Energy Savings from Daylighting: A Controlled Experiment

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ABSTRACT

Measuring energy and demand impacts from daylighting-maximizing strategies in commercial buildings can be difficult, particularly when these involve changes in fenestration and fixture specifications in addition to lighting controls. Moreover, though it is well-known that daylighting strategies affect heating and cooling loads, actual measurement of these HVAC impacts is rare.

This paper attempts to address these issues by summarizing the results of a case/control experiment conducted at the highly-instrumented Energy Resource Station near Des Moines, Iowa. For the experiment, lighting and HVAC loads were monitored for two sets of identical rooms. The rooms differed only in their electric lighting and fenestration characteristics: one set of rooms (test rooms) used reduced transmission glazing, direct/indirect fluorescent fixtures, and photosensor lighting controls; the other set of rooms (control rooms) used clear glazing, conventional overhead fixtures, and no lighting controls. This arrangement allowed for a direct comparison of energy consumption and other parameters between the two configurations over three seasons and a variety of weather conditions.

The results indicate overall operating cost savings of 22 percent for the test rooms relative to the control rooms, with 32 percent lower lighting energy use, 25 percent lower cooling energy requirements, and a 28 percent reduction in estimated demand charges. A surprising result is that the experiment showed little heating load penalty from the daylighting strategy: while heating loads were indeed higher in these rooms in very cold weather, this was offset by reduced need for terminal reheat due to room-to-room load imbalances under milder conditions.

Introduction

A key feature of energy efficient commercial building design is maximizing the use of natural daylight to supplant electric lighting in interior spaces. Natural light entering through windows and skylights is not only free, but can also provide occupants with a feeling of connection to the outdoors. Moreover, when properly designed to minimize direct beam penetration, the use of natural daylight provides the most light for the least amount of internal heat gain—an important quality given that even in northern climates mechanical cooling of interior spaces is often needed for much of the year.

Measuring the energy savings from daylighting strategies can be difficult, however. First, there is the variable nature of daylight itself: since the amount of daylight varies diurnally, seasonally and according to the weather, the ability to supplant electric lighting is highly variable. Second, designs intended to maximize natural daylight may also involve other changes that themselves directly affect building energy use, such as the use of glazing with reduced visible transmission to control glare. Third, fully integrated daylighting designs are typically applied in new construction, obviating the ability to make direct before/after measurements of energy consumption.

For all of these reasons, energy impacts from daylighting strategies are more often derived from computer simulation than from direct measurement. This is especially true of the heating, ventilating and air conditioning (HVAC) impacts of daylighting. While a number of field monitoring studies have documented the direct energy impacts on electric lighting (see e.g., Benya et al., 2003 and Reed et al., 1995), we have seen none that attempted to directly isolate and measure HVAC impacts from daylighting strategies—although some studies have documented the impact of daylighting strategies on cooling equipment sizing (e.g., RPI, 2003 and Theyer, 1996). In at least one case, researchers compared overall energy consumption between new daylit and non-daylit schools (Nicklas and Bailey, 1996). However, none of these studies attempted to quantify the related performance benefits or penalties of daylighting designs on the HVAC system.

We therefore designed and implemented an experimental field study specifically to measure both the direct lighting and indirect HVAC impacts of a daylighting strategy that included photosensor lighting controls and reduced VT glazing to control glare. This paper reviews the results of this experiment, which was funded by the Association of State Energy Research and Technology Transfer Institutions, Inc. (ASERTTI), the National Association of State Energy Officials (NASEO), the Department of Energy (DOE) and the Energy Smart Schools Program as part of a larger joint project that encompassed applied research, field testing and technology integration. A more complete description of the research described here can be found in Pigg, 2005.

Methods

The Experimental Set-Up

The experiment was conducted at the Energy Resource Station in Ankeny, Iowa just north of Des Moines. This highly instrumented facility is specifically designed for multiple, full-scale tests and demonstrations involving commercial building lighting and HVAC systems.

The facility contains eight test rooms, each measuring 267 square feet in size. The rooms are paired into “A” and “B” sets, which are served by separate but identical HVAC systems. There are pairs of rooms on the east, south, and west faces of the building, as well as a pair of interior rooms (Figure 1).

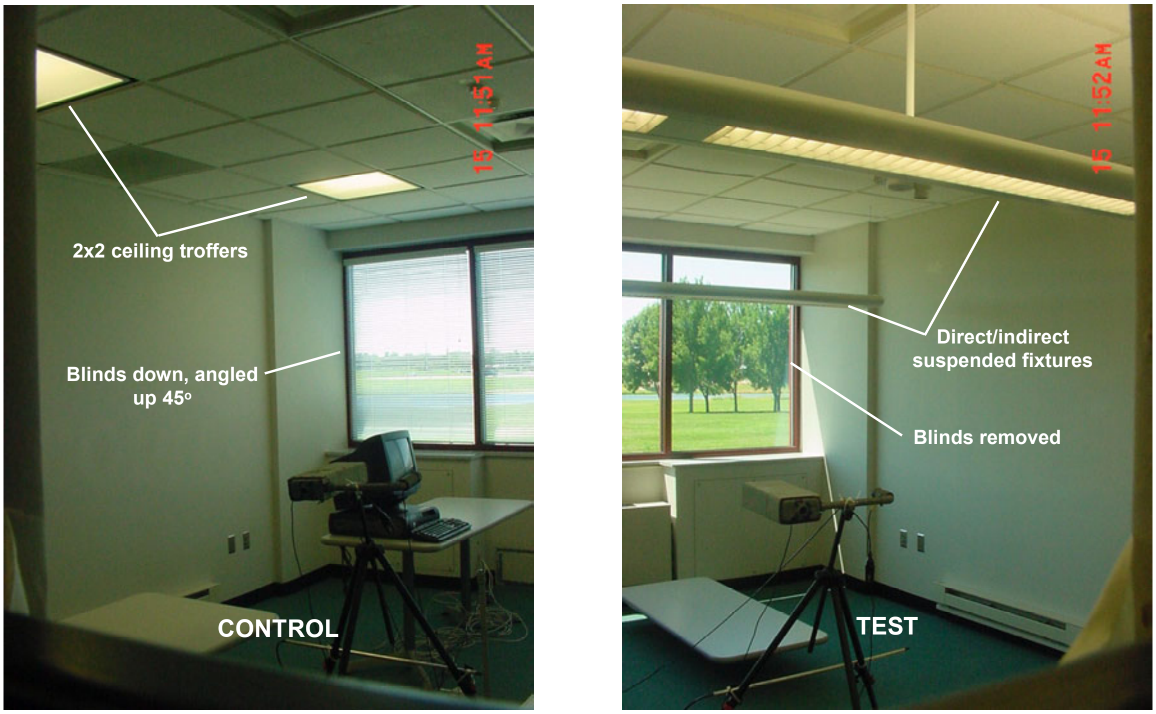
For the project, the control (“A”) rooms were set up to represent a typical standard commercial configuration with ceiling troffers and clear glazing (Table1, Figure 2). The test (“B”) rooms (except the interior room) were configured for a daylighting design that included automatic, photosensor-based dimming controls on direct/indirect suspended fixtures, and windows with reduced visible transmittance to reduce glare. Blinds were used in the control rooms, but were removed in the test rooms. The lighting in all rooms provided about 50 foot-candles of vertical illumination in the absence of daylight. Lighting in each of the control rooms on the exterior of the building drew about 354 Watts, while the test rooms drew about 365 watts of lighting electricity at full output. The two interior rooms were configured identically without dimming control, and each had about 530 Watts of lighting power draw. The dimming controls in the test rooms were commissioned to ensure that they were working properly.

Figure 1. Test Facility Layout

Table 1. Lighting and Window Configuration for Test and Control Rooms

		Daylighting Configuration (Test rooms)	Standard Configuration (Control rooms)
Electric Lighting			
	Fixtures	Two 1x12 suspended direct/indirect fixtures.	Four 2x2 lay-in troffers.
	Lamps	Six 4-foot T-8 lamps per fixture.	Three T-8, U-tube lamps per fixture.
	Controls	Photosensor-controlled continuous dimming from 40% to 100% of full output.	None
Windows			
Transmittance	*visible*	23%	73%
	solar energy	14%	52%
	ultraviolet	5%	36%
Shading coefficient		0.26	0.76
Solar Heat Gain Coefficient (SHGC)		0.22	0.66
U-value	*winter night time*	0.31	0.33
	summer daytime	0.33	0.35
Blinds		Removed	Down, angled up 45°

Figure 2. Views of South Test and Control Rooms



In other respects, the two sets of rooms were configured and operated identically. Electric lighting was turned on from 7 a.m. to 6 p.m. in both sets of rooms to simulate a typical classroom or office environment, and 1 kW of electric heat load was introduced into each room between 8 am and 6pm to simulate internal gains from equipment and people.

The Energy Resource Station has the flexibility to operate in a number of HVAC configurations: for the purposes of this project, the system was configured as a typical variable-air-volume (VAV) system with hydronic reheat. Cooling is provided by a single 10-ton (nominal) air-cooled chiller, which supplies chilled glycol solution to separate central coils for each air handler loop. The system was configured to economize cooling energy by introducing outdoor air when outdoor conditions were amenable. Heating is provided by a single condensing boiler that provides hot water to reheat coils in the VAV boxes for each room.

Each set of rooms has a separate air distribution system with supply and return fans, economizer dampers, and dampers for each room. The VAV system works by modulating airflow to the rooms based on the demand for heating or cooling from the thermostats in each room, with a minimum flow of 200 cfm to each room. All rooms were operated with a 72^{o}F heating setpoint during the defined occupied period of 7 am to 6 pm and a 60^{o}F heating setpoint during unoccupied periods. Cooling set points were set to 75^{o}F during occupied periods and 80F during unoccupied periods.

For the test, ventilation air was based on 15 cfm per person with an assumed occupancy of six people per room. The outdoor air damper was set at a fixed position to achieve this ventilation rate at 1,800 cfm total supply air.

Testing and Monitoring

Three rounds of monitoring were conducted for the project between July 2003 and January 2004: Summer (early July to early August), Fall (late September to late October), and Winter (early December to early January). Within each round, three slightly different configurations of the test rooms were employed for roughly one-week each:

- Base case
- Reduced fenestration
- Interior light shelf

The base case was as described above. The daylighting rooms were simply operated with blinds up and photosensor dimming. For the second configuration, exterior panels were used to effectively reduce the window area in the daylighting rooms by about one third. These panels had an insulating value approximately equivalent to the wall sections they were meant to simulate. In the third configuration, a temporary interior light shelf was created to help daylight reflect more deeply into the rooms.

The strategy behind these configurations was to allow for additional comparisons across the daylighting configuration variants. However, while the overall experimental design allowed for a direct comparison between the test and control rooms under identical weather conditions, comparisons across the daylighting variants were subject to differences in weather conditions, since they were implemented sequentially within each test round.

About 600 parameters are routinely tracked and stored (as one-minute averages) at the Iowa Resource Station. Key parameters for this study included lighting energy use, light levels, space heating and cooling loads, HVAC system airflow, psychrometrics and energy use, indoor temperatures and humidity and outdoor weather conditions.

Results

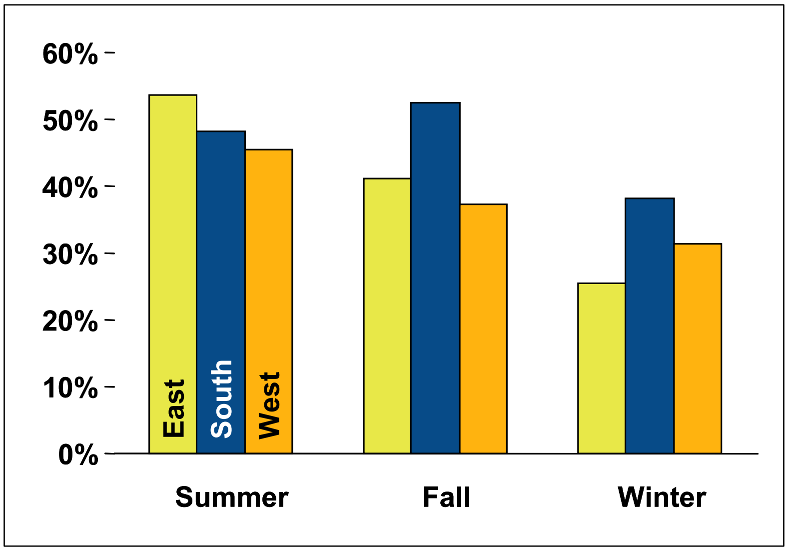
Lighting Energy

As expected, lighting energy was substantially lower for the test rooms with direct/indirect fixtures and dimming controls (Figure 3). Electric lighting in each of the control rooms (excluding the interior room) averaged 353 watts of power consumption during operating hours, with less than one percent variation across rooms and test periods. Overall, the test rooms averaged 208 watts of power draw during operating hours, indicating an average savings of 41 percent relative to the control rooms. These savings are diluted to 32 percent when the interior rooms—which were identical for the test and control setups, and account for a quarter of the floor space—are included.

Differences in lighting energy use across the three test conditions (base case, reduced fenestration and light shelf) were minor. The reduced-fenestration test case exhibited somewhat lower savings for given sky conditions than the other two test conditions. Because differences in lighting energy across the test conditions were small, we did not distinguish among these in subsequent analyses.

Center-of-room, vertical illuminance light levels in the control rooms were generally higher than the design target of 50 foot-candles because of daylight penetration into the rooms, which were configured for 50 foot-candles of uncontrolled electric lighting. Light levels in the test rooms were at about 50 foot-candles except during periods of direct solar beam penetration through the windows.

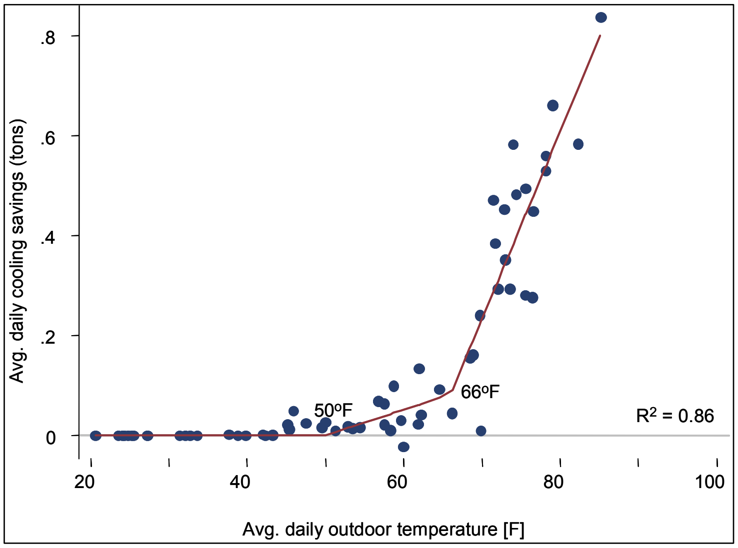
Figure 3. Lighting Savings (Relative to Control Rooms)



Cooling Energy and Peak Load

We analyzed cooling impacts by calculating the daily average cooling load on the central chiller coil for each set of rooms. The data show a need for mechanical cooling down to a daily average outdoor temperature of 45°F with a fairly linear relationship between daily cooling load and daily outdoor temperature.

Figure 4. Cooling Energy Savings versus Outdoor Temperature



To assess cooling energy savings, we directly modeled the observed difference in daily average cooling load between the two sets of rooms with a two-slope function that allowed for a separate savings relationship when the systems were in the temperature range for economizer operation (Figure 4). Cooling energy was substantially lower for the test rooms in hot weather: the observed difference in cooling load between the test rooms and the control rooms averaged about 45 percent on hot days that reached above 90°F, but was only about 10 percent lower on days where the temperature reached into the 70s. When combined with the long-term average temperature distribution for Des Moines (and accounting for changing chiller efficiency with temperature), the data indicate that the test rooms will average about 25 percent less cooling energy than the control rooms on an annual basis, for a savings of about 0.83 kWh/ft^2.

These savings derive from three differences between the two configurations: (1) reduced need to remove heat from dimmed electric lighting; (2) reduced heat gain through the high-performance windows; and, (3) reduced cooling required to condition ventilation air, which increases as the other cooling loads increase. Under hot conditions, the last two factors dominate, as electric lighting represents only about 10 percent of the building's cooling load on 90°F+ days. Indeed, the data suggest that about half of the cooling energy savings arise from reduced need to condition outdoor air introduced by the system.

The differential impact of direct solar gain through the windows is exemplified in the fact that on a number of warm summer evenings, solar gain through the window of the west control room pushed the room temperature above the unoccupied-mode setpoint of 80°F, which triggered additional cooling operation for the control rooms. While temperature in the west test room also rose during these periods, it never exceeded the thermostat setpoint.

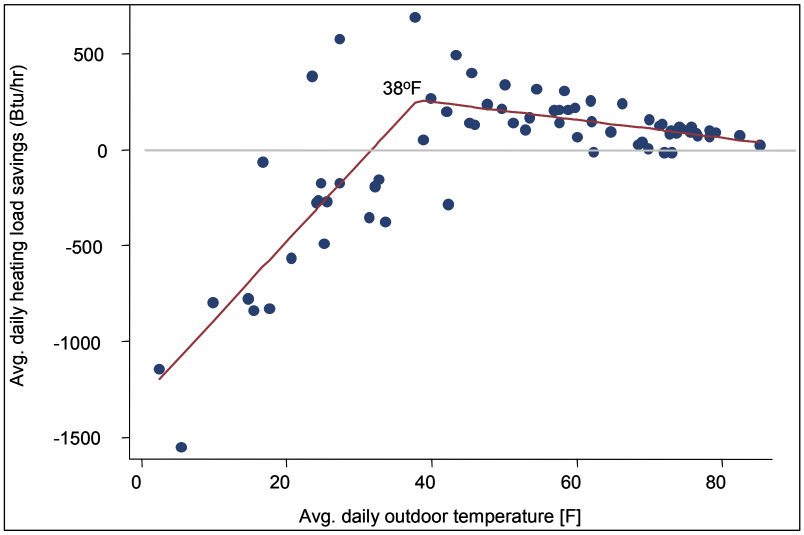
When we examined peak hourly chiller loads across the two sets of rooms (which tended to fall between 2pm and 5pm), we found that the test rooms averaged 26 percent lower peak cooling load at a Des Moines design temperature of 93°F.

Heating Energy

We analyzed heating energy use in a fashion similar to cooling energy; that is, by modeling total daily heating energy consumption versus outdoor temperature. The data indicate that heating energy is used on days when the outdoor temperature averages about 68°F or less. On the upper end of the temperature range, heating is mostly needed for re-heat in the VAV system when some rooms are calling for cooling but others are not; on days when the heating load on the building exceeds the building balance-point temperature, heating is needed to maintain the heating setpoint temperature.

As with the analysis of cooling energy, we directly analyzed the difference in heating energy requirements between the test rooms and the control rooms as a function of outdoor temperature (Figure 5). As one would expect, the reduced internal heat gains from electric lighting and solar gains in the test rooms mean that additional heating is required when the building is in heating mode. However, the data also reveal that somewhat *less* heating energy is needed for re-heat purposes at warmer temperatures. The data suggest that reduced cooling loads in the exterior test rooms translates into less re-heat energy for the interior room to prevent overcooling.

Figure 5. Heating Savings versus Outdoor Temperature



When combined with long-term temperature data for Des Moines, the data suggest that there is only a small net difference between the test and control rooms in terms of heating energy needs: extra heating requirements for the test rooms under the relatively infrequent cold conditions are almost completely offset by reduced heating needs for cooling-mode reheat that occur over many more days. The end result is that the test rooms use only about one percent more heating energy than the control rooms.

Fan Energy

Each set of rooms is served by a supply and return air handler. Fan energy tends to be highest under cold and hot conditions when heating and cooling loads are more extreme, and lowest at moderate temperatures. The data suggest that the test rooms have somewhat lower fan energy when the system is in cooling mode and the outdoor temperature averages more than 66^{o}F; at other temperatures we found no statistically significant difference in fan energy between the two sets of rooms. Extrapolated to long-run Des Moines temperatures, the analysis indicates about three percent lower fan energy consumption for the test rooms, or about 0.06 kWh per square foot per year.

Demand Charge Savings

Most commercial facilities incur utility charges not only for the electrical energy used in the building but also for the maximum power draw, or demand. These charges are typically divided into a monthly demand charge for the maximum 15-minute average power draw during the billing period and a rolling annual (or ratchet) charge for the largest power draw during the preceding year. Chiller electrical load and lighting are often key contributors to peak demand charges. We analyzed the difference in monthly peak and annual rolling demand between the two sets of rooms as follows:

1. We assumed a 25 percent smaller chiller for the test rooms compared to the control rooms.
2. We collapsed the 1-minute data to 15-minute averages for chiller load, HVAC fan and lighting electrical demand.
3. We analyzed the chiller load data for each 15-minute period. If cooling load was present but was half or less than the full capacity of the assumed chiller size, we assigned one-half the full chiller power draw to the 15-minute period; if the cooling load was more than half the full output capacity, we assigned the full chiller power draw to the period. This step was intended to reflect the operation of the two-stage chiller at the site. (We also adjusted chiller power draw for the empirical variation in efficiency with outdoor temperature.)
4. We then combined the lighting, chiller power and air handler 15-minute demand values, and found the maximum total electrical demand for each day.
5. Finally, we analyzed differences in the maximum daily lighting and HVAC demand between the test and control rooms, and extrapolated these to typical monthly weather for Des Moines.

We found that chiller operation dominated the difference between the two sets of rooms, and there was little difference in peak demand on days with no chiller operation. While it would seem intuitive that there should be substantial demand savings from the electric lighting alone, in fact the daylighting system calls for close to full output at some point during the short days of the winter months. Since our analysis does not take into account the contribution of plug loads to peak demand, this result could well be conservative: facilities that have substantial middle-of-the-day plug load peaks could see demand charge savings from the lighting controls alone during non-cooling months.

Nonetheless, given the results from our data that cooling loads alone determined peak demand reduction, it is not surprising that we calculated demand-charge savings that were comparable to the observed cooling load savings: about 22 percent savings on monthly demand charges, and 29 percent savings on the rolling annual charges which typically involve the high cooling demand on hot summer days. Note that these savings are predicated on the assumption that a smaller chiller is installed for the daylighting configuration.

Overall Operating Cost Savings

Using the savings estimates described in the previous sections, we applied typical Midwestern utility rates for commercial buildings (Table 2) to calculate the total operating cost savings between the test and control rooms.

The results are shown below in Table 3 in terms of operating costs and savings per square foot. Overall the calculations suggest about 22 percent savings for the test rooms, or about 24 cents per square foot savings on annual lighting and HVAC operating costs of a bit more than a dollar per square foot. Demand charge savings—stemming mainly from reduced cooling loads—make up nearly half of this amount. Energy savings for lighting and cooling make up most of the rest of the savings.

Table 2. Utility Rates Used in the Analysis

Electricity	on-peak energy	6	cents/kWh
	off-peak energy	3	cents/kWh
	monthly peak demand	6	$/KW
	annual peak demand ratchet	1	$/KW
Gas		75	cents/therm

Table 3. Annual Operating Costs and Savings per Square Foot

	Control room annual operating costs (cents/ft^2)	Test room savings (cents/ft^2)	Test room savings Percent
Lighting energy	21.6	6.8	32%
Cooling energy	19.2	4.8	25%
Heating energy	6.1	-0.1	-1%
Fan energy	13.0	0.3	3%
Demand charges	53.3	12.5	24%
Total	113.2	24.3	22%

Discussion

The data from this experiment demonstrate clear and substantial reductions in lighting and HVAC energy due to the lighting and window specifications. We have not attempted to extrapolate these findings to other building types and daylighting strategies: however, this experiment does provide some general lessons that may have wider applicability.

About two-thirds of the operating cost savings are due to reduced cooling loads in the building, and much of the cooling load reduction appears to be attributable to the high-performance windows, which have a solar heat gain coefficient that is one-third that of the windows in the control rooms. This may argue for optimizing fenestration to minimize solar gain (and glare) even if it comes at the expense of some electric lighting to realize an overall better performing building.

Also, the high performance windows—and to a lesser extent, the lighting controls—affect cooling both directly by reducing the amount of heat introduced into the conditioned space, and indirectly as reduced cooling loads translate first into reduced VAV system airflow and then into reduced outdoor air drawn into the system. It is somewhat surprising that about half of the cooling load savings in the test rooms are attributable to reduced need to condition ventilation air. This suggests that strategies to actively control the amount of outdoor air drawn into the system have the potential to further reduce cooling energy consumption. Alternatively, this angle also suggests that savings from the daylighting strategies tested here may be less in buildings that use active control of the outdoor-air damper to mitigate the introduction of excessive outdoor air as the need for cooling rises.

It is also important to note that half of the overall operating cost savings arise from the estimated reduction in monthly demand charges. These estimates are based on the important assumption that a 25 percent smaller chiller would be installed in buildings that use the daylighting strategy tested here. Without such downsizing, these demand charge savings would mostly be eliminated, since a larger chiller draws more power when it operates, even if it operates less frequently. In addition, the analysis here considers only HVAC and lighting loads; other electrical loads and occupancy patterns can also affect the overall electrical demand profile for a building.

In terms of lighting energy, the observed lighting energy savings, while substantial, could be increased further by employing controls that shut the lights off entirely when daylight levels are sufficient. This also raises the question of the use of blinds or other window treatments with reduced visible-transmission glass and daylighting controls. The experiment for this project effectively assumed no use of blinds, and therefore maximum daylight harvesting; in reality, use of blinds or other window treatments might mitigate the lighting savings.

Lighting savings are also obviously strongly dependent on building orientation and geometry: the results here reflect a simple rectangular geometry with 75 percent of the square footage in perimeter areas amenable to side daylighting and 25 percent in building core areas without side daylighting capability. Savings would undoubtedly be different for buildings where these factors differ.

Finally, note that savings from daylighting controls are notoriously sensitive to commissioning—or the lack thereof (Reed, 1996; Vaidya et al., 2004). The savings seen in this reflect careful performance tuning that might not always occur in the field.

Despite these caveats, we believe that the experiment described here provides an encouraging step towards quantifying and capitalizing on the energy benefits of daylighting.

The promising and (in the case of heating impacts) unexpected results indicate that more integrated system field research is needed if we are to find successful—and practical—strategies for whole building integrated design. While the research community acknowledges the importance of whole building design, we often attempt to find the penultimate solution for a specific system, ignoring the resulting performance impacts (both positive and negative) on other systems.

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