own fan provides warm air to dual duct VAV boxes. The furnace includes a constant speed fan. The system recirculates indoor air; all ventilation air is supplied through the cooling ducts. The heating dampers in the VAV boxes can close completely if the zone requires no heating.

A direct-digital control (DDC) system starts and stops the system and resets the supply air temperature based on the temperature of the warmest zone. The DDC system also includes an optimal start algorithm that calculates the latest possible start time before the occupied period begins. The

[1] Antioch is located east of San Francisco, CA, along the Sacramento River Delta with heating degree days of 2730 (base 65°F) and cooling degree days of 970 (base 65°F).

DDC system turns the furnace on when any zone temperature drops below 71°F, otherwise it remains off.

Most of the CSAA building is provided with daylight through windows or skylights. Electric lighting with continuous dimming control is designed to maintain a minimum of 30 foot-candles (fc) of illumination. Photocell control is intended to turn off the lights when illumination exceeds 50 fc. Skylights in the interior zone include automatically controlled louvers that limit daylight illumination to 75 fc. Perforated mini blinds on the windows are set at an angle to reflect light into the perimeter zones. Most of the area lighting is provided by 2-by-4 foot recessed fixtures with parabolic louvers and T-8 lamps. Actual installed lighting power is 0.66 W/ft^2. Occupancy sensors in both the open and enclosed office areas also control lighting.

Internal loads are reduced by installing "Energy Star" computers and monitors, and efficient task lights with occupant sensors. Other efficiency measures include an efficient refrigerator and coffee maker in the lunch room.

Evalulation Methodology

Simulation Program. Savings calculations were performed with DOE2.1 version 110 from J.J. Hirsch & Associates. This version allows modeling of dual-fan, dual-duct HVAC systems in addition to the daylighting savings algorithms already available in the earlier versions of DOE2.1E.

Model Calibration. The simulation model of the actual building was calibrated using measured data collected at 15 minute intervals over the first year of building operation. Climate data include temperature, humidity, wind speed and solar radiation used to produce a DOE2.1E weather file. Extensive energy end-use and indoor conditions data were also recorded. Details of the calibration results are reported in Eley 1997.

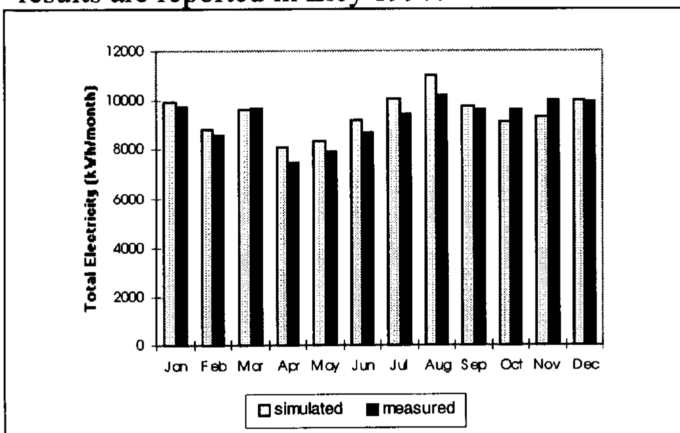

Figure 1 Comparison of Measured and Simulated Total Electricity Consumption for Actual Building

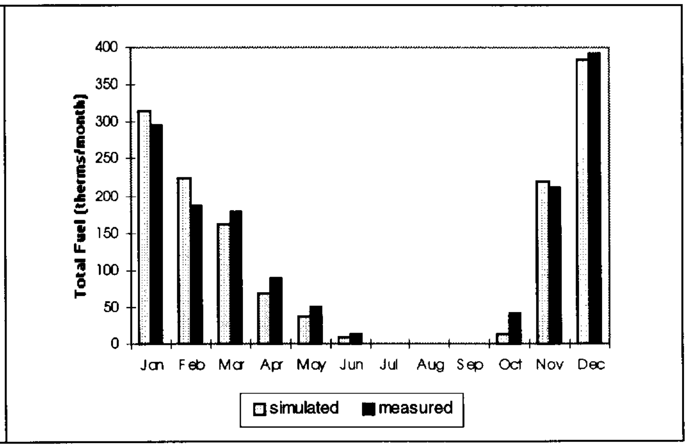

Figure 2 Comparison of Measured and Simulated Total Fuel Consumption for Actual Building

Base case building. The base case model is based on surveys and measurements at an existing CSAA office building. The base case is close to a minimum code complying building for features such as lighting, envelope and HVAC systems that are governed by California's energy standards.

Savings calculations. Savings for the first measure (form & siting) is the difference in energy consumption between the base case model and the actual building model without later EEMs installed.

The savings for additional measures are determined by adding the measures one-by-one to the form & siting model. These savings calculations are performed with standard weather data.

Results

EEM Package Results

The weather-normalized savings for the total EEM package are estimated to be 64% compared to the base case building. These savings are smaller than the predicted value of 70%. The package of EEMs reduces summer maximum peak electricity demand from 144 kW to 44 kW.

Table 1 Electricity Consumption and Savings by End Use

End Use	Base Case (kWh/y)		EEM Package (kWh/y)		Savings (kWh/y)		Savings (%)		Variance in Savings (kWh/y)
	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
Cool	58,632	65,002	14,257	21,870	44,375	43,133	76%	66%	-1,242
Heat	5,655	5,516	0	0	5,655	5,516	100%	100%	-139
Fans	36,833	33,974	4,288	9,945	32,545	24,028	88%	71%	-8,517
Lights	120,908	120,910	25,321	27,297	95,587	93,612	79%	77%	-1,975
DHW	5,992	900	2,696	72	3,296	828	55%	92%	-2,468
Misc.	123,352	123,352	59,818	71,494	63,534	51,858	52%	42%	-11,676
Total	351,372	349,654	106,380	130,679	244,992	218,975	70%	63%	-26,016

Table 2 Gas Consumption and Savings by End Use

End Use	Base Case (therms/y)		EEM Package (therms/y)		Savings (therms/y)		Savings (%)		Variance in Savings (therms/y)
	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
Heat	4,327	4,221	1,320	1,193	3,007	3,028	69%	72%	21

Table 3 Source Energy Consumption and Savings by End Use

End Use	Base Case (MBtu/y)		EEM Package (Mbtu/y)		Savings (MBtu/y)		Savings (%)		Variance in Savings (MBtu/y)
	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	
Cool	469.1	520.0	114.1	175.0	355.0	345.1	76%	66%	-10
Heat	477.9	466.2	132.0	119.3	345.9	347.0	72%	74%	1
Fans	294.7	271.8	34.3	79.6	260.4	192.2	88%	71%	-68
Lights	967.3	967.3	202.6	218.4	764.7	748.9	79%	77%	-16
DHW	47.9	7.2	21.6	0.6	26.4	6.6	55%	92%	-20
Misc.	986.8	986.8	478.5	572.0	508.3	414.9	52%	42%	-93
Total	3,244	3,219	983	1,165	2,261	2,055	70%	64%	-206

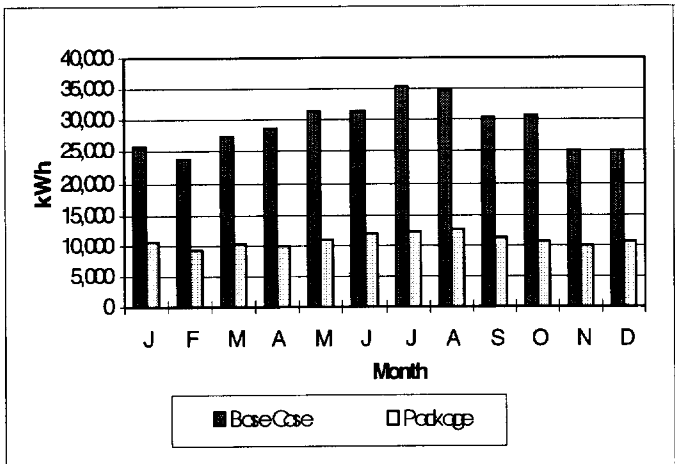

Figure 2 Comparison of Monthly Electricity

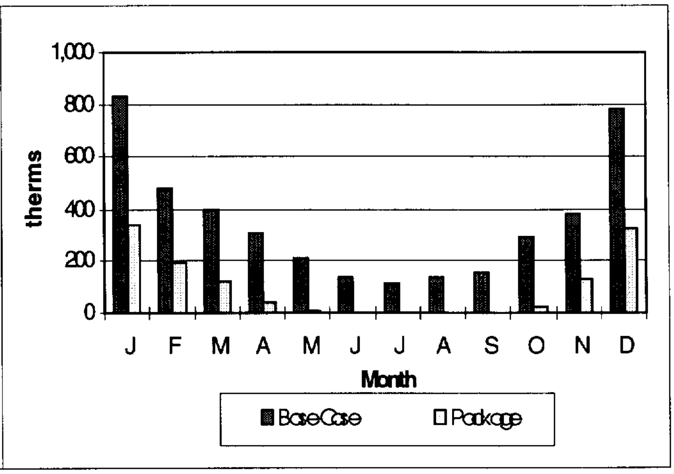

Figure 3 Comparison of Monthly Gas

The mature market cost of the EEM package is estimated to be $114,993.[2] The present value of energy savings is $224,753, using the utility's economics. Therefore, the overall benefit-cost ratio for the entire package is 1.95, slightly lower than the predicted value of 2.24. (TCA, 1996, Eley, 1997)

Table 4 Figures of Merit

	BASE CASE		EEM PACKAGE	
	Predicted	**Measured**	**Predicted**	**Measured**
General Characteristics				
Floor Area				
Conditioned	16,740		15,704	
Unconditioned	840		0	
Total	17,130		15,704	
Total Energy Use				
kBtu/ft²-y	107.00	96.5	32.45	36.0
kWh/ft²-y	31.35	20.9	9.51	8.32
therms/ft²-y	0.003	0.25	0.87	0.076
Peak kW (annual)	?	144	?	45
End-Use Energy (site kBtu/sf)				
Heating	29.73	26.3	8.67	7.6
Cooling	13.10	13.3	3.19	4.8
Fans	8.23	6.9	0.96	2.2
DHW	1.34	0.2	0.60	0.0
Lighting	27.02	24.7	5.66	5.9
Misc	27.57	25.1	13.37	15.5
Building Envelope				
Windows				
Total area (ft²)	1,507		1,459	2,033
North area (ft²)	637		486	405
South area (ft²)	303		486	525
East area (ft²)	204		244	519
West area(ft²)	363		244	583
Visible Transmittance (N/W/ES)	0.47		0.60	.61/.41/.47
Shading Coefficient (N/W/ES)	0.57		0.36	.49/.35/.39
U-value	0.48		0.31	0.36
Efficacy	0.82		1.67	1.24/1.17/1.21
Skylights				
Area (ft²)	0			630
Visible Transmittance	n.a.			0.64
Shading Coefficient	n.a.			0.68
U-value	n.a.			0.54
Efficacy	n.a.			0.94
Wall U-value (R-value)	0.05 (R-19)			0.05 (R-22)
Roof U-value (R-value)	0.03 (R-29)			0.03 (R-32)
Cooling				
Cooling capacity (tons)		74		31
Peak cooling demand (tons)	48.9	53	18.0	24
Cooling efficiency, excluding fan (kW/ton)	1.63	1.27	0.80	0.74
Supply fan efficiency (kW/cfm)	0.000493	0.000685	0.00042	0.00476
Supply air flow at design cond. (cfm)	21,896	24,607	6,300	14,000
Heating				
Heating capacity (kBtu/h)	511	589		216
Heating efficiency	80%	80%		70%
Static head for pump (ft. w.g.)	60	60		n.a.
Supply air flow, max (cfm)	n.a.	n.a.		5,315
Fan efficiency (kW/cfm)	n.a.	n.a.		0.000698
Lighting				
Ambient lighting power (W/ft²)	1.74	1.63	0.58	0.66
Task lighting power (W/ft²)	0.19	0.15	0.09	0.03
Total lighting power (W/ft²)	1.93	1.78	0.67	0.69
Miscellaneous				
Misc. equipment power (W/ft²)		1.62		0.57

[2] Mature market cost is an estimate of the cost of advanced technologies if they were widely available on the market.

Discussion of Individual EEMs

The EEMs are listed below in approximate order of their cost effectiveness. During the design process, savings were calculated for individual measures and were ranked according to their benefit-cost ratio. As the measures were added one-by-one to the design they were re-evaluated to ensure that they were incrementally cost effective. In the evaluation described in this report, the measures were analyzed in the same order determined by the design team in their calculations.

Note that some of the EEMs described below are actually packages of related measures. The first EEM, form and siting, combines a number of lighting and building envelope measures. In the third measure, a direct digital control (DDC) system is packaged with a variable speed drive for the supply fan.

Form & Siting. The base case is a two-floor design representing the building that would have been constructed in absence of the integrated design process. The form and siting EEM changes the design to a slightly smaller one-story design that allows daylighting of the interior zones using skylights. Rearranging the parking lot to maintain the same number of spaces accommodated the larger footprint of the one-story design. Most of the energy savings are due to daylighting controls and reduced lighting power. Some of the energy savings features are described below.

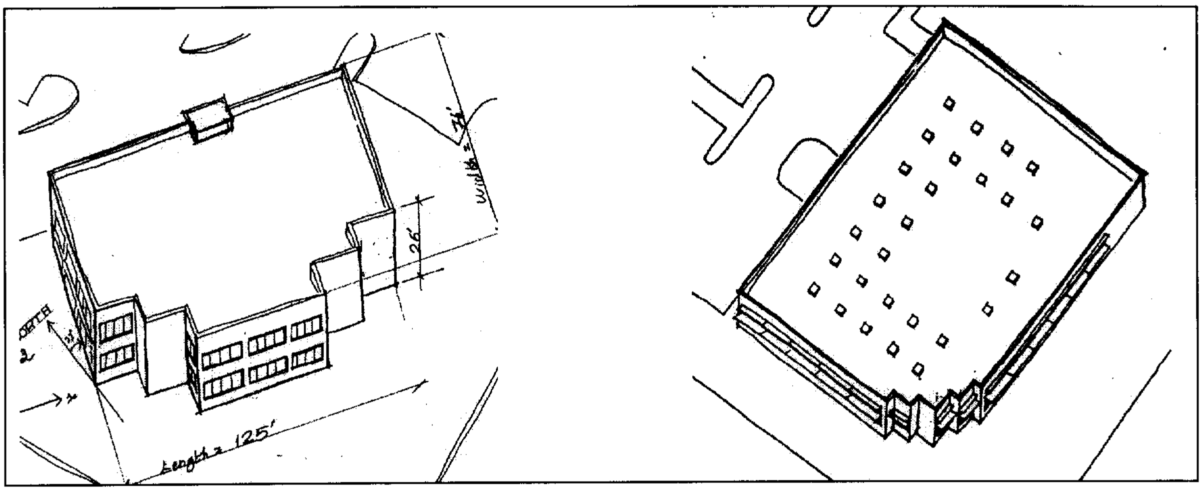

Figure 3 Two-story Base Case Configuration and Single-Story, Daylighted Configuration (approx.)

- *Reduced lighting power.* Lighting power is significantly lower than in the base case due to the use of fewer lighting fixtures in the "task/ambient" system designed for 30 footcandles (maintained) of general illumination (more efficient lamps and ballasts are included in a later EEM).
- *Daylighting controls.* Daylighting savings are achieved with dimming electronic ballasts in perimeter and interior zones.
- *Skylight louvers and barometric relief dampers.* Photocell-controlled louvers are located under the skylights in the interior zone to limit the daylight illumination to about 70 footcandles. The skylights also include dampers that provide a exit path for warm exhaust air. This system and savings are described in (Allen 1996).

- *Spectrally-selective windows.* The new design also includes spectrally-selective windows to improve daylighting savings while reducing solar heat gain. Window type is varied by orientation to provide shading where it is needed most. The original design specified double-pane low-e glazings with a green-tinted outer pane, but the window contractor substituted double-pane glazings with a suspended Heat Mirror film and green-tinted glass, which provided similar performance.
- *Elevator elimination.* Eliminating the need for an elevator saves energy.

The form and siting EEM provides the largest savings, reducing source energy consumption by 33% compared to the base case. Electricity savings are 114,206 kWh/y, gas savings are 1603 therms/y, and source energy use drops by 1,074 MBtu/y. The peak electricity demand drops from 144 kW to 86 kW, equivalent to 8.3 W/ft^2 and 5.5 W/ft^2 respectively.

Lighting accounts for 63% of the savings for this measure, saving 72,101 kWh/y. Lighting energy consumption drops by 65%, due to reduced lighting power and daylighting. The daylighting controls reduce annual lighting energy consumption by 32%, with savings ranging from 14% in December to 45% in June. Without controls, the average lighting power at mid-day is 0.56 W/ft^2. With controls, mid-day lighting power drops to 0.37 W/ft^2 in winter and 0.20 W/ft^2 in summer. For more information on the daylighting system refer to (Allen 1996).

Dual Fan HVAC System. The base case is a single-duct variable-air-volume (VAV) system with reheat coils in the perimeter-zone VAV boxes, and this measure specifies switching to a VAV dual-fan, dual-duct system. Cool air is provided by a custom-built packaged air conditioner located on the roof. A packaged gas furnace at the opposite side of the roof produces warm air. Air from the two ducts is combined in a VAV mixing box at each zone (except for interior zones that are cooling-only). Ventilation air is provided through the cool duct, using the outside air economizer dampers in the air conditioning unit (economizers are included in both the base case and dual-duct systems).

This system is intended to save energy in the following ways:

- *Reduced reheat energy.* In the base case VAV system, a single duct carries cool air to the VAV box. The air must be cool enough to satisfy the warmest zone, which means that it is cooler than necessary to provide enough cooling in the remaining zones. In some cases, the VAV damper closes to its minimum ventilation position and the zone still receives too much cooling. At that point, the control valve on the hot water reheat coil opens and warms the air for that zone. Therefore, energy is required to reheat cool air in order to maintain comfort in the zone. By contrast, in the dual-duct system, the warm air duct uses recirculated indoor air. In a dual-duct VAV box, the cool air damper closes to its minimum position as the cooling load in the space drops. Then the warm air damper begins to open to increase the temperature of the supply air and avoid overcooling the zone. For much of the year (in the warm months), the furnace never turns on and warm recirculated air satisfies the demand. Therefore, heating energy is used only when a true heating load exists, not to reheat cooled air. Note that total fan energy increases somewhat (for the heating fan), but the increase is almost completely offset by the elimination of hot water pump energy.
- *Reduced cooling energy.* Cooling energy drops because minimum zone air flow settings are lower in the dual duct system and less cool air is required during time of moderate loads. In the base case system, minimum flow is assumed to be 50% in the perimeter zones and 30% in the

interior. These values are common practice in California for small commercial projects, where DDC systems and electronic controls are not common (pneumatic controls would probably have been used for the base case building). Although these values are higher than necessary for outside air ventilation purposes, they are sometimes used to provide adequate heating air flow for warmup periods. In the dual-duct design, the minimum settings for the cool air damper in the mixing boxes range from 0% in the interior zones to 56% in one of the perimeter zones, and the average is about 20% (roughly the amount necessary for ventilation air). All of the heating dampers in the dual-duct boxes shut completely when no heating is required in the zone (however, 5% leakage is assumed in the model). The lower settings are possible in the dual-duct system because heating air flow is independent of the cooling (and ventilation) flow. Therefore, cool air flow may reduce to the minimum level required for ventilation rather than be limited by the air flow required to meet peak heating loads.

- *Reduced cooling fan energy.* The removal of reheat coils from the VAV boxes reduces the static pressure required in the supply duct. The pressure drop is assumed to decrease by 0.25 in. w.g. for the dual duct system. Lower pressure leads to lower fan power and energy savings. Note that total fan power increases compared to the base system because of the additional heating fan, but the cooling fan energy decreases.

Other measures included along with the switch to the dual duct system include:

- A high efficiency air-foil fan is modeled as part of this measure, increasing the fan efficiency about 8% relative to the base case fan.
- The supply air temperature control method is changed. The base case model assumes a constant cooling supply air temperature of 57°F, while in the dual-duct system, cool duct temperature is reset so that it is just cool enough to meet demand in the warmest zone and warm duct temperature is reset to meet loads in the coolest zone.
- Improved duct design is assumed to reduce pressure drop and, therefore, reduce fan electricity consumption. Measures include turning vanes, elimination of unnecessary bends, and reduced leakage. These measures are expected to drop fan pressure by 0.35 in. w.g. (Together with the elimination of reheat coils, the dual duct system is assumed to reduce static pressure by 0.6 in. w.g. The base case pressure is assumed to be 3.3 in. w.g., and this measure drops it to the measured value of 2.7 in. w.g.)

Although the dual-duct system appears to work very well, there are a few features that might improve future designs.

- First, the heating duct fan energy consumption could be reduced by using a variable speed fan drive and a furnace designed to handle low air flow.
- It may have been possible to reduce energy consumption even further by modifying the VAV mixing box controls to measure flow at the outlet of each box and allow the cool duct to close completely and maintain the minimum outlet flow using the warm duct air. As long as the necessary amount of outside air enters the system at the air handler, then it is distributed via recirculated air in the warm duct.[3]

[3] Transfer air may not be allowed for ventilation purposes by all standards.

The net savings for the dual-fan, dual-duct system are 11,690 kWh/y and 1,968 therms/y. Cooling energy drops by 13%, but the bigger impact is the 38% drop in heating fuel consumption due to reduced reheat energy. Fan energy increases by 22% due to the addition of the heating fan, which had relatively poor part load efficiency.

DDC Controls, VSD Supply Fan. This EEM combines a DDC system with a number of measures to improve cool duct supply fan performance. The DDC system is used to save energy in the following ways:

- *Optimal start controls.* Rather than turning the system on at the same times each morning, the control system calculates the latest start time so that the building will be at the desired temperature at the start of occupancy.
- *Optimal stop controls.* The system also shuts off heating or cooling, not ventilation, a short time before the end of the day, allowing the temperature to drift slightly. This measure saves some heating and cooling energy but not fan energy.
- *Improved compressor performance.* The DDC system is assumed to improve the air conditioning compressor performance, and is modeled as improving the peak efficiency by 7% and lowering the minimum unloading ratio from 25% to 20%.
- *Supply air temperature reset.* The DDC system controls the setpoints for cool and warm duct air temperatures based on zone temperatures.
- *Variable speed drive for the cool duct supply fan.* A variable speed drive replaces the base case inlet vanes to provide constant duct static pressure. Measured data is used to develop a part load efficiency curve for the fan (see Calibration Report, Eley 1997).
- *Synchronous fan belt drive and energy efficient motor.* A cogged fan belt improves the efficiency of the fan drive compared to standard V-belts. Together with a premium efficiency motor the improvement is assumed to be a 5% improvement in efficiency.

Savings are 9,897 kWh/y and 130 therms/y. Fan energy drops by 29% and cooling drops by 12%. Heating gas consumption drops 20%.

Undercabinet Task Lights. Twenty-four task lights with electronic ballasts (single, two-foot long, 17 W, T-8 lamp) and a built-in occupancy sensor replace the 30 W base-case fixtures (T-12 lamp with magnetic ballast and no occupancy sensor). Electricity savings are 2,259 kWh/y, and gas consumption increases by 16 therms/y.

Desktop Task Lights. Ten desktop task lights with electronic ballasts and a manual switch are installed with 13 W compact fluorescent bulbs replacing 60 W incandescent lamps. Electricity savings are 1,001 kWh/y, and heating increases by 8 therms.

Cooktop Hood Retrofit. The 75 W incandescent lightbulb was replaced with a compact fluorescent lamp. Operating hours are measured to be only 40 hours during the year. The lamp replacement reduces power by 68 W for total savings of 2.7 kWh/y.

External Insolation Control. This measure reduces cooling loads with a white roof surface (white elastomeric coating over mineral cap sheet) that reflects solar heat. The base case roof is a standard built-up type with a gravel surface. The improvement applies only to the flat portion of the roof, which covers about 6,000 ft^2. Electricity savings are 1,577 kWh/y, while heating fuel consumption increases by 37 therms. The impact is a 4% decrease in cooling and 7% increase in heating.

Non-Conductive Window Assembly. Non-metallic thermal breaks are installed between the interior and exterior metal window frames. The window frames save 856 kWh/y and 36 therms/y. Cooling drops by 3% and heating drops by 6%.

Low-Flow Fixtures. A total of five low-flow faucets are installed in the building. Savings are estimated to be 57 kWh/y.

Energy Star Computers. Forty-six Energy Star computers and monitors are installed throughout the office. This Energy Star system consists of a 486 CPU consuming 28-34 W, and a 17 inch color SVGA monitor consuming 80-95 W. After a specified period of inactivity, the monitor goes into a sleep mode that consumes almost no power, and the CPU reduces its consumption by about 4 W. Therefore, each system consumes 108-129 W during active mode and 25-29 W in sleep mode. The base case computer consumes 135 W continuously. The Energy Star computers provide the second greatest energy savings after the Form & Siting EEM. Electricity savings are 47,250 kWh/y, including a 41,939 kWh/y drop in plug loads (36% savings) and a decrease of 5,310 kWh/y in cooling and fans (13% savings). Heating rises by 434 therms/y, an 80% increase.

Energy-Efficient Coffee Maker. The base case coffee maker, a 1,700 W three-warmer automatic unit, is replaced with a more efficient 1400 W air pot system with no warmers.

Soft Drink Honor System. In place of installing a vending machine, soft drinks are sold from a refrigerator using an honor system. Assuming there is ample space in the existing refrigerator to avoid buying a second one from lack of space, the energy consumed by the avoided vending machine can be considered savings. The total electricity savings are 2,725 kWh/y, including 674 kWh/y for cooling and fans. Heating increases by 17 therms/y.

Storage Area Occupancy Sensors. Two occupancy sensors are installed in the storage room to control about 180 W of lighting. The lighting energy savings is 105 kWh/y.

High Efficiency Lighting. Several measures are included under this heading: T-8 lamps, high efficiency phosphors, compact fluorescent lamps, high efficiency fixtures (louvers, reflectors and heat removal), LED exit signs, and design methods. The result of this measure is to reduce the connected ambient lighting power from 0.88 W/ft^2 to 0.66 W/ft^2, a savings of about 25%. Other lighting measures were already implemented in the Form & Siting EEM. These include dimmable electronic ballasts, daylighting controls, lumen maintenance controls, and improved lighting design. Those measures combined to reduce area lighting power from the base case of 1.63 W/ft^2 to 0.88 W/ft^2. The direct lighting energy savings are 9,724 kWh/y, cooling savings are 1,114 kWh/y, and heating increases by 116 therms/y. The total electricity savings are 10,799 kWh/y.

Perimeter Blinds. To improve daylight penetration in the perimeter zones, perforated mini blinds were installed on the windows. The blinds are fixed at an angle that blocks most of the direct sun and that reflects light upward to the ceiling. The perforations allow some diffuse light to pass directly through and also allow a view of the outdoors when viewed from a distance. Because the perforated blinds do not completely block the view, they are more likely to be left in the down position by occupants. Lighting savings due to increased daylight penetration are estimated to be 1,270 kWh/y (4%).

SERP Refrigerator. A new Whirlpool SERP (super efficiency refrigerator program) refrigerator is installed in the lunchroom. The base case is a standard efficiency unit. The measured annual consumption is 822 kWh during the calibration year. Electricity usage for a typical (residential) new refrigerator is around 1,000 kWh/y. The original savings estimate of 230 kWh/y is slightly higher than suggested by measured consumption, but there are several reasons to believe that the original estimate is reasonable. First, usage may be higher in this commercial application than in a typical household. Second, there are two other EEMs that affect the refrigerator energy consumption: the soft drink honor system and the water filtration system. Both of those measures tend to increase the refrigerator energy consumption, although the exact size of the impact is not known. SERP refrigerators use 600 to 700 kWh/y in a typical residential application.

Point-of-Use DHW. A single 7,500 W point-of-use electric water heater is installed in the lunchroom. There is little standby loss since the water is heated on demand; there is no storage tank. The base case is a 30 gallon 4,500 W storage electric resistance heater serving the lavatories and lunchroom. Measured water heating energy usage is about 72 kWh/y.

Water Filtration System. Rather than install a standard electric water cooler, the refrigerator was ordered with a through-the-door water dispenser. An inline replaceable charcoal filter is installed on the water supply to the refrigerator to improve water quality without having to order bottled water. Total electricity savings are 156 kWh/y, and heating energy increases by about 1 therm/y.

Office Area Occupancy Sensors. Occupancy sensors are installed to control lights throughout the building, including office area, toilets, lunchroom, conference rooms and the foyer. The only exceptions are lights on 24-hour emergency circuits. These exceptions account for about 11% of installed lighting power. The design includes 27 control zones using about 60 motion sensors. Original savings estimates were 3,551 kWh/y of lighting energy and 215 kWh/y of indirect cooling energy. Actual savings appear to be about 4,950 kWh/y, an 18% reduction. Indirect cooling savings are 334 kWh/y and heating impact is an increase of 65 therms/y.

Evaporative Condenser. In the packaged air conditioner, the base case air-cooled condenser is replaced with an evaporative condenser. Water is sprayed on the condenser coils, and a fan draws outdoor air over the wet coils to evaporatively cool the refrigerant. The water is recirculated with a 1.5 hp pump that draws about 1.2 kW and runs whenever the compressors are running. The fan is cycled on and off to maintain the water temperature around 75 °F. The 3 hp fan motor draws 2.2 kW. The evaporative condenser improves system efficiency, providing most benefit on hot days. The peak cooling efficiency is about 0.74 kW/ton, excluding the supply fan (Eley 1997). However, the improvement in compressor efficiency is partially offset by the combined condenser pump and fan energy, which is greater than the power required for a condenser fan in a typical air-cooled unit (2 to 3 kW for a 30 ton unit). Therefore, at low loads when the outdoor air is cool, the evaporative condenser does not provide as much benefit and typically operates between 1.0 and 2.0 kW/ton. The original savings estimate was 9,783 kWh/y, a 37% reduction in cooling energy. The actual savings are estimated to be 4,853 kWh/y, a 16% reduction in cooling energy. Actual savings are lower because the partial-load performance was not as efficient as anticipated.

Variable Speed Compressor. The packaged air conditioning unit contains three scroll compressors with a total capacity of about 31 tons. In this measure, the first compressor (about 12 tons) is fitted with a variable speed drive to improve its part load performance. The variable speed drive eliminates the need for hot gas bypass at low load. Savings are estimated to be 3,496 kWh/y, a 14% decrease in cooling energy.

Conclusions and Observations

1. Measured electricity savings are 63% (vs. 70% predicted) and gas savings are 72% (vs. 69%).
2. The total mature market net present value of costs for the package is $115,000 and the total benefit (present value of energy savings) is about $224,700. The overall benefit-cost ratio is 1.95.
3. The EEM with the largest energy savings is Form & Siting, accounting for 52% of the total package savings. This EEM changes the base case two-story office to a one-story building with skylights for daylighting. The majority of the Form and Siting savings is in lighting energy and the associated cooling impact. The lighting savings are due to reduced lighting power and to daylighting controls.
4. The second largest EEM is Energy Star computers. These computers have controls to shut off the monitor and to reduce CPU energy consumption when the machine has been inactive for a specified period of time. The measure accounts for 16% of total package savings.
5. The measure with the greatest net present value (NPV) is the dual-fan dual-duct HVAC system. The measure accounts for about 14% of the total source energy savings and is estimated to have a negative first cost in the mature market case. The $31,277 NPV accounts for 28% of the $110,112 NPV for the entire package.
6. The EEMs reduce peak demand by 69%, from 144kW to 45kW. More than one-half of the demand savings are due to the Form & Siting EEM, which includes daylighting controls.
7. The commissioning process probably saved additional energy, although no attempt is made here to estimate the amount. This analysis assumes that systems in both the base case and the EEM package case work as they are intended. The actual building was commissioned and it appears that the systems work properly. It is possible that the base case would not have been as well commissioned and would not have operated as efficiently as assumed here.
8. Anecdotal information from occupants suggests fewer absences and greater occupant satisfaction compared to the previous office building.
9. The variable speed fan control appears to work well. Electric consumption for the cooling fan (3,300 kWh/y) is less than for the heating fan (4,100 kWh/y), even though the heating fan operates fewer hours and has a peak flow less than one-half of the cooling fan. Static pressure reset controls were not implemented due to control system limitations, and they would have reduced cooling fan consumption even further.
10. Heating fan part-load efficiency is relatively poor. The power varies from a peak of 3.5 kW to a minimum of 2.3 kW (except that the fan is off when no zones require heating). The system uses a bypass damper to ensure that a minimum amount of air flows across the furnace heat

exchanger. A furnace designed to allow lower air flow together with variable speed control of the heating fan would probably lead to improved energy savings.

11. The full load efficiency of the cooling system appears to match predicted performance, providing cooling at 0.75 kW/ton at theoretical full load (excluding supply fan energy). However, the highest measured efficiency is about 1.0 kW/ton at roughly 70% load, and much of the operation is at efficiencies between 1.0 and 2.0 kW/ton.
12. The primary cooling system controls appear to consume an unusually large amount of energy. The measured data reveal a fairly constant 500 W demand for the packaged unit throughout the calibration year. Together with the HVAC controls (including the building management system and VAV box power), the constant load climbs to around 750 W. The project's Calibration Report (Eley 1997) shows that controls account for 19% of the cooling energy in the month of August. In the winter it is a much larger fraction.
13. It appears that the third compressor is seldom necessary. The control program used for the cooling system often turns on both compressor #2 and #3 when zone temperatures rise and the supply air temperature is reset down to 55°F. Generally, compressor #3 stays on for a couple of minutes and then turns off. Revised controls might significantly reduce the operating time for the third compressor.
14. Savings for the Energy Star computers are based on the assumption that the computers are left on 24 h/day This assumption is considered reasonable because it appears that it was standard practice when the occupants moved in. However, the savings would be significantly lower, by 70% to 80%, if the base case computers were assumed to be shut off at night.

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