



Conservation Applied Research
& Development (CARD) Program
FINAL REPORT

Commissioning for Optimal Savings from Daylight Control

Prepared for: Minnesota Department of Commerce, Division of Energy Resources
Prepared by: Energy Center of Wisconsin



ENERGY CENTER
OF WISCONSIN

FEBRUARY 19, 2013
OES-04042011-34558

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ACKNOWLEDGEMENTS

This project was supported in part (or in whole) by a grant from the Minnesota Department of Commerce, Division of Energy Resources through the Conservation Applied Research and Development (CARD) program, which is funded by Minnesota ratepayers.

The authors would also like to acknowledge the following Energy Center of Wisconsin staff who contributed to this project including Mark Vincent, Dan Cautley, and Tom Holaday. Staff from Lutron Electronics also generously assisted with the commissioning step for Lutron control systems; contractors assisted in commissioning of other systems. The project also benefitted greatly from the time and effort of each of the building managers and engineers at the sites we studied. Thank you to all who participated.

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ABSTRACT

Automatic daylighting control is an energy savings strategy employed in many sustainable building projects. While considerable effort is often expended in the architectural and lighting design of daylighting control strategies, the actual execution of the controls is an area for substantial improvement. Best practices suggest that successful automatic daylighting controls require a significant commissioning effort (including calibration and functional testing) in order to reach full energy-savings potential. In this report, we discuss the results of monitoring and commissioning several daylighting control systems in Minnesota and Wisconsin. Results show potential for economical energy savings from daylighting controls, but that there are challenges in reaching that potential. Significant additional savings was observed with commissioning of the systems. Guidelines for successful execution, startup, and commissioning of these systems are also addressed in the report.

REPORT SUMMARY

BACKGROUND AND OBJECTIVE

Daylighting control, or daylight harvesting, is an energy savings strategy employed in many sustainable building projects. The technology, as it is defined in this report, refers to automatic daylighting control, in which the electric light levels in a building are automatically controlled (versus manually) based on the amount of natural daylight entering the space. Though the technology is still in a relatively early stage of adoption throughout much of the Midwest, it is growing in popularity, and new commercial building and energy codes are beginning to require it. But barriers still remain to *successful* implementation of the technology as mainstream practice in the region. The fundamental pieces of the system that generally receive much of the research and consulting focus are the fenestration design and the design/selection of the luminaires being controlled. However, in our experience the architectural and lighting design increasingly is proficient, and therefore the execution of the controls is more often the primary determinant of success. Even after a thorough design process, best practices suggest that successful automatic daylighting controls require significant calibration and commissioning efforts during and after construction in order to function properly and reach their energy savings potential. But—in addition to our own anecdotal evidence—research has suggested that operation falls well short of optimal after typical field calibration and startup procedures.

In this study we measure, analyze, and demonstrate the importance of commissioning daylighting systems, with specific focus on the calibration and functional testing aspect of commissioning that occur at startup. We hoped to determine the typical level of success achieved in commissioning, as well as the amount of savings being missed (and conversely, the amount of savings captured). If our hypothesis was correct and systems were falling short of optimal savings, then building professionals may be able to adjust practices, modify control specifications, and restate or simply include commissioning guidelines in projects where they are currently not applied to lighting. Efficiency programs in Minnesota and elsewhere could also use the results of the study to provide guidance when recommending daylighting controls and possibly add commissioning as a requirement of certain daylighting control savings measures.

To that end, we collected sub-hourly measurements of illuminance, lighting power, and heating/cooling data for 20 office and public assembly spaces in Minnesota and Wisconsin (a third major daylit building

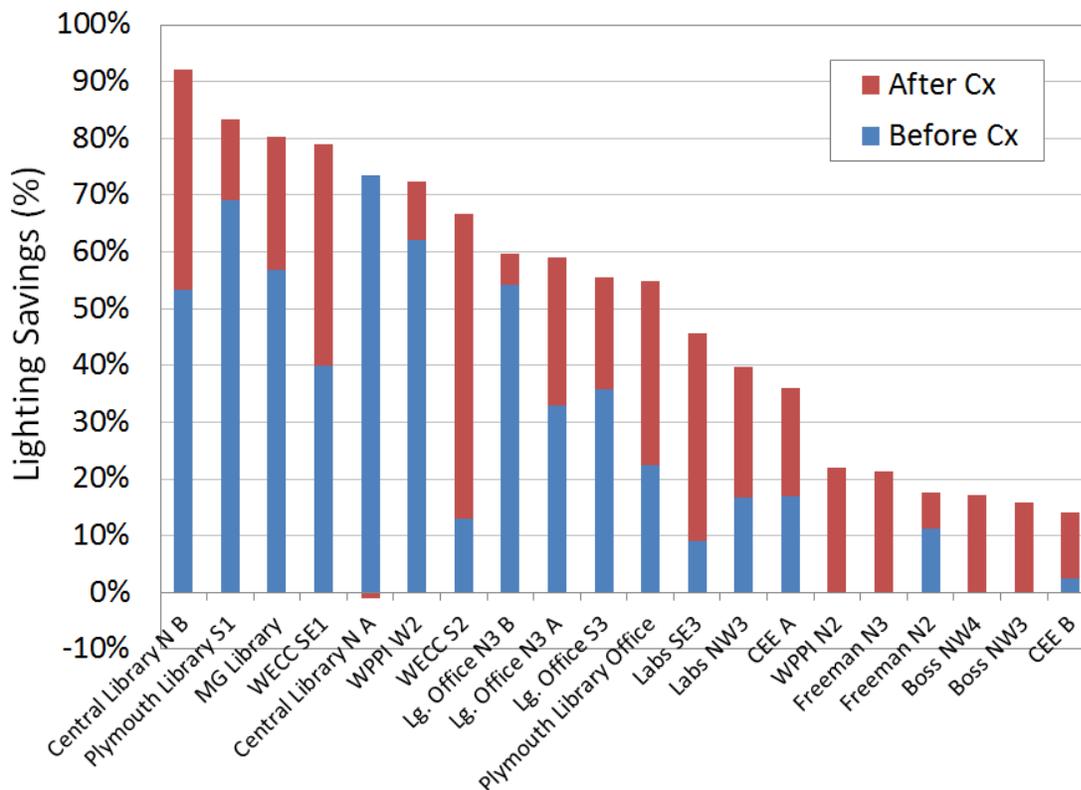
type, education, was left out of this study). Measurements were taken with the controls as they were found, and then repeated with the controls recommissioned¹ as closely as possible to ideal operation.

RESULTS

The median daylighting control system was saving 23% of lighting energy, including impacts on heating and cooling, during our initial measurements. This translated to 915 kWh saved for every kW of lighting controlled. But the average effectiveness (the energy saved versus energy saved with ideal control) of the controls as we found them was only 51%. This meant that almost half of the potential savings from these controls was not captured due to imperfect controls operation. In fact, four of the spaces had zero savings when we first measured them.

This low level of effectiveness was evidence of the lack of controls execution that we predicted. To demonstrate the positive impact of commissioning and subsequent controls operation on performance of a system, we recommissioned each system and then collected more data. We spent an hour or two in each space completing basic startup tasks such as tuning/calibration, shielding, and redirecting sensors, connecting disconnected systems, changing timing settings, and other adjustments. Figure S1 demonstrates the change in savings from before commissioning to after. Median lighting energy savings increased to 63%, or 1,976 kWh for each kW of lighting controlled (including heating/cooling impacts).

Figure S1. Energy savings in each space shown both before and after our recommissioning effort.



¹ We use the term recommissioned because all of these systems have operated for multiple years already, but note that it is possible that some were never initially commissioned.

We identified several problems that contributed to the initially lower performance level of the controls. Some of these problems (in decreasing order of frequency were): control calibration, improper zoning, heavy internal shading, improper relay connection, and furniture selection. Most of these problems were solved or mitigated through our basic commissioning process. Two issues could not be solved by this process. First, furniture selection issues occurred with cubicle walls that were too high; control systems performed well when the walls were at least five feet lower than the window head height. And secondly, the heavy internal shading was a result of glare problems, which should have been studied more closely in design.

With the results of our study showing potential for energy savings from daylighting controls but challenges in reaching that potential, we close by summarizing three opportunities for the industry to achieve the potential that daylighting controls offer.

OPPORTUNITY #1

When installed, commissioned, and operated to perform as designed, daylighting controls can be an economically attractive solution. With the levels of performance we measured, owners break even at a cost of \$1,000-2,200 per kW of controlled lighting for these systems, which is in line with current system costs. This opportunity is most promising in new construction or major renovation, where daylighting can be included as part of the design. But there are retrofit opportunities wherever daylight is abundant. Some utility programs (in Minnesota, Conservation Improvement Programs) take advantage of this savings opportunity already, in prescriptive and comprehensive programs. Those that do not could acquire additional savings with this measure—we estimate annual achievable potential between 1,100 – 5,600 MWh for the state.

OPPORTUNITY #2

We have identified a significant amount of savings being ‘left on the table’ in systems that are designed for substantial energy savings but which fall short. The median improvement in system savings with our commissioning effort was 88%, or 690 kWh per kW controlled. A path to retaining these savings in projects is a more robust, formalized commissioning focus on daylighting control systems. This value needs to be communicated in discussions among owners, designers, contractors, and utility program managers. The pieces of this commissioning effort that we found lacking and in need of formalization include: establishment of illuminance targets, review of design documents for component location, orientation, and sequence, functional testing of controls (including tuning), and verification that proper owner training has occurred (and the importance of those controls conveyed to the owner). In theory, commissioning of daylighting should already occur on projects with 3rd-party commissioning authorities, but several of the buildings we studied that had such an arrangement, had not commissioned the controls. The daylighting controls should be formalized into the commissioning scope and specifications early in design. Manufacturers can also get involved by providing thorough commissioning along with products, and perhaps more importantly by simplifying the controls interfaces. For utility program managers, this opportunity does not represent potential for new savings, but a risk mitigation strategy for the existing daylighting savings stream.

OPPORTUNITY #3

Finally, there is a substantial number of daylighting control systems already implemented that have room for improvement due to incomplete execution. Recommissioning saved an additional 690 kWh per kW of

lighting energy in the median case, and up to 2,420 kWh per kW in the worst case. This potential exists as an opportunity for consultants and contractors to offer a service in recommissioning of daylighting control systems, as well as an opportunity for Minnesota utility programs to include as a targeted component of lighting programs. We estimate a statewide annual achievable potential at 400 – 1,500 MWh from this opportunity.

INTRODUCTION

BACKGROUND

Daylighting control, or daylight harvesting, has matured into a common energy savings strategy employed in many sustainable building projects. The technology, as it is defined in this report, refers to automatic daylighting control, in which the electric light levels in a building are automatically controlled (versus manually) based on the amount of natural daylight entering the space. A common approach in commercial buildings is to configure the daylighting controls in a closed loop. This involves placing a photosensor in the controlled space such that it measures light level in the space directly, and is therefore affected by both electric and natural light. For this project we studied this type of system: closed loop, automatic daylighting controls.

As in other areas of the country, daylighting controls are increasingly being installed in buildings in the Midwest. But, the technology is still in a relatively early stage of adoption by much of the region's construction industry. And retrofits of these systems are even less common. Recently, new commercial building and energy codes are beginning to require daylighting control. But several barriers still remain to *successful* implementation of the technology as mainstream practice in the region. A significant focus of research and consulting efforts in this area has been the architectural and lighting design of daylighting control strategies. This is reasonable since the fenestration allowing the daylight to enter the space and the luminaires being controlled are the two fundamental pieces of the system. If the daylighting strategy is not explicitly considered in these two design disciplines, the system has a high chance of failure.² However, in our experience consulting on, auditing, and simply occupying spaces with daylighting control, we have found that the architectural and lighting design increasingly is proficient, although still not universally optimal (there is room for improvement in the industry here as well).

More often, at least anecdotally, we notice that the *execution* of the controls leads to performance issues. Even after a thorough design process, best practices suggest that successful automatic daylighting controls require significant calibration and commissioning efforts during and after construction in order to function properly and reach their energy savings potential.³ But in addition to our own anecdotal evidence, some research has suggested that operation falls well short of optimal with typical field calibration and startup procedures.^{4,5} This occurs even after significant effort and cost have gone into producing an architectural *and* lighting design specifically for daylighting control. Finally, commissioning has been mentioned in the 2012 International Energy Conservation Code (IECC), the new energy code slowly being adopted around the country⁶. This code mandates commissioning of daylighting controls, though there are few specifics regarding the steps involved, and enforcement is a potential problem.

² "What's Wrong with Daylighting? Where It Goes Wrong and How Users Respond to Failure," Vaidya, P., McDougall, T., Steinbock, J., Douglas, J., and Eijadi, D., Proceedings of ACEEE Summer Study, Panel 7, August, 2004 and "Sidelighting Photocontrols Field Study," Heschong Mahone Group, Inc., Report #06-152, 2005

³ "Tips for Daylighting with Windows", Lawrence Berkeley Laboratory:
<http://windows.lbl.gov/daylighting/designguide/designguide.html>, accessed July 2012.

⁴ "On the Calibration and Commissioning of Lighting Controls," Rubinstein, F., Avery, D., Jennings, J., and Blanc, S., Proceedings of the Right Light 4 Conference, Copenhagen, Denmark, November 19 – 21, 1997.

⁵ "Sidelighting Photocontrols Field Study," Heschong Mahone Group, Inc., Report #06-152, 2005

⁶ This code will likely be proposed for adoption in Minnesota in late 2013.

This loss of potential savings from daylighting controls wastes on the order of one to three kWh for every square foot of daylit space each year throughout the United States (and the world). In Minnesota, utility efficiency programs (known as Conservation Improvement Programs, or CIPs) already widely recommend automatic daylighting controls as a solution to save energy in commercial buildings. Some of these programs provide financial incentives for doing so; incentives are common in new construction but can be found in retrofit programs (typically on a custom basis, especially in new construction, but prescriptively in some cases).⁷ Therefore, the state of Minnesota funded this research examining daylighting control operation in an effort to more effectively capture savings from this opportunity. The buildings we studied in Minnesota are similar enough to the rest of the Midwest and most of the country that the results should be widely applicable to those areas as well.

OBJECTIVE

In this study we measure, analyze, and demonstrate the importance of commissioning daylighting systems, with specific focus on the calibration and functional testing aspect of commissioning that occur at startup. While we recognize that there are other elements of commissioning, the steps surrounding startup of the system were, in our opinion, the ones needing the most improvement. We hoped to determine the typical level of success achieved in commissioning, as well as the amount of savings being missed (and conversely, the amount of savings captured). If our hypothesis was correct and systems were falling short of optimal savings by a significant margin, then building professionals may be able to adjust practices to ensure that those savings are captured in the future. Engineers designing systems could potentially change control specification practices. Commissioning guidelines should be broadened and strengthened, or simply included in projects where they are currently not applied to lighting. Contractors could be trained to better understand the steps necessary to execute a successful daylighting control system and identify factors that could affect this outcome. Efficiency programs in Minnesota and throughout the world could also use the results of the study to provide guidance when recommending daylighting controls and possibly add commissioning as a requirement for certain daylighting control measure incentives.

Also, since we measure absolute performance of a sample of daylighting control systems in this project, we can subsequently estimate the absolute energy savings from effective daylighting design and control in Minnesota buildings (beyond just the component of savings from commissioning). Though there is already field research on the topic of daylighting control systems and their associated savings, much of it took place either several years ago when daylighting implementation was still in its infancy, or on the West Coast where the climate for daylighting is significantly different than in the Midwest. Though secondary and somewhat limited in scope, this piece of our study provides some additional data describing the absolute savings achievable in these systems. This will be of use for utilities, program managers, building designers, and building owners. For the benefit of Minnesota planners and program managers, these results will also be extrapolated to the state of Minnesota based on our limited data set.

In addition to the primary and secondary objectives above, we completed additional comparisons with our measured data. We used life cycle cost analysis to compare both the daylighting controls and the commissioning of the controls to some typical cost parameters to help determine economic effectiveness.

⁷ Additionally, within the state government, automatic daylighting controls are required in most spaces in state buildings under the State of Minnesota Sustainable Building Guidelines.

Also, we compared the performance of the daylighting controls with mainstream building energy practices to determine our ability to predict this performance. Results are also extrapolated to estimate opportunities across the state of Minnesota. Finally, the qualitative lessons we learned through observing and working with these systems and their operators will be passed on to the broader buildings community.

LITERATURE REVIEW

As discussed above, this work builds on a substantial amount of research already conducted in the area of automatic daylighting control.

Rubinstein et al.⁸ analyzed three different algorithms for dimming electric lights in response to changing daylight availability. The three basic components of a photo-electrically controlled light system were identified as: a photosensor, a controller, and a dimming unit. The algorithms analyzed included integral reset (adjusts dimming such that measured illuminance is kept constant), open-loop proportional, and closed-loop proportional. The different algorithms were tested in scale models to determine their accuracy in controlling the illuminance level on the workplane to a set level. Different room shapes, window geometries, glass transmittance, and exterior shading devices were introduced. The closed-loop proportional control performed best. This was particularly true when it had a large field of view that did not include the window.

Floyd and Parker⁹ performed a lighting retrofit on an elementary school cafeteria in Florida. The retrofit included an upgrade to lamp and ballast combinations, as well as installation of photosensor control. The building's lighting and HVAC energy usage, desktop illuminance, and exterior solar insolation were all monitored both before and after the retrofit. The daylight controls were calibrated in order to enhance their energy savings potential. Multiple issues arose during this process including the necessity of utilizing the shields on the photosensors, the need to locate photosensor sensitivity range (which was not readily available), and the requirement of trial and error to properly calibrate the lights due to differences between day and night performance. In the end, the retrofit showed a 16% energy savings attributable to the photosensor dimming of the lights.

In another research project, Rubinstein et al.¹⁰ discussed the importance of commissioning and calibration of photosensors as well as offered advice for effectively performing these tasks. Commissioning was described as a process for ensuring the lighting system performs as the design intended (the authors note that the majority of systems are not commissioned at all) and calibration is defined as the adjustment of a sensor in order to get the desired output from a given input. Specific activities for both calibration and commissioning included: verifying photosensor placement and orientation, adjusting sensor and controller, adjusting the sensitivity and time delay, and setting upper and lower dimming limits. Three tips for calibrating a photosensor were also outlined: 1) place the sensor in the ceiling near the primary working area, 2) calibrate the sensor at a distance if possible, and 3) use a photometer at the workplane to provide feedback.

Another paper by Galasiu et al.¹¹ evaluated the performance of photosensor-controlled electric lighting under different configurations of office spaces. Four office spaces in Ottawa, Canada were studied, each having a floor area of 150 ft², height of 9.8 ft, high visible transmittance (T_{vis}) windows and low T_{vis}

⁸ "Improving the Performance of Photo-Electrically Controlled Lighting Systems," Rubinstein, F., Ward, G., and Verderber, R., Presented at the Illuminating Engineering Society Annual Conference, Minneapolis, MN, August 7 – 11, 1988.

⁹ "Field Commissioning of a Daylight-Dimming Lighting system," Floyd, D. and Parker, D., Presented at the Right Light Tree, 3rd European Conference on Energy Efficient Lighting, Newcastle upon Tyne, England, June 18 – 21, 1995.

¹⁰ "On the Calibration and Commissioning of Lighting Controls," Rubinstein, F., Avery, D., Jennings, J., and Blanc, S., Proceedings of the Right Light 4 Conference, Copenhagen, Denmark, November 19 – 21, 1997.

¹¹ "Field Performance of Daylight-Linked Lighting Controls," Galasiu, A., Atif, M., and MacDonald, R., IES Conference Proceedings, Ottawa, Ontario, August 2001.

clerestory. Two of the offices had electronic dimming ballasts, while the other two had on/off controls. One of the “dimming” offices and one of the “on/off” offices had motorized blinds tied to the photosensors. Preliminary results showed that adding static blinds increased the electric lighting usage by 40-45% for the “on/off” and 30-35% for the “dimming” system.

Vaidya et. al¹² summarized eight case studies of various projects that employed daylighting controls. Each project encountered issues and the authors analyzed the failure mechanism and how the users coped with them. A method of failure analysis was developed and four typical failure modes were identified. Finally, a template for resolving each kind of failure was developed. The case studies covered a wide range of space types and daylighting control systems. Typical operational problems included too many photosensors, poor or no calibration, lack of operator education/buy-in, dark interiors, and poorly matched components. These led to failures that were characterized into four modes: under-dimming, over-dimming, cycling, and lights being left on overnight. These issues could have been mitigated through proper controls calibration or commissioning, better coordination between design disciplines, and more checks of the contractor shop drawings.

The Hescong Mahone Group¹³ conducted a very broad study of existing daylight-responsive lighting controls in sidelit buildings. The study covered 123 spaces in 49 different buildings mostly consisting of offices and classrooms. Measurements were taken for two weeks of controlled electric lighting current, uncontrolled electric lighting current, and the vertical illuminance entering the window. Through these measurements, the electric lighting savings for the actual, installed daylight control system was calculated by comparing the measured current to the total current during occupied periods. An eQUEST energy model of each space was then constructed with real-time weather to approximate the electric lighting savings for an idealized, perfectly operating daylight control system. The ratio of measured savings to predicted savings (called RSR), was then calculated for each space. A little more than half of the spaces had controls that were either not functioning or achieving no savings. Roughly half of those systems were intentionally disabled. It was common that all of the spaces in a building with daylight controls were disabled together, instead of only in problematic spaces.

The daylighting control systems in the remaining spaces were achieving actual energy savings of roughly half of the predicted savings. This equated to a lighting energy savings of approximately 1.1 kWh/ft²-yr and a net peak demand reduction of approximately 0.6 W/ft² of photosensor controlled area. Higher levels of energy savings were correlated with more uniform daylighting. These were often accomplished via windows on multiple facades, utilizing glazing with high visible transmittance, ensuring that the interior surfaces had high reflectances, and minimizing partition heights. Dimming controls had higher rates of functionality with only slightly less overall energy savings when compared to stepped systems. Further, the highest performing systems were in spaces with controlled zone depths no greater than two times the window head height. Older systems were actually found to save more energy than newer ones. The study concluded that both integrating the design of the architecture, lighting and controls as well as educating the building occupants were instrumental in the success of daylighting controls systems.

¹² “What’s Wrong with Daylighting? Where It Goes Wrong and How Users Respond to Failure,” Vaidya, P., McDougall, T., Steinbock, J., Douglas, J., and Eijadi, D., Proceedings of ACEEE Summer Study, Panel 7, August, 2004.

¹³ “Sidelighting Photocontrols Field Study,” Hescong Mahone Group, Inc., Report #06-152, 2005

In addition to the field research in this area, consultants and researchers have also compiled some guiding documents for proper calibration and commissioning of daylighting systems. The International Energy Agency compiled a Calibration and Commissioning Guide for such systems, covering commissioning from pre-design through occupancy.¹⁴ Rubinstein et. al published guidance that included best practices, challenges in commissioning today's lighting controls, and advice to specifiers for identifying the most appropriate control systems.¹⁵ Lawrence Berkeley Laboratory has also compiled an online design guide for daylighting with an entire section on calibration with specific steps for calibrating several system types.¹⁶

¹⁴ *Daylight Control Systems Calibration and Commissioning Guide*, Butcher, M.; IEA Solar Heating and Cooling Programme; May 2006.

¹⁵ "On the Calibration and Commissioning of Lighting Controls," Rubinstein, F., Avery, D., Jennings, J., and Blanc, S., Proceedings of the Right Light 4 Conference, Copenhagen, Denmark, November 19 – 21, 1997.

¹⁶ "Tips for Daylighting with Windows", Lawrence Berkeley Laboratory:
<http://windows.lbl.gov/daylighting/designguide/designguide.html>, accessed July 2012.

DATA COLLECTION

The first step in collecting daylighting controls data involved creating a sample of buildings and spaces representative of the average Minnesota daylighting system. Our budget dictated a sample of approximately 20 spaces.

Our general strategy was to collect data over three separate periods of time. In period 1, the control system would be monitored in its as-found state. In period 2, the daylighting part of the control system would be disabled, while the other lighting controls, such as occupancy sensors, switches, and time clocks, would remain functional such that the system would behave exactly as it would without daylighting controls. Prior to period 3, we would, with the help of knowledgeable contractors and manufacturer technicians, complete a basic recommissioning¹⁷ of the system.

Various levels of commissioning had been completed initially to the spaces that we sampled, ranging from no commissioning to significant commissioning. Therefore, the results of period 1 would yield a measure of the typical performance of these systems with typical levels of startup calibration and functional testing. Conversely, the results of period 3 would yield a measure of the systems' near-optimal performance or at least as close to optimal as an ideal startup and functional testing process would have achieved. The difference between these two periods would also be a key focus as it would describe how much savings is being missed in systems that are not properly commissioned. Period 2 was primarily used as a benchmark for our daylighting energy savings calculations. Due to time constraints, these three periods of data collection were spread over a six-month period, and then normalized for daylight levels across each.

THE SPACES

We began locating daylit spaces for our study by reaching out to members of the architecture, engineering, education, utility, and research communities. We found a range of space types, owner types, and system types, but several similarities arose. A majority of the daylighting designs were sidelit with continuous dimming, and faced nearer to north or south than east or west.¹⁸ The space types identified were largely in three sectors: 55% office, 13% public assembly, and 23% education.

With this information, and a statistically small number of spaces (20) in the budget, we quickly narrowed the field to include only buildings from two common daylighting applications: offices and public assembly. The public assembly spaces were specifically focused on libraries in our study, but seemed indicative of any public assembly space with long operating hours.¹⁹ Initial data collection for the project occurred in 43 of these spaces. We visited each of these spaces and recorded 32 parameters to describe the space, with a primary goal of selecting 20 typical spaces for in-depth study. We collected information on geometry, daylighting control parameters, lighting parameters, and architectural properties. Table 1

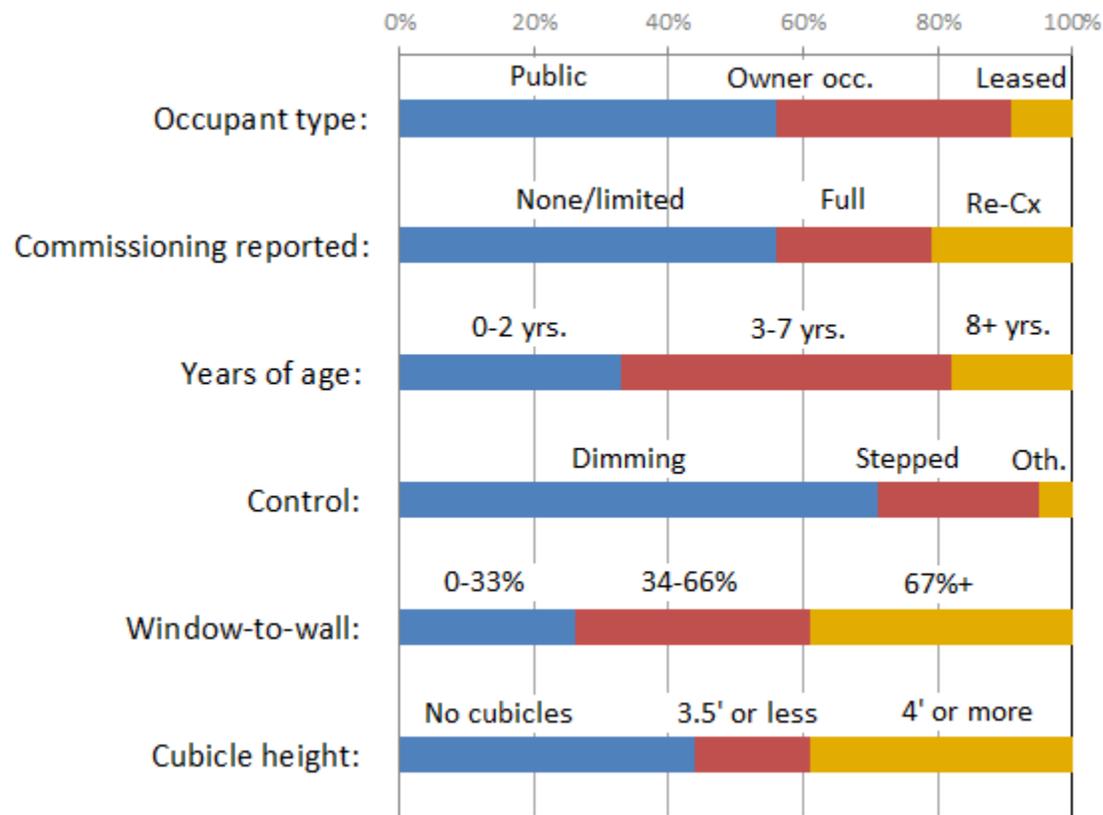
¹⁷ We use the term recommissioned because all of these systems have operated for multiple years already, but note that it is possible that some were never initially commissioned.

¹⁸ Interestingly, most of the spaces weren't due south or north, but rather within 20 degrees of north or south.

¹⁹ This left 'education' buildings as the only fundamental building type with substantial daylighting control penetration that is not considered here. It has been the subject of other studies, but more importantly is much more difficult to study than our subject building types because of the random usage and significant use of manual control and A/V lighting.

summarizes the spaces that were considered in this initial set of site visits, and approximates a characterization of typical daylit offices and public assembly spaces in Minnesota.²⁰

Table 1. Summary of space population considered for study (N=43).



The spaces ultimately chosen for in-depth monitoring were from 10 different buildings, an average of two spaces per building. When multiple spaces were chosen in a particular building they were chosen to be significantly different in orientation, usage, or perceived level of commissioning in an attempt to achieve a representative sampling of spaces. These final 20 spaces are listed in Table 2, along with key daylighting characteristics including orientation, control method (dimming, etc.), and net window-to-wall ration (WWR).

²⁰ In the end, the sample size was not big enough for three building types. Education was deemed problematic for inclusion in the study due to AV considerations, dynamic occupancy, and other interfering lighting controls (occupancy sensors). Additionally, the open study areas in the library were more similar to open office.

Table 2. The twenty spaces we monitored for the study.

Space Identifier	City	Space Type	Orientation	Year Installed	Owner type	Sensor Location	On-off / Stepped / Dimming	Net WWR	Furniture?
Boss NW3	St. Paul	Open office	NW	2004	Owner occ.	Ceiling	Combination	45%	5.5' cubes
Boss NW4	St. Paul	Open office	NW	2004	Owner occ.	Ceiling	Combination	45%	5.5' cubes
Labs NW3	St. Paul	Open office	NW	2005	Public	Ceiling	Dimming	60%	3.5' cubes
Labs SE3	St. Paul	Open office	SE	2005	Public	Ceiling	Dimming	60%	3.5' cubes
Freeman N3	St. Paul	Open office	NW	2005	Public	Ceiling	Dimming	58%	5.5' cubes
Freeman N2	St. Paul	Open office	NW	2005	Public	Ceiling	Dimming	58%	5.5' cubes
Lg. Office N3 A	Not disclosed	Open office	N	2008	Owner occ.	Ceiling	Dimming	75%	3.5' cubes
Lg. Office S3	Not disclosed	Open office	S	2008	Owner occ.	Ceiling	Dimming	70%	3.5' cubes
Lg. Office N3 B	Not disclosed	Private office	N	2008	Owner occ.	Ceiling	Dimming	75%	Desktops
MG Library	Maple Grove	Libr. rdg. area/stacks	S	2010	Public	Suspended	Dimming	75%	Mixed
CEE A	Minneapolis	Open office	Prim. Toplit	2009	Leased	Fixture	Dimming	N/A	5.5' cubes
CEE B	Minneapolis	Private office	Prim. Toplit	2009	Leased	Fixture	Dimming	N/A	Desktops
Central Library N A	Minneapolis	Libr. reading area	N-NE	2006	Public	Suspended	Dimming	95%	Desktops
Central Library N B	Minneapolis	Libr. reading area	N-NE	2006	Public	Suspended	Dimming	95%	Desktops
Plymouth Library Off.	Plymouth	Open office	N	2010	Public	Suspended	Dimming	25%	5.3' cubes
Plymouth Library S1	Plymouth	Libr. reading area	S	2010	Public	Ceiling	Dimming	80%	Desktops
WPPI W2	Madison (WI)	Open office	W-NW	2009	Owner occ.	Ceiling	2 stepped	95%	4.5' cubes
WPPI N2	Madison (WI)	Open office	N-NW	2009	Owner occ.	Ceiling	2 stepped	28%	4.5' cubes
WECC SE1	Madison (WI)	Open office	S	2007	Owner occ.	Fixture	Dimming	34%	3.5' cubes
WECC S2	Madison (WI)	Open office	S	2007	Owner occ.	Fixture	Dimming	34%	3.5' cubes

Note that the final four spaces are in Wisconsin rather than Minnesota. It was beneficial to study a few spaces in immediate proximity so we could conduct more frequent, detailed visits, especially early in experimental setup. The Wisconsin locations had a similar climate to the Minnesota sites.

DATA ACQUISITION PROTOCOL

In each space we installed continuous monitoring equipment to collect several data points, across all three periods discussed above. Period 1 of continuous data monitoring began on Friday, January 13th, 2012 at midnight, and monitoring concluded at the end of Period 3 on Tuesday, July 10th, 2012. The following points were continuously monitored with individual data loggers:

- **Current of controlled lighting circuit(s).** A properly rated current transducer was placed on the photosensor-controlled circuit or circuits to measure the electric lighting's current.
- **Critical 'Workplane' illuminance.** Illuminance at critical workplanes was measured indirectly via factory-calibrated photosensors placed in the space; the process for deriving workplace illuminance from these measurements is described in the section on *Methodology and Analysis*.
- **'Open loop' illuminance.** Low resolution photosensors were placed directly in front of the window or windows in the space to measure the relative amount of light entering the space through the window.
- **HVAC supply air temperature.** The air temperature at the HVAC diffuser was measured using a temperature data logger. This was used to determine when the space was being heated and when it was being cooled. All the spaces studied used some type of air distribution for both heating and cooling.

In addition to these continuous measurements, handheld equipment was also used to take spot measurements of the following:

- **Voltage and power factor.** A power quality meter was used to measure the voltage and power factor of the controlled lighting circuit or circuits. Though spot measurements, this data was

collected multiple times to determine the effect of lighting control scenarios on voltage and power factor.

- **Window treatment position.** At each of five visits, we recorded the position of the window treatments to determine what effect they may have on daylighting, and whether it was a static or changing parameter.
- **Workplane and current measurements for illuminance calibration.** We also took multiple spot measurements of illuminance at the critical workplanes using a factory-calibrated handheld illuminance meter while current and photosensor readings were also taken. These coincident measurements were used to achieve continuous indirect measurement of critical workplane illuminance; the process for deriving workplace illuminance from these measurements is described in the section on *Methodology and A*.

Finally, we collected data on occupant perception of the spaces and lighting systems. We first briefly interviewed each primary building contact, who was generally a facility manager or engineer. We then distributed a brief survey for the occupants who actually used the spaces we studied (see *Appendix A*). The results of this survey alerted us to any unusual operational impacts or space constraints that might make our results less relevant. More importantly, we wanted to be sure this report included qualitative explanations for the quantitative results that went beyond our own suppositions. This is especially important when the key conclusions focused on the startup period, a time during which the facility management staff was heavily involved.

The ultimate goal of all these measurements was to determine the energy savings of the daylighting controls. The measurements outlined above ultimately lead to this savings calculation. This calculation is summarized in detail in the next section.

METHODOLOGY AND ANALYSIS

Two different savings metrics are considered key outcomes of this study: 1) the energy savings associated with having a daylighting control system and 2) the energy savings associated only with the act of fully commissioning that system. Each metric was calculated only for the area and the lights *controlled by the daylighting control system*.

LIGHTING ENERGY USAGE AND SAVINGS

The measured lighting energy usage, W_{meas} , was calculated using the electrical current measurement, which was taken in 5-minute intervals, and the spot measurement of the circuit's voltage and power factor. This allowed us to calculate lighting energy usage for a given space for a given period:

$$W_{meas} = V \cdot PF \cdot \sum_{i=1}^{n_{measurements}} I_i \cdot \left(\frac{1 \text{ hr}}{12 \text{ samples}} \right)$$

where V is the voltage of the electrical circuit, PF is the power factor of the electrical circuit, I_i is the sampled current at timestep i , and $n_{measurements}$ is the number of measurements in the particular period.

To translate energy usage into energy savings, we also calculated the energy that would have been used by the lighting system with no controls present. The first step of this calculation was to determine, for each timestep, whether the electric lights were on or off. We accomplished this by first inferring a minimum, I_{min} , and maximum, I_{max} , current from the data. The minimum and maximum current corresponded to all of the electric lighting associated with the monitored, controlled circuit being at minimum or full power, respectively. If the measured current was at or below the minimum current, we considered the electric lights to be off. If the monitored current was greater than the minimum current, we assumed the lights were on. The next step was to determine what the current would have been had there been no photocontrol. In the absence of photocontrol the current ($I_{i, no pc}$) would be the minimum current during times the lights were off and the current would be the maximum current during times the lights were on:

$$I_{i, no pc} = \begin{cases} I_{min}, & I_i = I_{min} \\ I_{max}, & I_i > I_{min} \end{cases}$$

The lighting energy usage for this case, $W_{no pc}$, is then found by substituting $I_{i, no pc}$ into the $W(I)$ function above. Lighting energy savings, ΔW_{light} , for a given period of time is then simply the difference between W_{meas} and $W_{no pc}$:

$$\Delta W_{light} = W_{no pc} - W_{meas}$$

WORKPLANE ILLUMINANCE

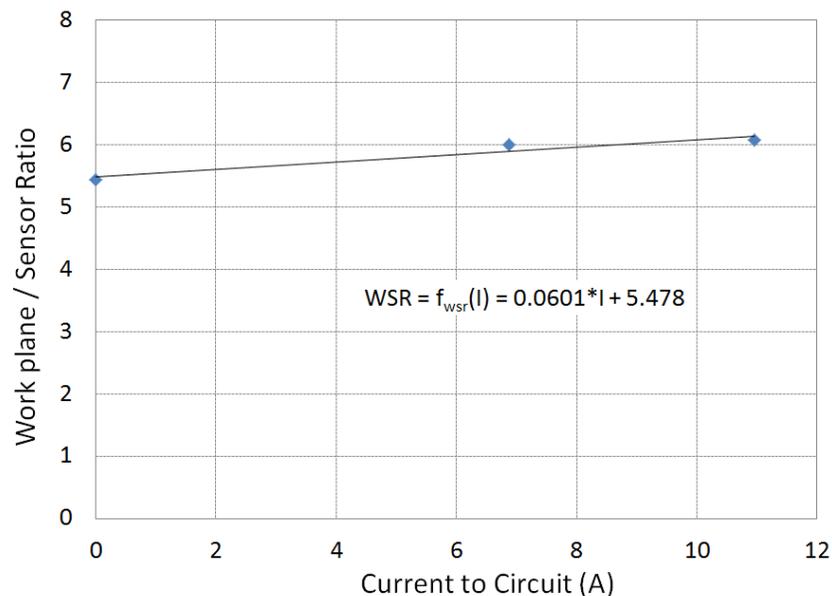
For a variety of reasons, we also indirectly measured the illuminance at the critical workplane. This measurement would allow us to better interpret energy performance, complete quality assurance checks on our results, and calculate an additional metric that we call controls effectiveness, which proved useful in evaluating commissioning potential. Due to potential occupant interference, light meters cannot be

placed directly at the workplane to measure illuminance as they would likely be tampered with or covered. Instead, the light meters were either placed on a cubicle wall with approximately the same view factor of the windows and lights as the desktop, or were placed on the ceiling and shielded from the window. In both cases, a calibration procedure was completed to allow us to correlate the sensor illuminance with workplane illuminance using a ratio of the total workplane illuminance, E_{wp} , and the sensor illuminance, E_s . This ratio was observed to be a function of the electric light output in the space, especially in areas where the sensor had some direct input from the electric lights. The ratio was assumed, and limited daytime testing confirmed this, to not be as significant a function of daylight level. Literature has shown this to be true in other cases as well when sensors are properly shielded.²¹ In this case the ratio is a function of current:

$$WSR = \frac{E_{wp}}{E_s} = f_{wsr}(I)$$

where WSR is the workplane-to-sensor ratio. The specific function, $f_{wsr}(I)$, of each space was determined by taking current, workplane illuminance and sensor illuminance readings at the undimmed and fully-dimmed lighting states, and a few intermediate points and then creating a mathematical fit. An example correlation is shown in Figure 1.

Figure 1. Example of the correlations used to determine workplane-to-sensor ratio, for calculation of workplane illuminance.



The hourly total workplane illuminance at each point in time was then calculated based on the measured current at that time, using the correlation for the given space.

²¹ “Improving the Performance of Photo-Electrically Controlled Lighting Systems,” Rubinstein, F., Ward, G., and Verderber, R., Presented at the Illuminating Engineering Society Annual Conference, Minneapolis, MN, August 7 – 11, 1988. WSR was shown to be relatively constant for well-shielded ceiling-mounted sensors placed near the back of the daylight zone (near the critical workplane). Those sensors placed on the ceiling in our study were fully-shielded on all sides; sensors placed on cubicle walls next to the workplane were bare (in fully cosine-corrected sensor heads).

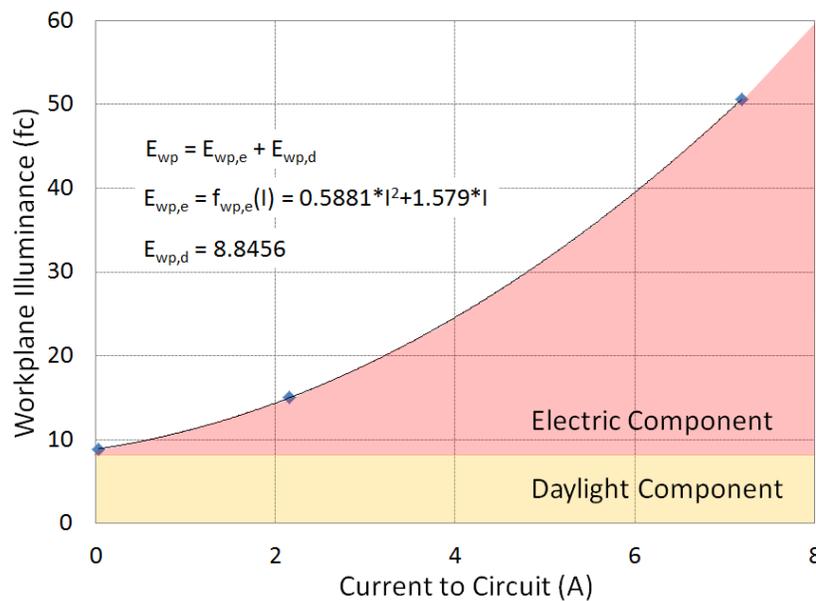
$$E_{wp} = WSR \cdot E_S = f_{wsr}(I) \cdot E_S$$

To calculate our controls effectiveness metric, we also needed to calculate the *daylight* portion of the workplane illuminance. E_{wp} , is the sum of electric, $E_{wp,e}$, and daylight, $E_{wp,d}$, illuminance components:

$$E_{wp} = E_{wp,e} + E_{wp,d}$$

We began by finding the electric component of illuminance, $E_{wp,e}$. In a similar fashion to WSR , a correlation, $f_{wp,e}(I)$, was developed to define the relationship between E_{wp} and coincident current at several states of lighting power, while daylight levels remained constant. An example correlation is shown in Figure 2.

Figure 2. An example of the correlation between workplane illuminance and current at constant levels of daylight.



The daylight component of lighting in the space was constant across the correlation's currents. Since the y-intercept occurs when the electric lights are off, it is by definition the workplane illuminance from daylighting at that time. The rest of the curve therefore demonstrates the impact of electric lighting output on illuminance. The electric workplane illuminance $E_{wp,e}$ may then be calculated from the current at any time by the correlation equation for each space.

The hourly daylight component of workplane illuminance is then simply:

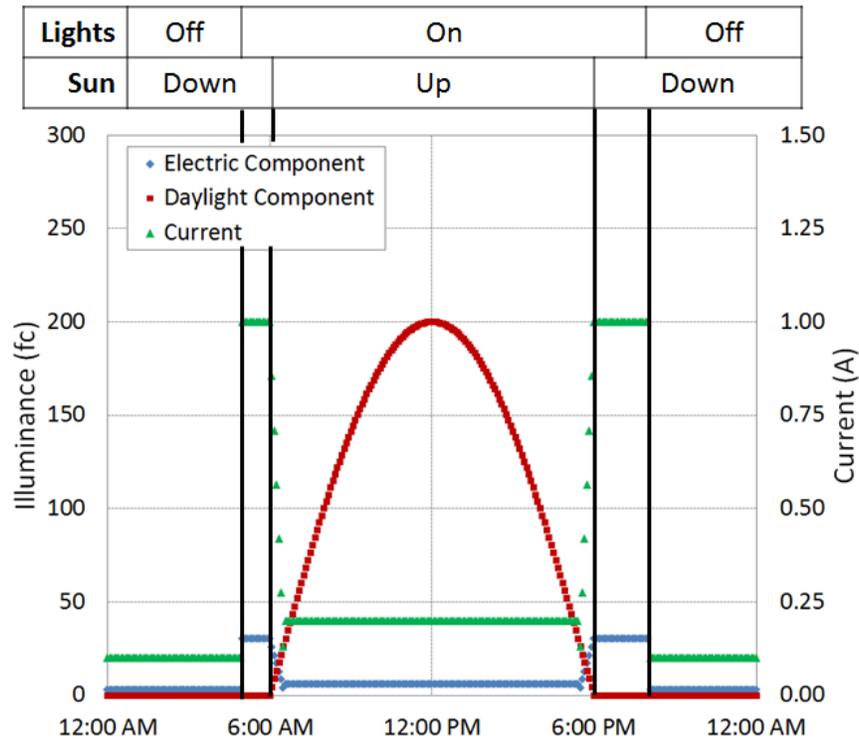
$$E_{wp,d} = E_{wp} - E_{wp,e} \text{ where } E_{wp,e} = f_{wp,e}(I)$$

As an example, for the space used in Figure 2, $E_{wp,e}$ is found by the following function:

$$E_{wp,e} = 0.5881 \cdot I^2 + 1.579 \cdot I$$

It is useful to observe this calculation plotted out for an idealized system across an entire day. Figure 3 shows the illuminance and current trends over a typical day for a space with an operable, dimming daylight control system.

Figure 3. Idealized daily profile for different illuminances in a space with continuous dimming that is operating successfully.

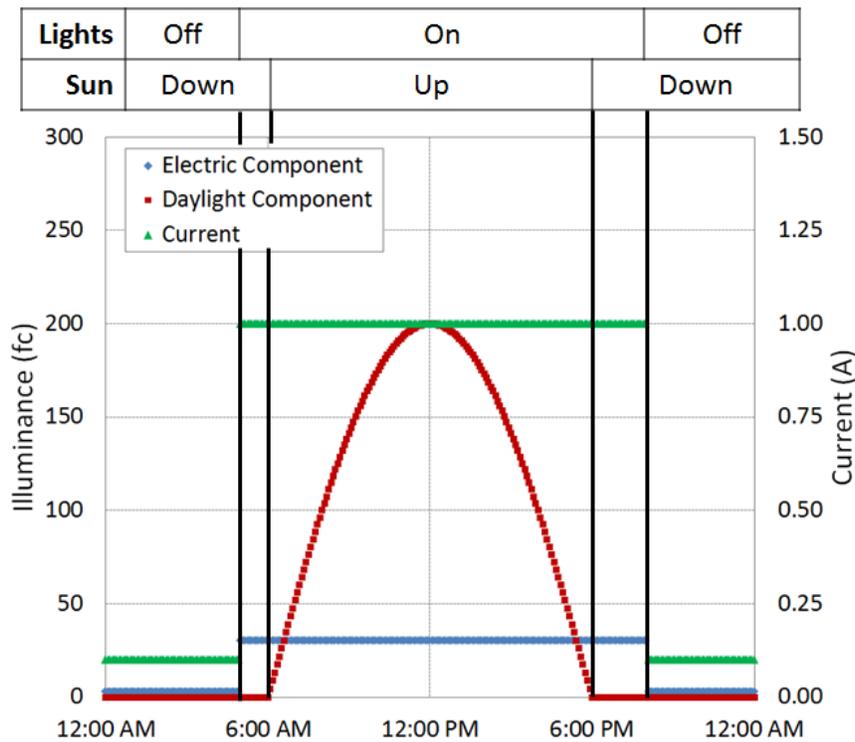


Note that there are two important states that combine to define a space's illuminance hourly profile; whether the sun is up and whether the controlled lighting is enabled either by occupants or timeclocks. For the space illustrated above, the lights are off (except for emergency fixtures) and the sun is down for the first several hours of the day. This leads to no daylight illuminance, low electric illuminance from emergency lighting and associated base load of current. The lights are switched on at 5:00 am, causing a step-change in electric illuminance and current. However, the sun is still down, so the daylight illuminance is still zero. At 6:00 am, the sun begins to rise. This leads to increasing daylight illuminance and decreasing electric illuminance and current. The illuminance from daylight peaks around noon. At this point, the electric illuminance and current are at their lowest. The opposite behavior is reflected in the evening, with decreasing daylight illuminance and increasing electric illuminance and current.

It should be noted that during the sun down, lights-enabled state, the target design illuminance at the critical workplane may be determined. In the case above, the target illuminance, E_t , is about 30 fc. To reiterate, this is at the critical workplane, so it is often a minimum lighting condition.

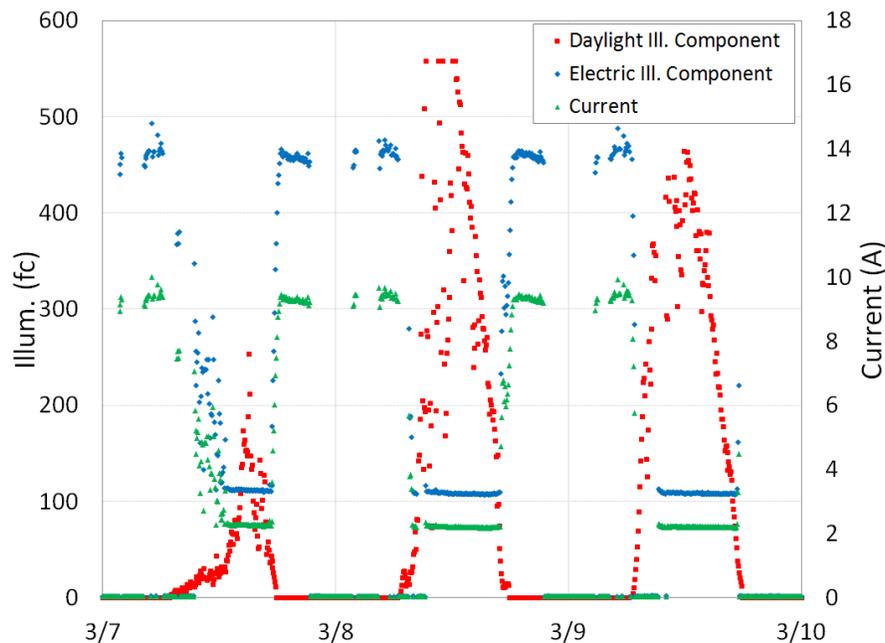
As a counter example, the following figure shows the illuminance and current trends over a typical day for a space with an *inoperable*, dimming daylight control system.

Figure 4. Typical daily profile for different illuminances in a space with continuous dimming that is *not* operating successfully.



As with the previous case, the electric lights remain off until 5:00 am. Again, the sun begins to rise at 6:00 am, causing increasing daylight illuminance. However, the electric lights do not react to the increasing daylight levels. Instead they remain constant throughout the day and turn off during unoccupied hours in the evening.

A more complete view of the performance of one of our monitored, typical systems is shown in Figure 5. This particular space had western and northern exposures and therefore shows an increase in daylight in the afternoon. Note that the daylight illuminance rises and falls in the first day as expected for this type of space, with interruptions that follow a pattern indicative of scattered clouds. The electric lighting current responds to balance out the falling daylight levels. The third day shows a different pattern, in which the morning is likely mostly cloudy, with a very clear afternoon. The middle day is a mix of the other two.

Figure 5. Illuminance analysis for a three day period for the Plymouth Library south space.

In addition to these continuous dimming systems, we also studied one space with switching controls. This space was somewhat simpler to analyze. By placing a current switch on the manual light switch, we were able to determine whether the lights were manually switched off or on. If they were manually switched on but current was zero, then the daylight control was switching the lights off. If the lights were on, a constant illuminance was assumed from the electric lighting, essentially creating a constant correlation for the electric component of illuminance. The remaining component of illuminance was from daylight.

CONTROLS EFFECTIVENESS

As discussed in the introduction, the primary goal of our study was not to look at the architectural or lighting design impacts of daylighting, but rather to focus specifically on the commissioning of the control system applied to the lights and physical space as they were designed and constructed. Overall lighting system energy savings is not the best metric to help us reach conclusions about the commissioning of the control system, because savings is impacted heavily by the architectural (glazing size and properties, furniture, material finishes) and lighting design (lighting power density, zoning, layout) aspects of the space.

As a result, we created a metric called ‘controls effectiveness,’ here represented by the term ε :

$$\varepsilon = \frac{\text{Actual Savings}}{\text{Ideal Achievable Savings}}$$

The need to calculate effectiveness as opposed to just savings is best illustrated by considering an example space that we encountered in this study. This space had poor daylighting attributes with a daylighting zone that was too deep, dark finishes, and obstructing furniture. The savings from daylighting controls in such a space will generally be low. But the effectiveness may be quite high, indicating that the

controls are properly installed, started up, and calibrated. Put another way, if you were to use effectiveness to gauge the performance of your controls installation, startup, and commissioning personnel, they would not be as readily penalized by decisions made by the designers.

Calculation of *actual savings* has already been established. Calculating *ideal achievable savings* is more complex. We must calculate how much energy would have been consumed if the space was perfectly photocontrolled such that the design target illuminance was always maintained at the critical workplane (or exceeded, when daylight alone was bright enough). In this case, an ideal electrical current, I_{ideal} , was calculated such that the electric lights deliver exactly the target illuminance at the working plane. This was accomplished by substituting the target illuminance into the correlation for the electric component of illuminance and solving for current:

$$E_t = f_{wp,e}(I_{ideal})$$

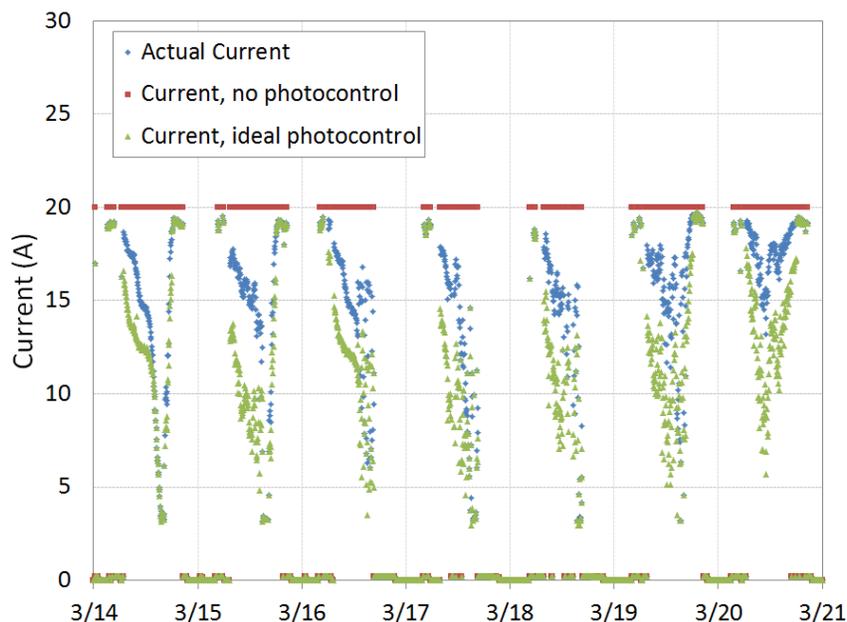
This adjustment was only applied to sampled data that occurred during times when the sun was up and the lights were on, and only when I_{ideal} was lower than I . When the sun was down and the lights were on, the measured data was unaltered.

This logic is illustrated in the following equation.

$$I_{i,ideal\ pc} = \begin{cases} I_{ideal}, I_i > I_{min}, \text{ sun up} \\ I_i, I_i > I_{min}, \text{ sun down} \\ I_i, I_i \leq I_{min}, \end{cases}$$

This analysis is possibly better understood visually. Figure 6 shows electric current measurement and analysis for one of the spaces over a typical week. In this figure, the actual current, adjusted current for no photocontrol, and adjusted current for ideal photocontrol are displayed. For the no photocontrol case ($I_{no\ pc}$), the value of current was adjusted to the maximum current whenever the lights were on and to zero current whenever the lights were off. For the ideal photocontrol case, the electric current (I_{ideal}) varies throughout the day directly with light levels, occasionally reaching the minimum current of around three amps, which it will not go below. The actual current always falls somewhere between these extremes. As the actual current approaches the ideal current, the space's effectiveness approaches one. As the actual current approaches the no photocontrol current, the space's effectiveness approaches zero.

Figure 6. Electrical current for actual, ideal, and ‘no photocontrol’ cases for the Plymouth Library building for a typical week in March.



Once an ideal current was known, the electrical energy for the case with ideal photocontrols, $W_{ideal\ pc}$, was then found by:

$$W_{ideal\ pc} = V \cdot PF \cdot \sum_{i=1}^{n_{samples}} I_{i,ideal\ pc} \cdot \left(\frac{1\ hr}{12\ samples} \right)$$

From these three cases, the photocontrol system's controls effectiveness, ε , was calculated by:

$$\varepsilon = \frac{W_{no\ pc} - W_{meas}}{W_{no\ pc} - W_{ideal\ pc}}$$

The effectiveness ranges from one when the actual energy usage is equal to the ideal energy usage (perfect control), to zero when the actual energy usage is equal to the no photocontrol energy usage.

EFFECTS ON HEATING AND COOLING ENERGY

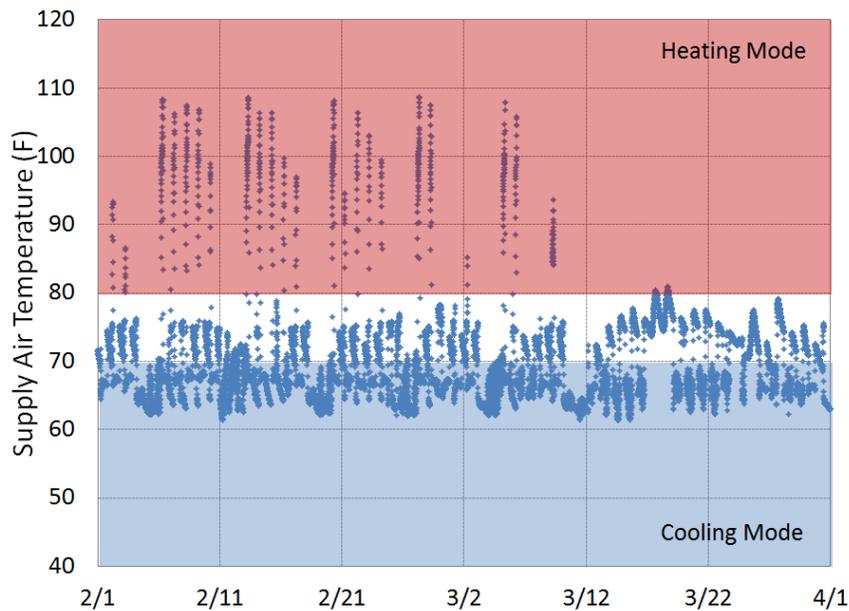
Though the predominant energy savings mechanism for automatic daylighting controls is in the direct savings from reduced lighting energy, there are other impacts as well. Namely, the reduced lighting load in the space impacts HVAC energy consumption. In cooling mode, savings results due to the HVAC system serving a smaller cooling load as a result of less heat put off by the lighting system in its dimmed state. Alternatively, in heating mode the system must work harder to make up for the lack of lighting load in the space when the lights are dimmed.

In order to calculate the cooling and heating energy savings, supply air temperature measurements in each individual space were used to determine whether the HVAC system *for the given space* was in heating or cooling mode for a given sample time. First, a minimum heating supply air temperature, T_{heat} , and a

maximum cooling supply air temperature, T_{cool} , were identified based on the thermostat setpoint in the space. If the sampled temperature, T_i , was above the T_{heat} , the space was determined to be in heating mode. If the sampled temperature was below T_{cool} , the space was determined to be in cooling mode. If the sampled temperature was between the two temperatures, then the space was considered to be generally balanced or presumably only receiving ventilation. Note that the results of these temperatures were only utilized in the study for sample times where the lights were on, so this system of heating/cooling status with temperature does not need to account for setback temperatures.

For example, in the space depicted in Figure 7 the temperature setpoint during occupied hours is approximately 72-76°F. This is actually observable because in cooling mode the temperature peaks at about 76°F, and in heating mode the temperature only dips as low as about 72°F. A safety ‘deadband’ was added to the heating minimum, resulting in a T_{heat} of 80°F. A similar ‘deadband’ was added to the cooling maximum, resulting in a T_{cool} of 69°F. These account for transitions, and make our heating/cooling impact more conservative. When the supply air temperature was above the T_{heat} the calculation assumes that this space was in heating mode. When the supply air temperature was below T_{cool} the calculation assumes that this space was in cooling mode.

Figure 7. Supply air temperatures for the WECC S2 space.



The cooling energy savings is a function of the lighting energy savings at each sample time:

$$\Delta W_{cool} = \sum_{i=1}^{n_{samples}} \begin{cases} \frac{\Delta W_{i,light}}{COP_{cool}}, T_i < T_{cool} \\ 0, T_i \geq T_{cool} \end{cases}$$

where COP_{cool} is the *system* coefficient of performance of the cooling plant. The heating energy penalty is also a function of the lighting energy savings.

$$\Delta W_{heat} = \sum_{i=1}^{n_{samples}} \begin{cases} -\frac{\Delta W_{i,light}}{COP_{heat}}, T_i > T_{heat} \\ 0, T_i \leq T_{heat} \end{cases}$$

where COP_{heat} is the *system* coefficient of performance of the heating plant. A multiplier coefficient, C_{HVAC} , may then be developed that can be used to express the magnitude of the heating and cooling savings when compared to the lighting energy savings.

$$C_{HVAC} = 1 + \frac{\Delta W_{cool} + \Delta W_{heat}}{\Delta W_{light}}$$

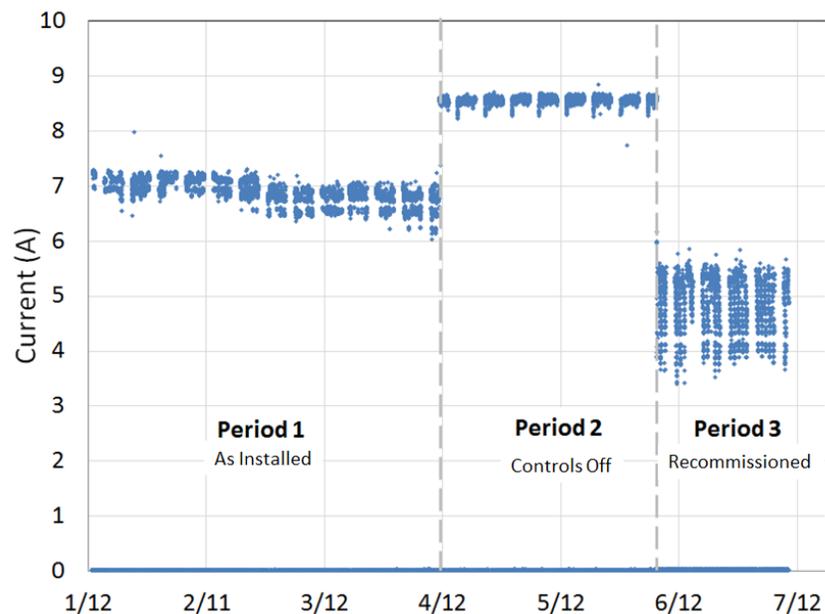
where ΔW_{light} is the energy savings due solely to lighting, as discussed above. The total energy saved by the daylighting control system, ΔW , is then:

$$\Delta W = C_{HVAC} \cdot \Delta W_{light}$$

UTILIZING MULTIPLE PERIODS OF DATA COLLECTION

The energy savings and effectiveness of these three systems, as installed, are key metrics in determining the quality of the lighting controls, their installation, and the level of commissioning that they received prior to our involvement. In addition to the ‘as-installed’ case that we observed in period 1 of our measurement, we also conducted an additional two periods of measurement. In period 2, we turned off the daylighting controls and completed the same measurement and calculations. Then prior to period 3, we completed a basic *recommissioning* of the system. The goal in period 3 was to monitor the system at a near-optimal level of control, or at least as optimal as an ‘ideal’ half or full day of startup and functional testing would have been able to achieve. The operation of the lights across these three periods is demonstrated for one somewhat typical space in Figure 8. Note that in many cases the difference in performance between the three periods is quite stark, as they are in Figure 8.

Figure 8. Lighting current for the three periods of data collection at the Labs North space. Note the distinct difference in lighting operation between the three periods, and the decreased lighting energy usage in period 3 (after recommissioning) as opposed to period 1.



Recommissioning Process

Our recommissioning process between period 2 and period 3 was relatively simple to reflect a fairly low-cost commissioning approach (which should occur at startup, not years later as in our study) that might be applicable to a wide range of buildings. We completed most of the tasks at the direction of one electrical engineer/designer with an elementary understanding of hands-on modification of controls. We employed manufacturers, including one technician in the field, specifically to help us understand the user interfaces on the more complex systems. This type of assistance is available from manufacturers for any team that is starting up a daylighting control system. Though a thorough commissioning process includes involvement early in the design process (such as review of floor plate zoning, coordinating trades, etc.) we focused our efforts and this research in general on the steps that take place at the end of design through occupancy. These are more minor changes that can be made at a control panel or in the zone itself with a building manager's or contractor's skill set, and no additional equipment need be installed.²² These tasks are summarized in Table 3 along with the design/construction stage at which they might normally take place if properly commissioned.

²² In fact, most of what was done could be done without an electrical contractor, though we would recommend that contractors, if not commissioning authorities, be the ones responsible for completing these tasks.

Table 3. The steps taken in our recommissioning process of each space, between period 2 and period 3.

Process	Typical Step
Shielding of the photosensor	Design
Orientation of the photosensor	Design; adjust at occupancy*
Rerouting improper connections	Functional testing
Tuning of the photocontrol gain	At occupancy*
Changing timing parameters (delay, fade rate, etc)	At occupancy*

* Completing these steps as late as possible, post-occupancy if possible, ensures that they will compensate for furniture and equipment, and any modifications to the space made by occupants initially. If it is not possible to wait, theoretically these steps can be completed at functional testing.

Normalization

Our analysis required calculation of the key metrics of savings and effectiveness across all the sample times in each period. Comparison between these periods would yield significant additional insight. One simple comparison we used in this study was to compare period 1 to period 3, which represents the net effect of commissioning the daylighting controls.

As in any multi-period energy study, we needed to normalize for weather effects between these periods. In this case, weather effects include any factors that impact light levels in the space, such as sun position throughout the day and year, cloud cover, and cloud thickness. Because the geometry and orientation of each space is different, the most thorough way to do this was to normalize the results based on observed daylight levels at the workplane according to a normalization coefficient, C_{Period} :

$$C_{Period} = \left(1 - \frac{E_{Avg,3} - E_{Avg,1}}{E_t} \right)$$

$$\Delta W_{adj,3} = \frac{\Delta W_3}{1 + C_{Period}}$$

Where $E_{Avg,3}$ is the average daylight illuminance at the workplane in period 3, $E_{Avg,1}$ is the average daylight illuminance at the workplane in period 1, ΔW_3 is the energy savings measured in period 3, and $\Delta W_{adj,3}$ is the energy savings for period 3, normalized for light levels. This value is used in all savings comparisons between period 1 and period 3 in the remainder of this report. Note that this direct comparison also compensates for internal changes, such as those to the blinds, furniture, or other items between period 1 and period 3. Because each period included several weeks of measurement, we assumed that occupancy effects, such as the coming and going of people, did not require additional normalization. Note that the metric of effectiveness automatically normalizes for occupancy.

A final step in preparing the data for meaningful comparisons is to normalize the data to a typical annual period, so it is most useful to practitioners. The standard method for creating typical annual data is to normalize using a typical meteorological year (TMY)²³ versus the actual 2012 site weather. TMY data is

²³ Our normalization methods, where applicable, followed the methods outlined in the International Performance Measurement and Verification Protocol. Use of TMY normalization is perhaps the most direct example of that.

readily available for all major cities. For actual 2012 measured weather data we purchased weather files for Minneapolis and Wisconsin.²⁴ We examined several correlations between daylight at the workplane and climatic parameters in the TMY datasets and determined that the only significant general correlation was with the ratio of global horizontal radiation (GHI) to extraterrestrial radiation (ETR). This ratio accounts well for the impacts of weather (mainly cloud cover) on light levels at the earth's surface. It does not account for the impact of variation in the sun's altitude during the year, but our total measurement period was a half year, ending shortly after the summer solstice, and therefore was conducted across the full range of the sun's altitude variation. C_{TMY} is the resulting ratio used to compare TMY with measured weather:

$$C_{TMY} = \frac{\frac{GHI_{TMY}}{ETR_{TMY}}}{\frac{GHI_{meas}}{ETR_{meas}}} C_{sav}$$

where C_{sav} is the correlation coefficient between changes in the value of GHI/ETR and changes in energy savings. After performing this calculation, we found the total value of C_{TMY} to be 1.03, which means weather normalization didn't have a major impact.

Finally, we use C_{TMY} , C_{Period} , and a factor to account for the different durations of each period, to extrapolate our period measurements to a TMY condition. First the extrapolation of period 1 represents the energy savings, $\Delta W_{TMY,as is}$, for each system as it was before we made any changes:

$$\Delta W_{TMY,1} = \Delta W_1 * (1 + C_{Period}/2) * C_{TMY} * \frac{365}{N_{days,1}}$$

where $N_{days,1}$ is the number of days in measurement period 1. The extrapolation of period 3 is similar, and represents the savings for each system after a significant commissioning effort:

$$\Delta W_{TMY,3} = \frac{\Delta W_3}{1 + C_{Period}/2} * C_{TMY} * \frac{365}{N_{days,3}}$$

We conducted the same calculations for savings as percentage of total energy usage and savings normalized by peak controlled lighting power, expressed as kWh per kW.

DATA QUALITY CONTROL

Data accuracy is of primary importance to ensure that results are useful to the design and research community, replicable by other researchers, and admissible for utility program design, calculations, and evaluation. This level of accuracy begins with quality measurements; in this case measurement tools were calibrated as discussed in the *Methodology and Analysis* section. However other considerations were also made.

²⁴ Weather files were purchased from Weather Analytics (<http://weatheranalytics.com/>); these are quality controlled hourly weather files from the actual hours that we conducted the study. We chose the weather from the nearest airport to represent the locations.

Much of our work relies primarily and directly on measuring the current of the lighting systems studied. Raw energy savings in all its forms, for example, is based almost solely on this measurement. Additionally, the extrapolation of the energy savings, the effectiveness metric, and the cross-period comparison of savings also depend on our illuminance measurements. We did not have any significant inaccuracies in the measurement of illumination itself, but the various uses of those light measurements were subject to more potential uncertainty. We attempted to mitigate this uncertainty in several ways.

First, both the critical workplane illuminance measurements and determination of design illuminance level were subject to potential errors in 1) the correlation between measurement point and workplane and in 2) choice of critical workplane position. Our primary mitigation strategy here was to measure multiple points, from 2-3 points in each space, and use a combination of averaging of these points with elimination of outliers.

In addition, our measurement of the daylight component of illuminance relied on a correlation of the electric lighting component of illuminance, which was subject to measurement error across several measurement points. The potential error in this limited data was mitigated by observing the value of the illuminance due to daylight at the end and/or the beginning of the day. At the end of a day, for example, the value of daylight illuminance should approach zero as the sun sets, even while the lights are on and modulating their power in response. This observation was checked across several days for each space, an example of which was illustrated in Figure 5.

The light levels measured by the photosensors pointed directly at the windows were originally intended for use as a backup to our ability to measure daylight at the workplane. As we were fortunate to be able to use our workplane measurements, we did not use open loop light levels directly in our primary calculation. However, they provided yet another benchmark for our light level measurement. We did not feel it was worth trying to create any type of correlation between open loop and workplane illuminances, but we were still able to use these illuminance measurements to check 1) that our daylight light levels changed throughout the day and season as they should and 2) as a check of our comparison and extrapolation factors between period 1, period 3, and TMY values.

Similarly, our period 2 measurements were in place as a potential point of comparison for savings calculations, in the event that the 'no photocontrol' case could not be translated accurately from the period 1 and period 3 current measurements. This could have occurred due to occupancy sensors, an inability to accurately define luminaire zoning, or other lighting controls that interfered with the photocontrols. Because this translation proceeded smoothly, the period 2 measurements were used primarily as another quality control tool. Using period 2 measured data, we were able to check that our methodology resulted in a controls effectiveness at or near zero for each space. We were also able to check that our filtering of both occupancy sensors and manual switching was adequate, and that the daylight illuminance calculation, with its multiple correlations, still yielded reasonable results across periods. (This was realized through period-to-period comparison of illuminance levels and sunrise daylight levels.)

EXTRAPOLATION METHODOLOGY

One of the other objectives of the study was to extrapolate our energy savings results from our sampled spaces to the entire state of Minnesota. Our extrapolation relies on the average energy savings potential

demonstrated by the systems in our study. We make three separate extrapolations here: the amount of energy to be saved by implementing daylighting controls in existing buildings ($W_{retrofit}$ below) with 1) ideal startup and 2) with typical startup, and 3) the amount of energy to be saved by recommissioning the daylighting control systems that currently exist in Minnesota (W_{reCx} below). Note that an additional area of daylighting control savings is that which could be applied to new construction, but we do not attempt to extrapolate our results to that population here. We use a variety of sources to determine the total amount of lighting energy in Minnesota that is applicable to these categories.

Our ultimate extrapolations begin with an estimation of the total technical potential, $W_{potential}$, of each measure. These values represent the total potential for completing these measures in all commercial buildings in Minnesota, regardless of economics or resources:

$$W_{retrofit,potential} = P_{savings} * F_{access} * F_{int.lighting} * (1 - F_{sat}) * W_{comm.,MN}$$

$$W_{reCx,potential} = P_{savings,reCx} * F_{access,reCx} * F_{int.lighting} * W_{comm.,MN} * \frac{Area_{MN,daylit}}{Area_{MN}} (1 + r_{exp})^9$$

In addition to the total technical potential, we've also estimated the annually achievable potential (subscript *annual*) of each measure. These values represent what may be actually achievable for building and efficiency professionals to save in a given year:

$$W_{retrofit,annual} = F_{annual} * F_{light ctrl} * E_{retrofit,potential}$$

$$W_{reCx,annual} = F_{annual} * E_{reCx,potential}$$

We used a range of sources for the inputs to these equations:

$P_{savings}$ is the median percentage savings demonstrated by automatic daylighting controls in this research, post-commissioning. See the *R* section for more details and values chosen.

$P_{savings,reCx}$ is the median percentage savings demonstrated by commissioning of the automatic daylighting controls in this research, defined as the differential between percentage savings before and after commissioning. See *Utilizing More Daylight in Minnesota Buildings* for more details and values chosen.

F_{access} is the fraction of lit commercial building floor area that has a high enough daylight factor to benefit from daylighting controls. Results of three different sources were considered and the median of 31% was used. The sources include a metastudy on national lighting control potential²⁵, a 2012 study of daylighting retrofit potential in California²⁶, and the daylit area in the commercial building reference models used to quantify national building energy codes.²⁷

$F_{access,reCx}$ is the fraction of space that is daylit in the population of CBECS buildings that is designated to have some type of daylighting controls. As we anecdotally believe the CBECS results to have

²⁵ "Quantifying National Energy Savings Potential of Lighting Controls in Commercial Buildings", Williams, A.; Atkinson, B.; Garbesi, K.; Rubinstein, F., Proceedings of 2012 ACEEE Summer Study, August 2012.

²⁶ "Daylighting in Existing Office Buildings: An Untapped Retrofit Resource", Saxena, M.; Hescong, L.; Perry, T.; Davis, D.; Scruton, C., Proceedings of 2012 ACEEE Summer Study, August 2012.

²⁷ "US Department of Energy Commercial Reference Building Models of the National Building Stock", National Renewable Energy Laboratory, Technical Report TP-5500-46861, February 2011.

overestimated the amount of total daylit buildings (likely including buildings that only have some very minor portion of the building on daylighting controls), we used the lowest cited number for daylight controlled fraction in the three studies footnoted here. This value was 17%.

$F_{int. lighting}$ is the fraction of commercial building energy usage in Minnesota that is attributable to interior lighting. Based on the results of CBECS²⁸ 2003 data for the region, this value is assumed to be 32%.

F_{sat} is the saturation, or the fraction of technically available daylit space that already has automatic daylighting controls installed. A conservative estimate based on CBECS yielded 3% for F_{sat} .

$W_{comm.,MN}$ is the energy used by commercial buildings in Minnesota. This value is simply taken from the US Energy Information Administration electricity sales data for the commercial sector in Minnesota; for the most recent year it is approximately 20,530,000 MWh.

$Area_{MN}$ is the floor area of commercial buildings in Minnesota. This value is estimated at 1,250 million ft² based on the commercial floor area in the West North Central Region (per CBECS) prorated by the ratio between commercial electricity usage in Minnesota, $W_{Comm,MN}$, and the commercial electricity usage in the West North Central Region with corrections for scope of the two separate surveys.

$Area_{MN,daylit}$ is the area of buildings in Minnesota that include some type of daylighting control. This value is based on CBECS estimates of share of buildings in the region that include daylighting control.

r_{exp} is the rate of growth in the market for daylighting controls; this is required because the values of $Area_{MN,daylit}$ are based on 2003 values, before most of the systems that we have observed in Minnesota existed. This value is not well known, so sensitivities are used to determine the result at different values of r_{exp} .

F_{annual} is the fraction of overall lighting technical potential that can be saved annually, i.e. what portion of the technical potential for lighting retrofits can be retrofitted each year based on existing lighting programs and methods. This value is approximately 6%, and is based on the 2010 Minnesota CARD Energy Efficiency Potential Study²⁹. This assumes that daylight recommissioning could potentially follow a similar technical-to-annual-achievable ratio as general lighting retrofit.

$F_{light ctrl}$ is the ratio of annual achievable controls retrofit to annual achievable lighting retrofit. This factor is included to recognize that the majority of lighting retrofits cannot feasibly include automatic daylighting control. Substantial program data is not yet available to accurately quantify $F_{light ctrl}$, so sensitivities were conducted using a range of values.

The calculations and results completed using these equations can be found in the *Utilizing More Daylight in Minnesota Buildings* section.

²⁸ Commercial Building Energy Consumption Survey, <http://www.eia.gov/consumption/commercial/>

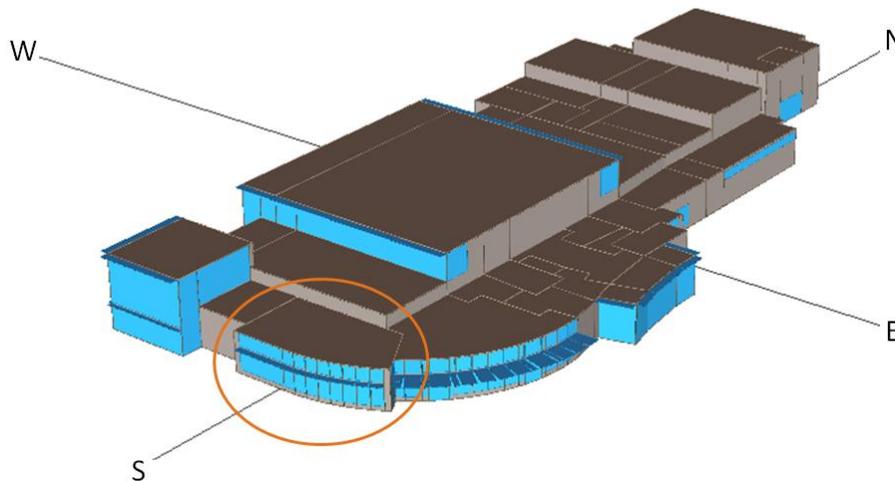
²⁹ "Minnesota Statewide Electricity Efficiency Potential Study DSM Potentials Report", Navigant Consulting, Submitted to Minnesota Office of Energy Security, April 2010.

MODELING METHODOLOGY

In addition to monitoring these spaces we also created energy models of 18 of the spaces in DOE-2, using eQUEST as a front end. The primary purpose of the modeling was to determine the ability to predict performance of these systems. Modeling is often used in energy efficiency programs in place of field measurement for predicting energy savings because it costs less. Therefore, if our models were accurate predictors of daylighting energy savings, program staff could more readily utilize modeling, making programs more cost-effective. The modeling also served as an additional quality control check on our energy savings methodology as described in previous sections. If the modeling and measured energy savings were in relative agreement then we could have greater confidence in our general approach. Our approach is summarized below.³⁰

Each model encompassed the entire building, not just the studied space(s), and included information about the building's size and orientation, wall and roof construction, window to wall ratio and window properties, zoning pattern and space specific loading, operating schedule, and HVAC system. We obtained the inputs for these building-wide parameters either from drawings or site measurements; some parameters were based on standard modeling practice, generally for systems other than lighting. Figure 9 illustrates the model of the Plymouth Library.

Figure 9. DOE-2 model of the Plymouth Library. The south reading area that was included in this study is circled (named Plymouth Library S1 in this report).



We included more detail in specifying the monitored spaces within the model. The geometry of each space was specified based on drawings and measurements taken on site. The window's exact size and location, as well as any exterior shading devices, were specified. The window's visible light transmittance, τ_{vis} , was determined from site measurements by:

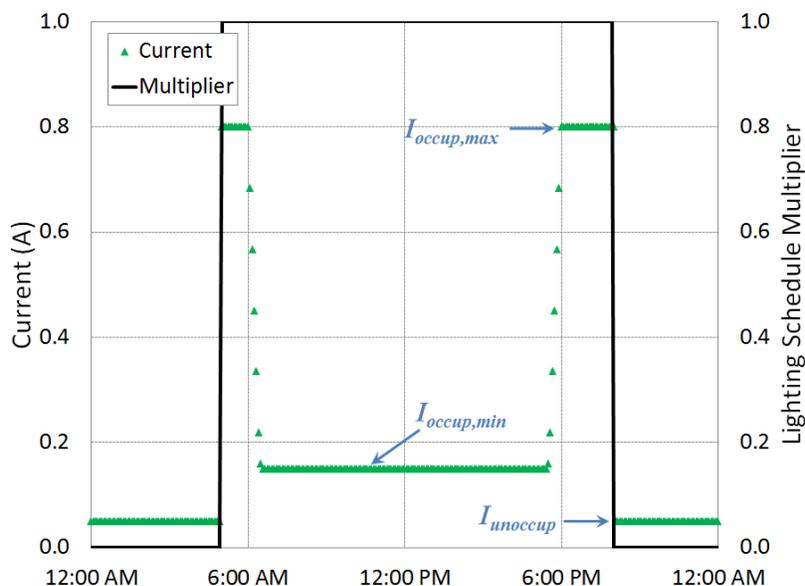
$$\tau_{vis} = \frac{E_{interior}}{E_{exterior}}$$

³⁰ Our modeling methodology generally followed the one used by HMG in "Sidelighting Photocontrols Field Study," Heschong Mahone Group, Inc., Report #06-152, 2005. Our method was varied somewhat from this, to fit the goals of our study.

where $E_{interior}$ and $E_{exterior}$ were measured illuminance levels taken on a handheld light meter immediately interior and exterior of the window, respectively. The interior surface (ceiling, floor, walls, furniture) reflectances were determined with site measurement using a simple Reflectance Sample Card.³¹ If interior shades were used in the space, a window shading schedule was created and given a visible light transmittance of 0.2. This value is essentially an average of the recommended visible transmittances for shades.³² A maximum glare coefficient of 22 was set in each space, as recommended for general office activity. This coefficient, when coupled with the window shading schedule, initiated DOE-2's blind control algorithm, approximating an occupant of the space operating the interior shades to prevent direct sunlight from causing glare.

Only the spaces with dimming controls were modeled, so the control strategy for each of the modeled spaces was set to dimming. Additionally, we only considered the photo-controlled portion of the lighting in each space in the model, allowing for more straightforward calculation of savings percentage and kWh saved per controlled kW. A lighting schedule was created with beginning and ending times taken from the measured current data. Figure 10 illustrates an idealized current profile and its corresponding lighting schedule.

Figure 10. Idealized current profile and corresponding lighting schedule for a typical day.



Note that we set the lighting schedule to one, or full lighting power, during periods of occupancy. The first step in zeroing out the uncontrolled portion of the circuit's current was to set the lighting schedule to zero, or no lighting power, during unoccupied periods. The second step was to adjust the maximum current to be just that of the controlled current. The maximum controlled lighting power, $P_{ctrl,max}$, was calculated based on the various currents outlined in Figure 10 by:

³¹ "Lighting Guide 11: Surface Reflectance and Color", Loe, D., Society of Light and Lighting and the National Physical Laboratory, London, 2001.

³² "Determination of the Effectiveness of Window Shading Materials on the Reduction of Solar Radiation Heat Gain" R.C. Jordan and J.L. Threlkeld, ASHRAE Transactions, Volume 65, 1959.

$$P_{ctrl,max} = V \cdot PF \cdot (I_{occup,max} - I_{unoccup}) \cdot \left(\frac{1 \text{ kW}}{1000 \text{ W}} \right)$$

Where $I_{occup,max}$ is the maximum current during occupied times and $I_{unoccup}$ is the current during unoccupied times. Note that this assumes that the uncontrolled lighting on a given circuit requires a constant power for every hour of the year. The calculated controlled lighting power was then entered explicitly into the appropriate space with the corresponding lighting schedule. The controlled power fraction in the space was set to one since the specified lighting power only pertained to the controlled portion. The minimum power fraction, f_{min} , was calculated via:

$$f_{min} = \frac{I_{occup,min} - I_{unoccup}}{I_{occup,max} - I_{unoccup}}$$

Where $I_{occup,min}$ is the minimum current during occupied times. Finally, we set the primary photosensor location in the model to correspond to the location of the actual photosensor in the space. A secondary photosensor location was created and located to correspond with our illuminance data logger. This secondary photosensor did not control any lighting power ($f_{min} \sim 0$), but did predict illuminance at the same location as our measurements, allowing for an hourly comparison which is described subsequently. Finally, target illuminance was set to correspond to that discussed in the *Workplane Illuminance* section.

Table 4 summarizes the architectural inputs used for each of the modeled spaces, along with their respective averages.

Table 4. Summary of architectural inputs for each modeled space.

	Reflectance			Visible Transmittance	
	Wall	Ceiling	Floor	Window	Shade
Boss NW3	73%	80%	15%	44%	N/A
Boss NW4	73%	80%	15%	44%	N/A
Labs NW3	81%	80%	13%	56%	20%
Labs SE3	81%	80%	13%	56%	20%
Freeman N3	79%	80%	15%	61%	20%
Freeman N2	79%	80%	15%	61%	20%
Lg. Office N3 A	75%	80%	25%	60%	N/A
Lg. Office S3	75%	80%	25%	60%	20%
Lg. Office N3 B	75%	80%	25%	60%	N/A
MG Library	79%	80%	10%	43%	N/A
CEE A	56%	27%	38%	20%	N/A
CEE B	56%	27%	38%	57%	N/A
Central Library N A	40%	80%	25%	45%	N/A
Central Library N B	40%	80%	25%	45%	N/A
Plymouth Library Office	77%	80%	16%	65%	N/A
Plymouth Library S1	77%	80%	16%	65%	N/A
WECC SE1	64%	80%	15%	50%	20%
WECC S2	64%	80%	15%	50%	20%
Average	69%	74%	20%	52%	20%

Note the high average wall reflectance (69%) and average window visible transmittance (52%) of these spaces. Table 5 summarizes the lighting inputs used for each of the modeled spaces, along with their respective averages.

Table 5. Summary of lighting inputs for each modeled space.

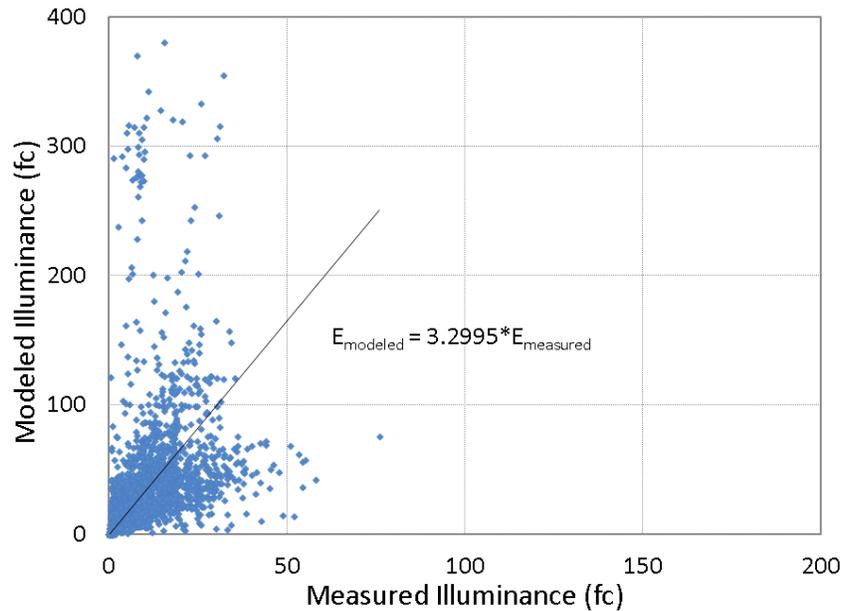
	Ctrl. Lighting Power (kW)	Min. Power Frac. (%)	Target Illuminance (fc)	Lighting Schedule (-)
Boss NW3	0.20	25%	25	WD: 5:00 am to 6:00 pm
Boss NW4	0.60	25%	25	WD: 5:00 am to 6:00 pm
Labs NW3	1.93	31%	50	WD: 5:00 am to 7:00 pm
Labs SE3	2.31	18%	50	WD: 5:00 am to 7:00 pm
Freeman N3	1.83	21%	45	WD: 5:00 am to 6:00 pm
Freeman N2	2.12	0%	35	WD: 5:00 am to 6:00 pm
Lg. Office N3 A	0.16	18%	15	WD: 5:00 am to 8:00 pm
Lg. Office S3	0.10	9%	20	WD: 5:00 am to 8:00 pm
Lg. Office N3 B	0.12	15%	15	WD: 5:00 am to 8:00 pm
MG Library	2.46	0%	25	WD: 5:00 am to 9:00 pm; WEH: 5:00 am to 5:00 pm
CEE A	0.21	12%	30	WD: 6:00 am to 7:00 pm
CEE B	0.10	13%	13	WD: 6:00 am to 7:00 pm
Central Library N A	1.63	8%	25	WD: 6:00 am to 6:00 pm; WEH: 6:00 am to 6:00 pm
Central Library N B	1.68	5%	25	WD: 6:00 am to 6:00 pm; WEH: 6:00 am to 6:00 pm
Plymouth Library Office	2.38	15%	50	WD: 5:00 am to 9:00 pm; WEH: 5:00 am to 5:00 pm
Plymouth Library S1	1.14	0%	12.5	WD: 5:00 am to 9:00 pm; WEH: 5:00 am to 5:00 pm
WECC SE1	0.38	5%	24	WD: 6:00 am to 7:00 pm
WECC S2	0.19	5%	25	WD: 6:00 am to 7:00 pm
Average	1.09	13%	28	

Note the average minimum power fraction (13%) and average target illuminance (28 fc).

The final model input was the obstruction factor (referred to as the furniture factor in Hescong Mahone Group's work.³³ This factor is defined as the percentage reduction of illuminance at a given location due to obstructions internal to the space, such as partitions or shelves. In their work, HMG determined this factor via on-site spot measurements. For our purposes, we used the measured illuminance values themselves to determine a single obstruction factor that took into account the impact on daylight across our period of study. Although more work is certainly needed, our hope was to begin to develop typical obstruction factors that can be used by modelers on their own projects. We ran each model (with real-time weather) to produce an hourly illuminance profile at the secondary photosensor corresponding to the critical workplane illuminance monitored in each space. We plotted the hourly modeled illuminance versus our measured illuminance levels. Figure 11 illustrates the modeled versus measured illuminance during period 3 for the Freeman N3 space.

³³ "Sidelighting Photocontrols Field Study," Hescong Mahone Group, Inc., Report #06-152, 2005.

Figure 11. Plot of hourly modeled versus measured illuminance during period 3 for the Freeman N3 space, without obstruction factor.

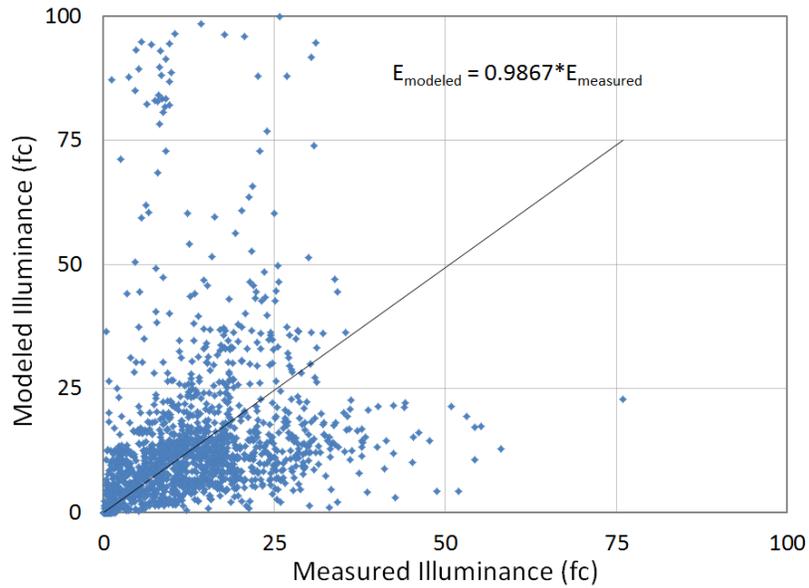


Note that the model originally predicted illuminance values consistently higher than the measured illuminance values. This is at least partially due to the omission of internal obstructions in the model that existed in the actual space. We then created a linear fit of this relationship and found the slope, m_{of} , (3.3 for Freeman N3) of this correlation. The obstruction factor, f_o , for a given space was calculated as the inverse of this slope.

$$f_o = \frac{1}{m_{of}}$$

Figure 12 illustrates the modeled versus measured illuminance values once the obstruction factor had been entered into the Freeman N3 model.

Figure 12. Plot of hourly modeled versus measured illuminance during Period 3 for the Freeman N3 space after the obstruction factor has been applied.



Note the substantially improved agreement between modeled and measured illuminance levels. Table 6 summarizes the obstruction factors, and corresponding furniture, found using this method for each of the modeled spaces.

Table 6. Summary of obstruction factors for each modeled space.

	Obstruction Factor (%)	Furniture? (-)
Boss NW3	49%	5.5' cubes
Boss NW4	21%	5.5' cubes
Labs NW3	21%	3.5' cubes
Labs SE3	17%	3.5' cubes
Freeman N3	30%	5.5' cubes
Freeman N2	13%	5.5' cubes
Lg. Office N3 A	28%	3.5' cubes
Lg. Office S3	18%	3.5' cubes
Lg. Office N3 B	N/A	Desktops
MG Library	29%	Mixed
CEE A	N/A	5.5' cubes
CEE B	N/A	Desktops
Central Library N A	63%	Desktops
Central Library N B	72%	Desktops
Plymouth Library Office	51%	5.3' cubes
Plymouth Library S1	75%	Desktops
WECC SE1	12%	3.5' cubes
WECC S2	31%	3.5' cubes
Average	35%	

A correlation appears to exist between obstruction factor and partition height, with higher partitions resulting in lower obstruction factors and therefore lower daylight levels. However, this correlation requires more detailed study.

Note that if the obstruction factor was found to be greater than one, then the obstruction factor was set to its default value of one. This assumes that an obstruction factor could never cause higher illuminance levels in a space, only lower levels. Once we entered the obstruction factor into the model, the model inputs were complete.

In order to compare the model's results to our measured results, we ran the models again with TMY weather, first without photosensor control and then with photosensor control. In much the same manner as with the measured results, the energy savings could be calculated from these two modeling runs by:

$$\Delta W_{model} = W_{model,no\ pc} - W_{model,pc}$$

Where ΔW_{model} is the modeled energy savings due to photocontrol for only the lighting in each space, $W_{model,no\ pc}$ is the modeled energy usage of the lighting without photocontrol, and $W_{model,pc}$ is the modeled energy usage of the lighting with photocontrol. Since the model's photosensor control algorithm assumed ideal control, we needed an additional step in order to directly compare the idealized modeling results to our measured annual TMY savings. This step involved using the effectiveness of the given space's control system by:

$$\Delta W_{\epsilon,model} = \epsilon \cdot \Delta W_{model}$$

Where $\Delta W_{\epsilon,model}$ is the modeled energy savings modified by system effectiveness.

Note that we chose DOE-2 for our modeling effort because it is a common, proven tool among energy modelers and is used often within energy efficiency programs for predicting savings. It produces hourly illuminance and energy calculations based on site-specific weather using well accepted methodologies. However, like any model, DOE-2 also has its inherent weaknesses. It uses the split-flux method instead of the more rigorous ray-tracing approach to predict illuminance levels. The split-flux method has the benefit of simulation speed, but is less accurate than its more sophisticated alternative. DOE-2 also attempts to predict the occupant behavior associated with adjusting interior blinds. However, its approach is limited; more recent attempts by Reinhart³⁴ have developed more sophisticated blind controls algorithms. Finally, the split-flux method does not account explicitly for interior object's effects on the light distribution. We attempted to correct for this by calibrating our model to measured illuminance levels with an obstruction factor. Our method is useful if measured illuminance levels exist. If they do not exist, a spot measurement of this obstruction factor can be made in the space using a handheld light meter. Alternatively, "typical" obstruction factors could be used. Establishing such typical factors is an opportunity for additional development in this field. We do provide just a few data points towards this end.

³⁴ [Lightswitch-2002: a model for manual and automated control of electric lighting and blinds](#) C. Reinhart. A version of this document is published in *Solar Energy*, v. 77, no. 1, 2004, pp. 15-28

RESULTS

DAYLIGHTING CONTROL ENERGY SAVINGS

The primary objective of this research is demonstration of the impact of proper commissioning, focusing on calibration and functional testing, on the performance of automatic daylighting controls. In the previous sections, we discussed development of several metrics to demonstrate this impact, including energy savings, controls effectiveness, and the comparison of these values across the as-found (period 1) and fully commissioned (period 3) time frames. We now present the results of those calculations, beginning first with the as-found savings, then effectiveness, and then comparisons from as-found to post-commissioning.

Typical Energy Savings

Data was initially collected to determine the performance of each system as-found. The primary metrics used to describe performance are electricity savings per kW of controlled lighting in units of kWh/kW and the percentage of energy saved for the controlled lighting. These primary metrics are summarized in Table 7 by space, with median values for the study highlighted at the bottom. Results are shown for lighting only on the left, and lighting with associated HVAC savings on the right.

Table 7. Primary metrics describing the performance of the daylighting control systems studied, in the 'as-found' condition. Note that average values are higher than medians because of two highly performing library systems.

Lighting Energy Savings in the 'As-Found' Condition

			with HVAC savings	
	(kWh/kW)	(%)	(kWh/kW)	(%)
Central Library N A	2463	74%	2438	73%
Plymouth Library S1	3913	69%	4610	81%
WPPI W2	2197	62%	2380	67%
MG Library	2237	57%	2578	65%
Lg. Office N3 B	1059	54%	1173	60%
Central Library N B	2277	53%	2433	57%
WECC SE1	1079	40%	1368	51%
Lg. Office S3	1507	36%	1651	39%
Lg. Office N3 A	2360	33%	2790	39%
Plymouth Library Office	1053	22%	1244	27%
CEE A	350	16.9%	387	18.8%
Labs NW3	529	16.8%	600	19.0%
WECC S2	408	13.1%	496	15.9%
Freeman N2	565	11.3%	657	13.1%
Labs SE3	321	9.1%	375	10.6%
CEE B	51	2.5%	56	2.8%
WPPI N2	0	0.0%	0	0.0%
Freeman N3	0	0.0%	0	0.0%
Boss NW3	0	0.0%	0	0.0%
Boss NW4	0	0.0%	0	0.0%
Average	1118	29%	1262	32%
Median	809	20%	915	23%
Minimum	0	0%	0	0%
Maximum	3913	74%	4610	81%

This initial data shows that the median automatic daylighting control system in a population represented by our sample would save approximately 809 kWh for every kW of lighting that is controlled by the system, or about 20%³⁵ of the controlled lighting energy. This number increases to 915 kWh per kW (23%) if we include the savings in associated HVAC energy.³⁶ If we look at the units of kWh/kW, this essentially simplifies to the number of equivalent *hours* in a year for which the lights would be fully off.

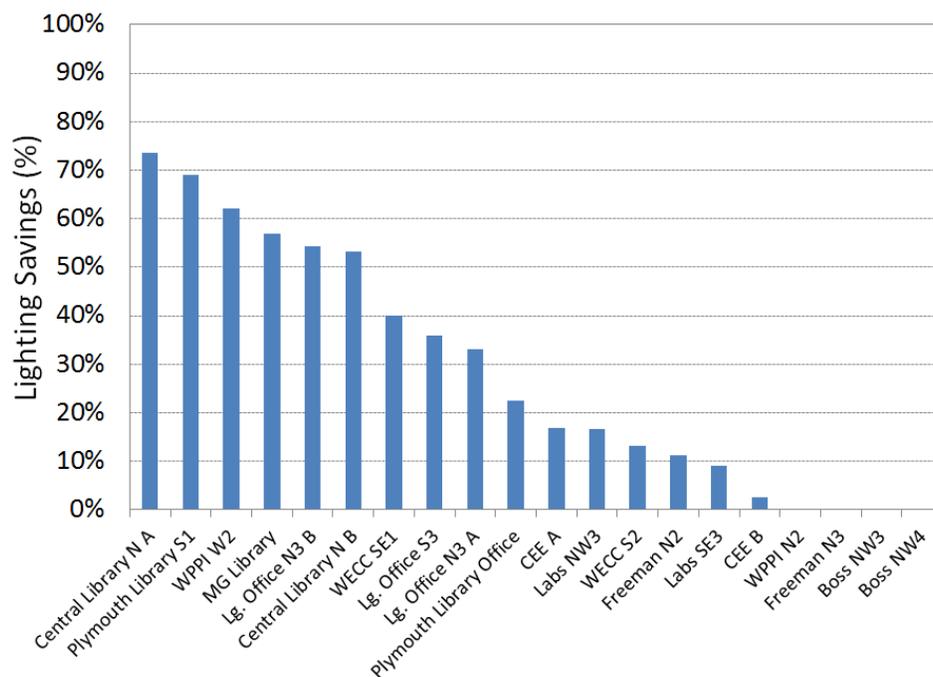
³⁵ With a range of performances selected, with some systems working and others not, the standard deviation of these values based on our sample size is 1250 kWh and 27%.

³⁶ It is useful to benchmark the results of this study against the most similar major study completed, which was done approximately seven years ago in California (HMG, 2005). They found that the average kWh per kW controlled was approximately 400 kWh for all systems studied, and 700 kWh for systems that were deemed 'functioning.' The results that we found agree with the upper end of this range. It is difficult to know why our results skew towards this upper end. It is possible that in the seven years since that study, system performance has improved, or that as such systems are (or seem based on our survey) less common in Minnesota than California and that factor influences the type and performance of systems. It is also possible that the sample itself skews somewhat towards higher performing systems, though no intended bias was used to select performing systems.

If a typical commercial space operates for 3,500 hours per year, it seems reasonable that a typical daylighting control system could keep the lights at or near off for a quarter of that time (or half off for half of the time, etc.). On a per square foot basis, for a typical commercial space lit with 1 W/ft², this savings equates to 0.9 kWh/ft².

Savings ranged from as high as 74% or 2,463 kWh/kW for controlled lighting (Central Library N A) in a fully glazed north façade, to as low as zero. In fact, four of the twenty systems that we studied were essentially not saving energy as they were found. Beyond the non-performers, there was a somewhat uniform distribution of performance levels ranging between 3% and 74% savings (see Figure 13).

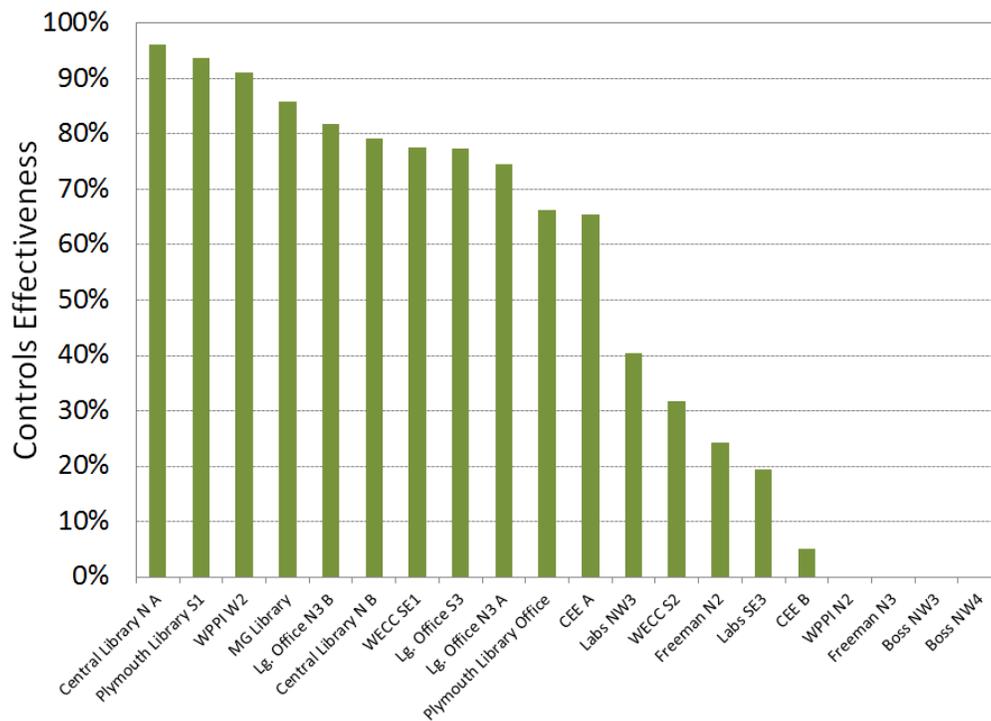
Figure 13. Distribution of lighting savings (by %) for the sample of spaces, prior to our recommissioning step.



The ability of a daylighting control system to save energy is impacted by many different space attributes: orientation, glazing, furniture layout, control design, control operation, interior finishes, and more. The primary objective of this effort was to study the controls themselves. To that end we created the metric of *controls effectiveness* (see *Methodology and A* section) which specifically looks at how well the controls are designed and operated to save energy based on available daylight.

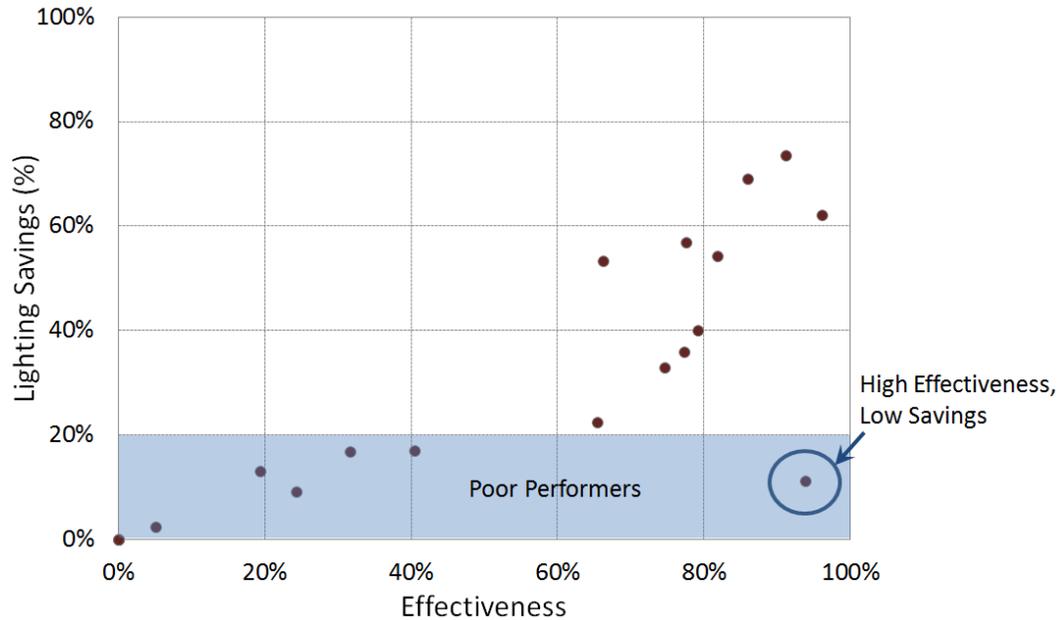
Simply put, controls effectiveness is the ratio of actual performance to performance with ideal or perfect controls. Therefore it is normalized for the performance of attributes like glazing and interior design, which are outside the realm of controls. In period 1, we found the average controls effectiveness to be 51% (with a median of 66%). The range of effectiveness values can be seen clearly in Figure 14.

Figure 14. Distribution of controls effectiveness found in period 1 of data collection.



It is also helpful to show the strength of the correlation between controls effectiveness and energy savings. As Figure 15 demonstrates, the effectiveness of these controls appears to be a primary driver of their overall performance—regardless of how much effort was put into glazing design, lighting layout, orientation, and other design parameters. In fact, of the poorer performing systems, or those with less than 20% (controlled) lighting savings, only one in ten had controls that were operating at a high level of effectiveness. This means that other causes outside of the control operation were responsible for poor performance in only one of the ten poor performers. If controls are designed, installed, and operated so that they are operating reasonably effectively, savings jump to between 22-74%.

Figure 15. Percentage savings as a function of controls effectiveness ($p < 0.001$ for this relationship).

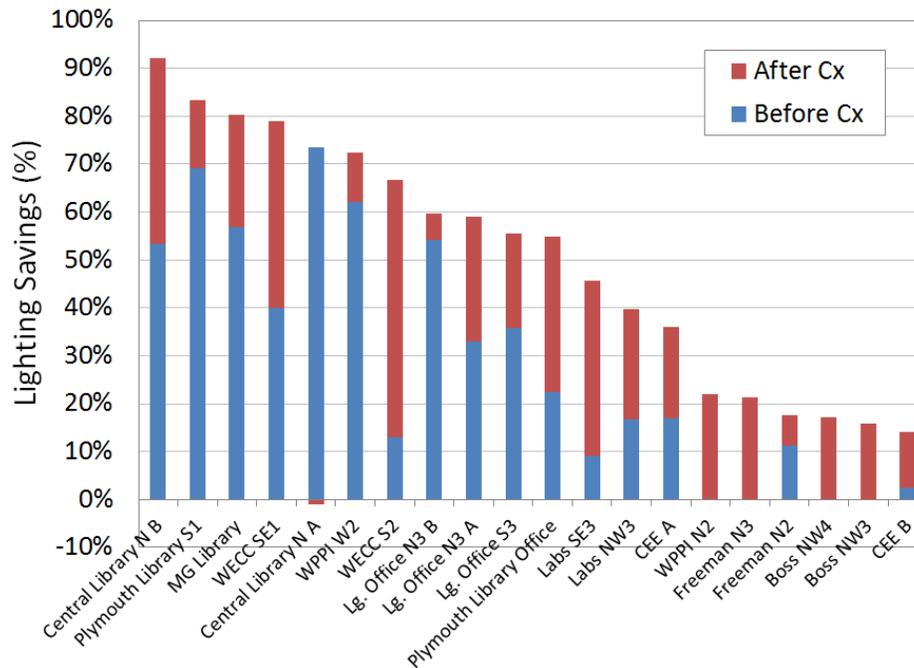


Savings Due to Commissioning

Our initial surveys of the building designs and products selected for these buildings revealed that there was generally significant attention paid to daylighting strategy in design, and that the daylighting controls selected were of high quality. Our hypothesis was that though a quality control system is part of the design, it is not always given enough attention throughout the entirety of the design and construction process. Put another way, it is not fully *executed* to perform well—primarily through documentation, installation, and startup stages of the project. This was demonstrated by some of the low effectiveness scores we observed in period 1.

One solution to this inadequate execution would be a commissioning process focused on execution of lighting control. Though often recommended and even included in the specification, it is unfortunately not often completed, or at least was not based on our interviews. To demonstrate the positive impact of commissioning and subsequent controls operation on performance of a system, we included a recommissioning step between periods of data collection. Technically what we completed on each system would be termed recommissioning because we commissioned systems after substantial use, but without any substantial change in the building. Prior to period 3 of data collection, we spent a few hours in each space completing basic startup tasks, such as calibration and functional testing, which might be part of an initial commissioning process. These tasks included items such as tuning, shielding, redirecting sensors, connecting disconnected systems, changing timing settings, and other adjustments that could be done fairly quickly without any additional equipment installation or even any significant work by an electrical contractor (see the *Recommissioning Process* section for details). Figure 16 demonstrates the change in savings from before recommissioning to after (represented by period 1 and period 3, respectively).

Figure 16. Energy savings before and after commissioning. Note that the ‘after’ case is represented by the sum of the two bar colors, and not only the red. In one space, WPPI W2, we did find that the commissioning effort resulted in negative savings (additional energy used) as the original setpoints resulted in lighting levels that were, at times, below the design condition.



As Figure 16 demonstrates, the recommissioning effort resulted in significant increases in performance in most spaces. The tabular results for the performance of these systems after commissioning is given in Table 8, with median values for the study highlighted at the bottom. Results are shown for lighting only on the left, and lighting with associated HVAC savings on the right. Note that in cases with significant HVAC savings, total savings can potentially be greater than 100% of the controlled lighting energy.

Table 8. Primary metrics describing the performance of the daylighting control systems studied, after the commissioning step.

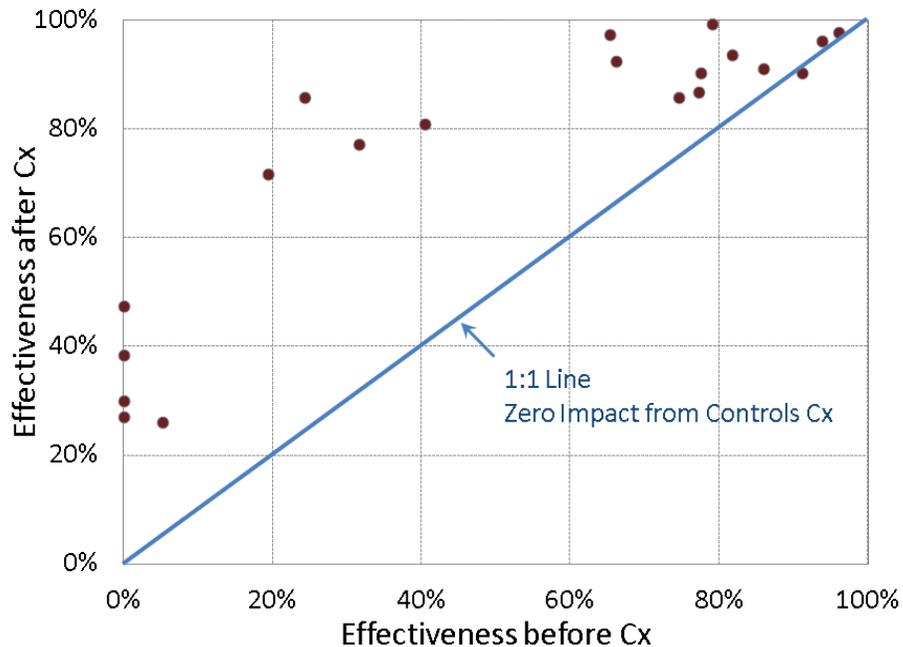
			with HVAC savings	
	(kWh/kW)	(%)	(kWh/kW)	(%)
Central Library N B	3954	92%	4226	98%
Plymouth Library S1	4220	83%	4972	98%
MG Library	4156	80%	4789	93%
WECC SE1	2042	79%	2590	100%
Central Library N A	3250	73%	3217	72%
WPPI W2	1902	72%	2060	78%
WECC S2	2396	67%	2913	81%
Lg. Office N3 B	1174	60%	1301	66%
Lg. Office N3 A	2341	59%	2767	70%
Lg. Office S3	2138	56%	2343	61%
Plymouth Library Office	2491	55%	2944	65%
Labs SE3	1622	46%	1891	53%
Labs NW3	1138	40%	1291	45%
CEE A	363	36%	402	40%
WPPI N2	199	22%	144	16%
Freeman N3	735	21%	704	20%
Freeman N2	884	17.5%	1029	20%
Boss NW4	702	17.1%	870	21%
Boss NW3	613	15.9%	663	17.2%
CEE B	245	14.2%	272	15.7%
Average	1828	50%	2069	57%
Median	1762	55%	1976	63%
Minimum	199	14.2%	144	15.7%
Maximum	4220	92%	4972	100%

With commissioning the median savings increase to approximately 1,762 kWh for every kW of lighting that is controlled by the system, or about 55% of the controlled lighting energy.³⁷ These savings numbers can be as high as 4,220 kWh per kW and 92% savings (again, including HVAC energy). More importantly, the minimum savings has increased from 0% prior to commissioning, to 14% after commissioning. Savings have increased substantially across all key metrics with the commissioning process. Median savings increases to approximately 1,976 kWh per kW, or 63% savings, if we include the savings in HVAC energy. For an average space at 1.0 W/ft², this equates to 2.0 kWh/ft² controlled.

Figure 17 compares the controls effectiveness after commissioning to the effectiveness prior to commissioning. This demonstrates that our commissioning process met its goal of improving controls effectiveness, bringing most systems more than halfway closer to being 100% effective.

³⁷ Though these savings values have nearly doubled from the pre-commissioning case, the absolute standard deviation remains similar at 1,260 kWh and 25%; there is considerably less (relative) variation in results when systems are all commissioned.

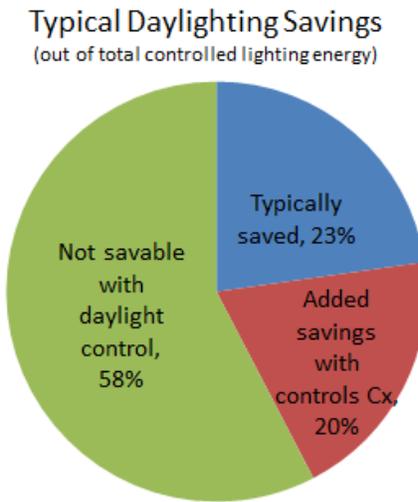
Figure 17. Controls effectiveness, after commissioning versus before commissioning. In general, the effectiveness was increased substantially through commissioning.



It is useful to quantify these specific improvements in terms of savings. Figure 18 shows a typical breakdown based on the average percent savings results from Table 8, with an increase for commissioning averaging 20% of total lighting energy, which is an 87% *improvement* over the savings from the pre-commissioning case. This increased savings from commissioning equates to an average of 810 additional kWh per kW of installed lighting.

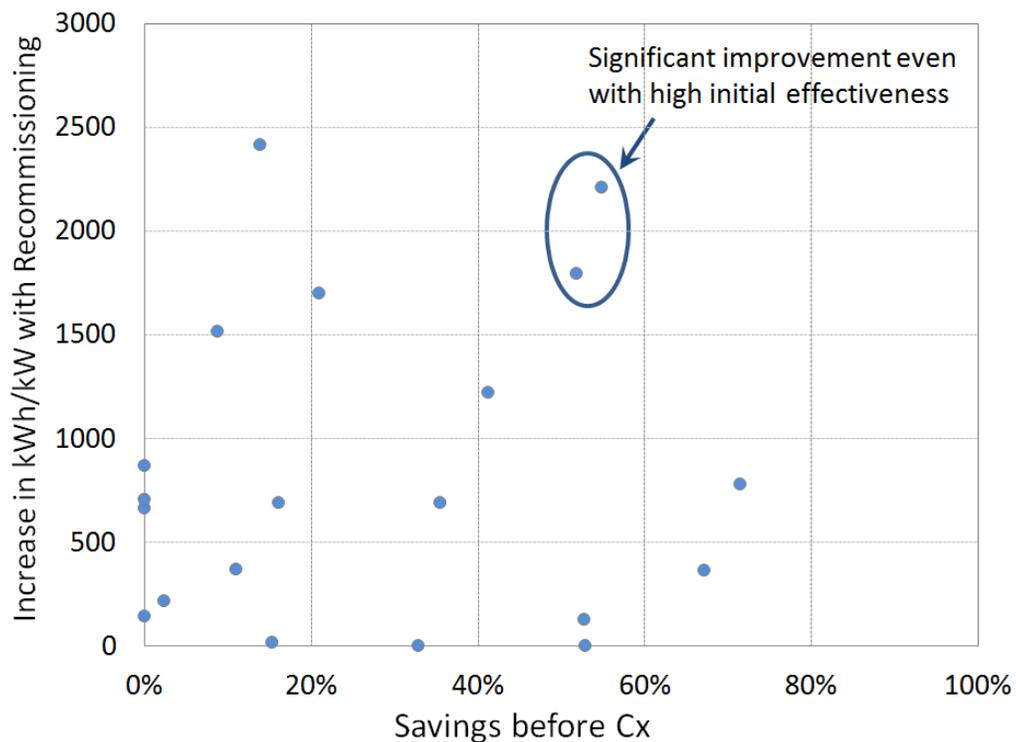
The third key metric, controls effectiveness, increased (on average) from 50% to over 75%, or a 50% *improvement*. This additional savings results solely from improving controls operation, not from any change to glazing design, blinds operation, furniture selection, or minimum dimming power of the ballasts—all generally more difficult or expensive items to modify.

Figure 18. Typical attribution of distribution of lighting energy in a daylit system, between energy that cannot be saved by daylighting controls, energy that is typically saved, and additional energy that could be saved if all control systems were fully executed and commissioned.



The distribution of potential for improvement in energy savings is shown in Figure 19. Plotting this improvement data as a function of effectiveness *prior to commissioning* also demonstrates that there is room for additional savings from commissioning in most systems, even those for which the controls were reasonably effective with a typical installation.

Figure 19. Increase in savings for each system from before to after the recommissioning step. The data is plotted as a function of the initial savings of each control system.

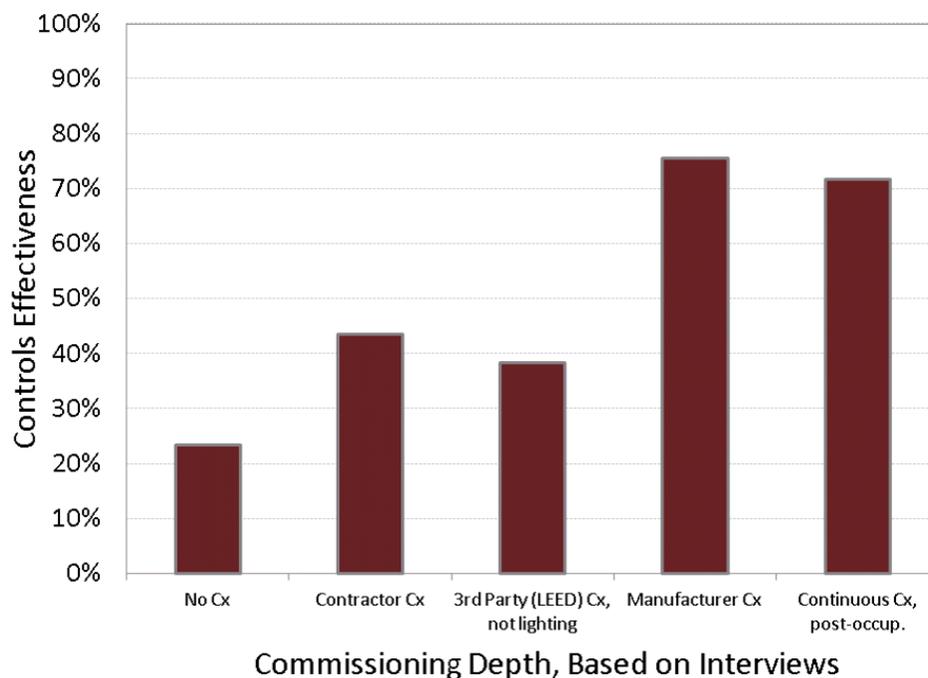


Recommissioning demonstrates a potential measure that could be implemented not just by building owners, but through energy efficiency programs. With a significant number of automatic daylighting controls systems already in place throughout the country, there is energy to be saved in finding these buildings and completing a fairly simple, brief recommissioning effort (see *Utilizing More Daylight in Minnesota Buildings* for actual extrapolation to the larger population). In our experience, making the adjustments required to bring each zone near optimal only took about 30 minutes once we had a few days of electrical current measurement and had located the controls equipment.³⁸

Owners of newly constructed buildings, however, do not need to wait for *recommissioning* of their spaces. An owner and their design and operating teams could make initial commissioning of the daylighting controls part of the scope of design services when the building is constructed. Leading design professionals, daylighting researchers, and even some energy standards have been suggesting this for some time, and offering steps to do so.³⁹ This work shows that implementation of this practice in this region is not yet widespread enough. Initial commissioning can be more cost effective than having a third party coming to the building later and needing to locate and decipher circuits and user interfaces before even beginning the calibration and testing process.

Our interviews with building staff suggest that initial commissioning processes can have a similar impact on performance as our recommissioning effort did (see Figure 20).

Figure 20. Average controls effectiveness (from period 1, as-found) of each system for the various levels of commissioning undertaken on the project during construction and startup. Sample sizes are small (N ranges from 2 to 6) so the values should not be used universally, but the overall trend is noteworthy.



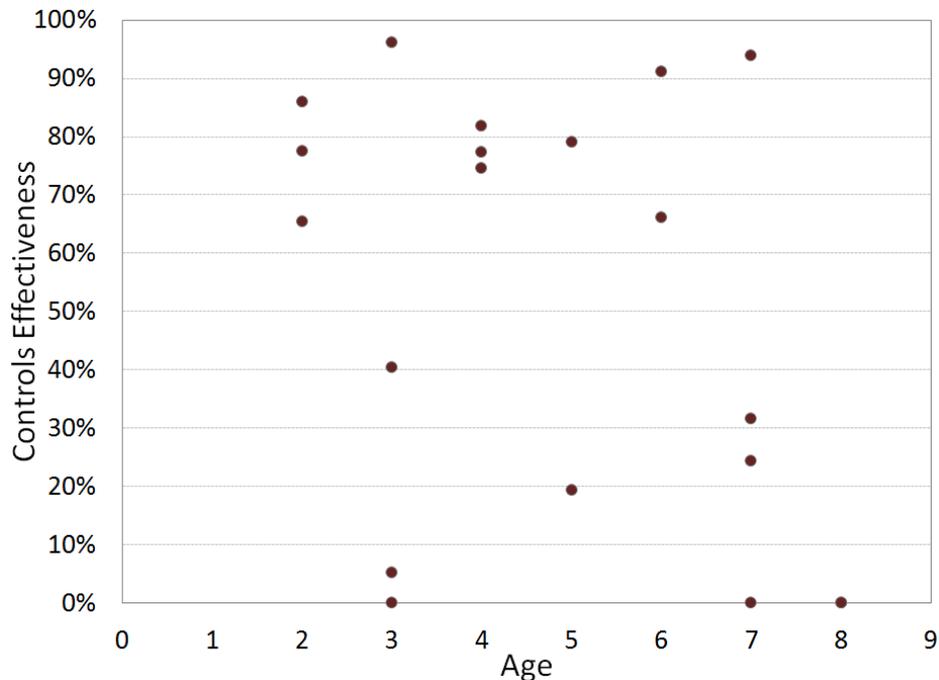
³⁸ Assumes some assistance from manufacturer in navigating controls interface, or prior knowledge of the interface.

³⁹ Seattle City Light, California Title 24, and Lawrence Berkeley National Laboratory (LBNL, 2012) are all examples of providers or enforcers of specific guidance and requirements in this area.

A similarly qualitative trend was found for training of building managers: the more training given to those managing the system, the higher the controls effectiveness for our sample.

We also looked at controls performance based on system age. As seen in Figure 21, controls operation was not a strong function of age. This suggests that performance can persist for many years if initial commissioning is done correctly and the system is made to perform optimally. (The same conclusion was reached on an even broader sample in research throughout California).⁴⁰

Figure 21. Controls effectiveness (from period 1, as-found) of each system as a function of the age of the system. There is no clear relationship between performance and age (p=0.12 for this relationship).



Heating and Cooling Effects of Daylighting Control

So far we have presented results with savings either 1) for lighting only or 2) for the combination of lighting and HVAC impacts. It is beneficial to explicitly examine the difference between the two, namely the impact of heating and cooling on the savings we estimated for these control systems.

In our examination of heating and cooling impacts of these systems, we examined the additional energy saved with lower lighting loads in a cooling condition, and the energy savings lost with lower lighting loads in a heating condition (see discussion in *Effects on Heating and Cooling Energy* for methodology). In general, most of these spaces were in cooling mode during the majority of the daylight hours. Therefore, there was generally additional HVAC savings resulting from daylighting controls, even in the cold Minnesota climate.

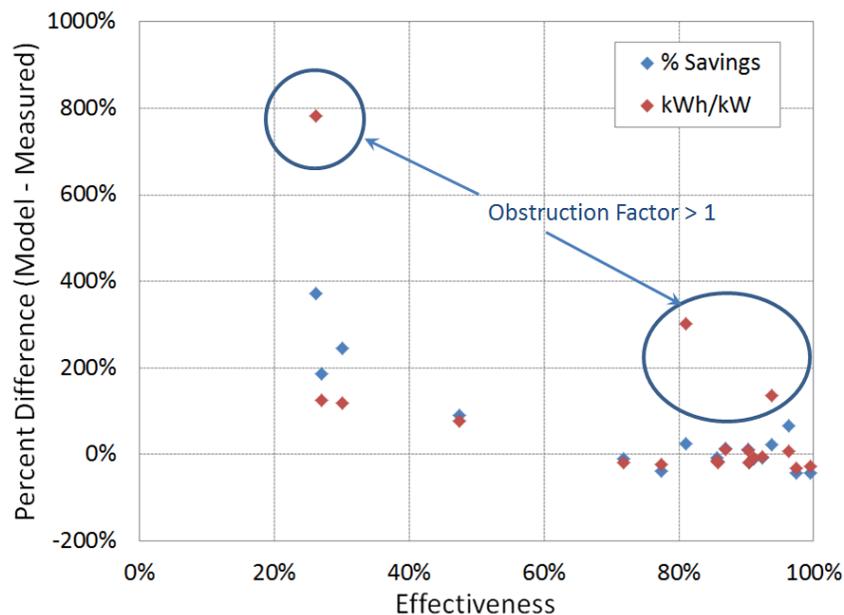
⁴⁰ "Sidelighting Photocontrols Field Study," Heschong Mahone Group, Inc., Report #06-152, 2005

The impacts of heating and cooling were normalized separately for TMY weather data, and then combined into a single factor. Each space in our study had *very* unique load conditions, including people, equipment, HVAC system type, and solar orientation. Therefore it is not useful to comment on the impacts of each space individually. In aggregate though, it is useful to point out that there was a net cooling benefit seen from daylighting control. Across all the spaces that we studied, in a typical meteorological year, this impact averages an additional 13% savings. This means that for every kWh of lighting energy saved, 0.13 kWh of HVAC energy were saved in addition.

Comparison to Modeling

It is useful to compare these measured results to the results of energy modeling of these spaces in the commonly used DOE-2 modeling platform (see *Modeling M* for our approach). This may help us better understand the magnitude of error inherent in typical energy models of daylighting systems. Figure 22 illustrates the percent difference between modeled and measured results as a function of the system's effectiveness.

Figure 22. Percent difference of modeled percent savings and savings per controlled power as a function of system effectiveness.



Note that as the system effectiveness increases the modeled and measured savings achieve much closer agreement. Energy modeling, with its assumption of ideal control, appears to have the potential of being an accurate predictive tool for highly effective (>75%) control systems. However, the agreement between modeled and measured savings diverges significantly for the poorly controlled systems, with the model significantly over-predicting savings as compared to the measured results. Several outliers existed that correspond to the three models in which the obstruction factor was calculated to be greater than one. In these models some other source of error was present such that DOE-2's split flux method could not accurately predict the illuminance in the space. Future work would involve a closer inspection of these outliers.

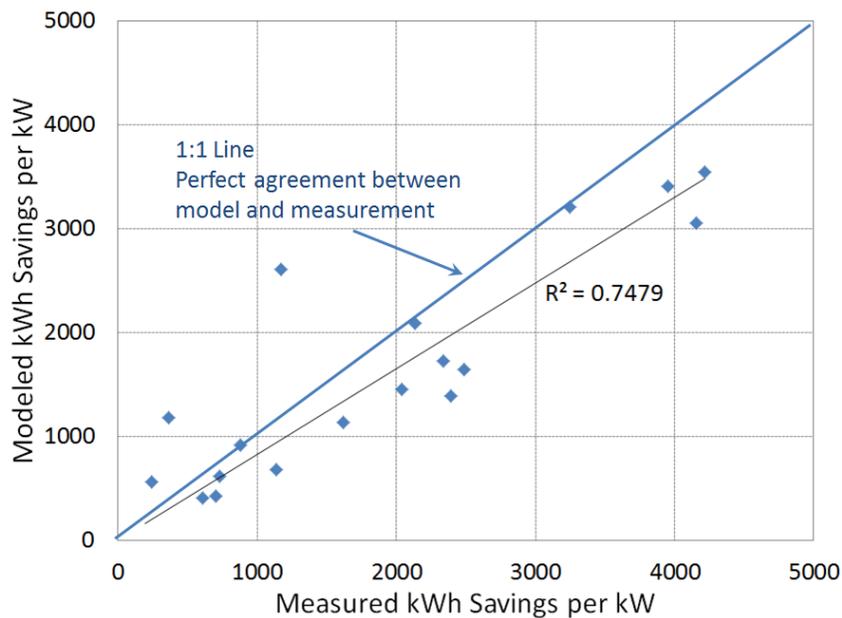
Our next step in this comparison was to apply the actual measured controls effectiveness (post-commissioning) to the model, as a modifier. When this is done, the agreement between measured and modeled savings increased. Table 9 summarizes the measured and modeled lighting savings results.

Table 9. Summary of measured and modeled savings results.

	Measured Lighting Savings		Modeled Lighting Savings	
	(kWh/kW)	(%)	(kWh/kW)	(%)
Boss NW3	613	16%	405	17%
Boss NW4	702	17%	428	13%
Labs NW3	1138	40%	680	19%
Labs SE3	1622	46%	1134	33%
Freeman N3	735	21%	617	19%
Freeman N2	884	18%	919	28%
Lg. Office N3 A	2341	59%	1731	46%
Lg. Office S3	2138	56%	2096	56%
Lg. Office N3 B	1174	60%	2609	69%
MG Library	4156	80%	3055	59%
CEE A	363	36%	1182	36%
CEE B	245	14%	566	18%
Central Library N A	3250	73%	3208	73%
Central Library N B	3954	92%	3412	78%
Plymouth Library Office	2491	55%	1648	31%
Plymouth Library S1	4220	83%	3552	67%
WPPI W2	1902	72%	N/A	N/A
WPPI N2	199	22%	N/A	N/A
WECC SE1	2042	79%	1454	45%
WECC S2	2396	67%	1390	43%
Average	1828	50%	1671	42%
Median	1762	56%	1422	40%
Minimum	199	14%	405	13%
Maximum	4220	92%	3552	78%

Note that the measured lighting savings pertain to the post-commissioning, TMY-extrapolated results that we previously outlined in the *Savings Due to Commissioning* section. The effectiveness-modified modeling results were then in good overall agreement with the measured results. Figure 23 illustrates the relationship between modeled and measured kWh savings per controlled kW.

Figure 23. Modeled versus measured kWh savings per controlled kW.



Note that with the effectiveness-modifier in place, the overall agreement is relatively high ($R^2 = 0.75$) but the model does under-predict savings as compared to the measured values. “Calibrating” a model using such an effectiveness modifier would therefore be a conservative estimate of energy savings. A comparison using percentage saving shows a similar agreement as the kWh savings per controlled kW with relatively high agreement ($R^2 = 0.75$) and consistent under-prediction of savings as compared to measured values.

Throughout the modeling effort, one variable with significant influence was the obstruction factor. This factor scales the predicted illuminance levels, linearly, to represent furniture or other obstructions. The average obstruction factor for our modeled spaces was 35%, which means our original models that did not include obstruction factors were over-predicting illuminance levels by 65%. A portion of this over-prediction came from interior obstructions such as furniture and partitions. Some of the over-prediction would likely come from other sources in the DOE-2 illuminance algorithm as well. Further research is warranted to develop typical obstruction factors for differing furniture and interior geometries. This, coupled with increased awareness within the modeling community of this input, would lead to higher modeling accuracy.

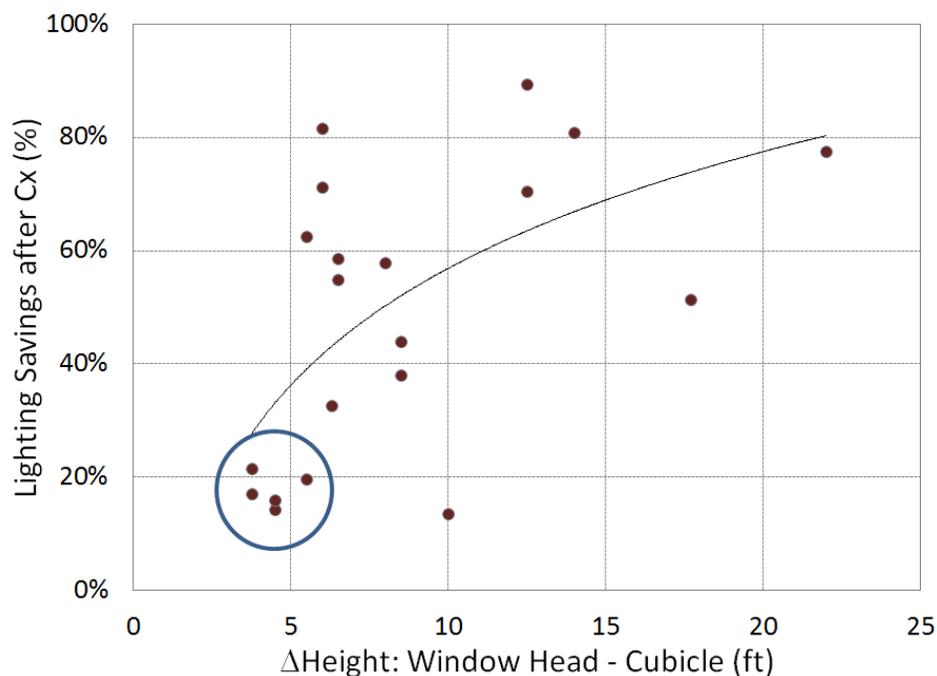
Some Daylighting Design Conclusions

Though the primary thrust of this research focused on the performance of controls systems and their operation, the data can be used for higher-level observations of other aspects of daylighting design as well. One trend that emerged from the accumulated lighting data at multiple points in every space, was the significant impact of furniture design on lighting levels. The height of walls, orientation of work surfaces, and reflectance of the furniture all had a large impact on lighting levels at the critical workplane.

Our energy savings data correlated to one such furniture property, workstation wall height or ‘cubicle height.’ Figure 24 demonstrates this correlation. Here lighting savings is plotted as a function of the

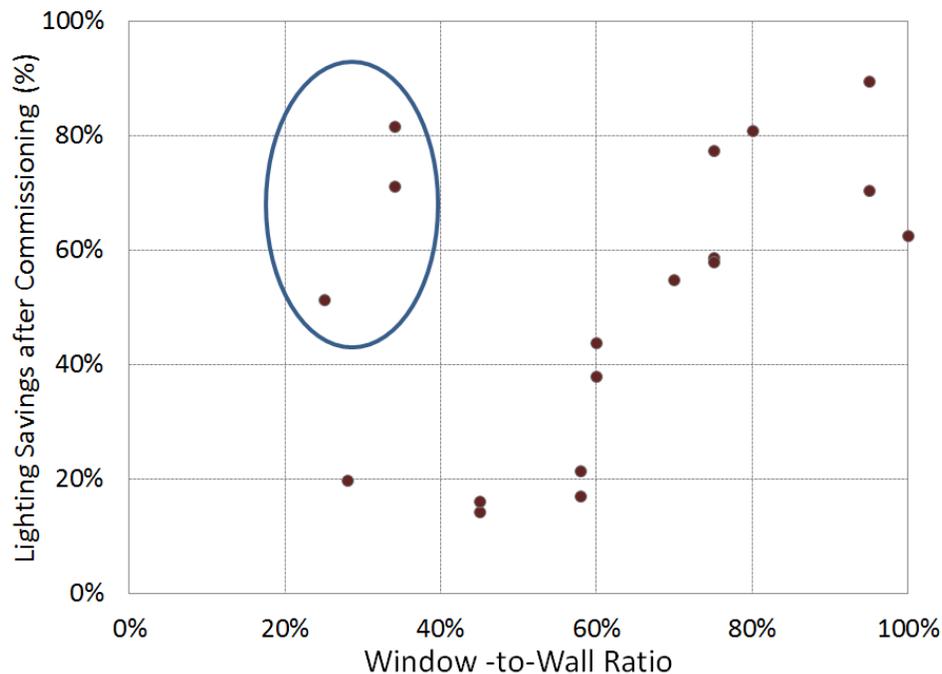
difference between the window head height (top of the windows) and the cubicle height (top of the workstation walls). The correlation utilizes twenty spaces with a broad range of architectural features, so the resulting correlation equation would contain a high degree of error across a larger population. However this trend is *qualitatively* noteworthy, specifically in that five of the six spaces with less than a 5.5 foot difference between window head and cubicle wall were poor performers with ~20% savings or less. In buildings with greater than a 5.5 foot difference, 13 out of 14 saved over 30% of their lighting energy. To put this in practical terms, for a typical building that may have a 9-foot window head height, the walls on cubicles should be at 3.5 feet or less, which is a common high performance target. Otherwise system performance will be penalized. This correlation suggests that interior design staff need to be involved in daylighting design as well.

Figure 24. Lighting savings (%) as a function of the differential between window head height and cubicle (workstation) wall height.

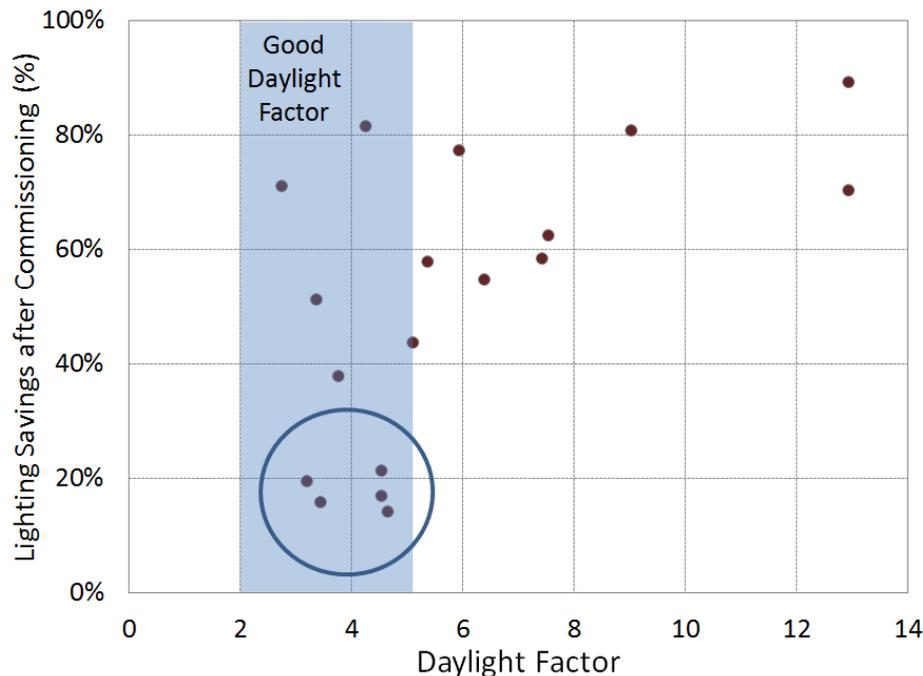


One design feature often correlated with daylighting performance is window-to-wall ratio (WWR). Enough glazing is needed for light to enter the space, but larger amounts of glazing equate to greater thermal losses through the windows, and greater potential for glare to impact occupants. All of the buildings that we studied were designed, to some extent, to take advantage of daylighting. Therefore the smallest window-to-wall ratio of the twenty spaces we studied was 25%. Again, describing a specific correlation function from this sample may not be useful for the larger population, but there is enough data to make some observations. First, there is no clear, strong trend between savings and glazing size, especially for non-curtainwalled spaces. Secondly, even at lower window-to-wall ratios of 25-35%, there is good potential for significant energy savings: three well-performing systems with less than 35% glazing saved between 51 and 82% of lighting energy.

Figure 25. Lighting savings (%) as a function of the window-to-wall ratio in the space. $p=0.03$ for this data – there is a trend towards greater daylighting benefit from full window walls (75%+ WWR), but 30% WWR can be as effective as buildings with more glazing (and correspondingly higher thermal losses).



A similar story emerges when the lighting savings is plotted against a space's daylight factor. Daylight factor is a parameter designed to quickly ascertain a space's daylight potential. It includes information about the space's total area, window area, window visible transmissivity, surface reflectances, and exterior shading. Daylight factors between two and five are considered good, providing a space with high enough natural light levels without being overlit. Although daylight factor is being replaced by more sophisticated, time-dependent parameters such as daylight autonomy, it still serves as a simple way to quickly understand a space's daylight potential. Figure 26 illustrates the relationship between post-commissioning lighting savings and a space's daylight factor.

Figure 26. Lighting savings (%) as a function of the daylight factor in the space.

The first thing to notice in Figure 26 is that half of the spaces are potentially overly daylight. Of these spaces, four are south facing, requiring interior blinds to minimize the impact of glare. This glare still resulted in a problem in some of those spaces (see *Regarding Occupant Comfort*). Also, five of the spaces in the range of good daylight factor are poor performers. This reinforces the point that a space can be architecturally well-designed, but still exhibit low daylight savings due to other factors.

ECONOMICS OF DAYLIGHTING

Daylighting controls come with significant additional up-front costs. From a review of relevant literature⁴¹ and from recent project experience, we have found costs can range anywhere from \$0.75 - \$3.00 per square foot depending on the complexity and flexibility of the system. The lower end of this range would generally apply to simple systems, such as controls integral to the luminaire (or fixture), while the upper end of the range applies to more complex systems, such as full-building automation with individual, digitally addressable ballasts. It is not obvious on most projects whether this first cost increase is justifiable based on energy savings. We have therefore completed a life cycle assessment based on the benefit of the energy cost saved only. This does not include other benefits such as incentives, increased productivity, carbon credits, etc. This assessment is valid for building design teams or owners looking to incorporate the technology, and also for utility program personnel in Minnesota who need this type of information to implement and evaluate these programs.

⁴¹ This information comes from cost data from multiple projects on which we have consulted, “Commercial Building Toplighting: Energy Saving Potential and Potential Paths Forward”, TIAX LLC for US Department of Energy, June 2008, and “Lighting and Daylighting Design with Efficiency”, Presentation for Energy Center University, Jim Benya, August 2010.

We conducted life cycle cost analysis in accordance with the procedures in the Federal Energy Management Program (FEMP).⁴² The inputs to this analysis are shown in Table 10. Note that we are not addressing maintenance cost here, as we have observed that most systems do not require additional maintenance on the daylighting controls. The one exception was a building with very sophisticated controls and the owner had a maintenance contract to operate them optimally. A system complex enough to require this level of oversight may have some additional operating cost beyond what is shown below.

Table 10. Economic inputs for life cycle cost analysis.

	Value	Basis
Electricity cost	\$0.093 / kWh	Average commercial electric rate in MN, according to EIA
General inflation	2.5%	Difference between 20 year treasury bills, inflation adjusted and not
Fuel inflation, electricity	1.5%	FEMP 10 year outlook
Total tax rate	45%	Nominal federal business tax rate + MN corporate tax rate
Depreciation of equipment	15 years	Straightline depreciation
Discount rate	5-9%	9% for the corporation scenario, 5% for an institutional scenario
Life cycle cost timespan	15 years	Lifespan of lighting systems; FEMP

We have divided building owners into two primary economic categories: corporation and institution. We considered the economic outcome of these owners choosing daylighting controls in Minnesota. Corporations are assumed to use a higher discount factor of 9%, and pay corporate tax rates typical of Minnesota businesses. Institutions are assumed to pay no taxes, and use a lower discount factor of 5%. Following FEMP guidelines to decide whether to adopt a technology, these organizations would need to determine whether the net present value of the technology was positive or negative. Because the costs of these systems can vary so much depending on the space in question, it is perhaps most useful to determine the cost at which the owner would break even (have a net present value of zero). For our median values of energy savings, this results in the break-even costs shown in Table 11 for a 1 kW system.

Table 11. Break-even costs for installing automatic daylighting controls on 1 kW across multiple project scenarios.

Break-even cost for controls on 1 kW of lighting		
	Typical System	Fully Commissioned System
Median energy savings (kWh/kW)	915	1,976
Break-even cost, institution	\$980	\$2,120
Break-even cost, corporation	\$1,050	\$2,270

For a typical system, an owner can afford to spend about \$1,000 for controls, which includes the premium for a dimming ballast, controllers, sensors, and installation, on a 1 kW system. This equates to about \$1.00 per square foot for a building with a lighting power density of 1 W/ft². If the system undergoes a full commissioning process, including optimization at startup, the owner can now afford to spend roughly \$2,200 for a 1 kW system, or about \$2.20 per square foot. The cost of the commissioning would need to fit into this higher cost, but with costs of controls reportedly between \$0.75 and \$3.00 per square foot, it's

⁴² NIST Handbook 135: Life-Cycle Costing Manual for the Federal Energy Management Program, US Department of Commerce National Institute of Standards and Technology, Prepared for the US Department of Energy, 1995.

likely that most projects would be able to afford the commissioning step too. In fact, several manufacturers will provide this service for free if prompted.

Though we would recommend that these more technical and thorough economic metrics be used to judge the merit of automatic daylighting controls, some readers will still be interested in payback metrics. For typical systems, if we assume an installed cost of \$1.25/ft² the payback is about 10-15 years. If we assume an installed cost of \$2.00/ft² the payback becomes 14-24 years. If the system undergoes a full commissioning process, these paybacks drop to 6-7 years at \$1.25/ft² upfront cost, and 8-11 years at \$2.00/ft² upfront cost (all paybacks assume a 1 W/ft² system).

UTILIZING MORE DAYLIGHT IN MINNESOTA BUILDINGS

We can use the savings measured in these 20 spaces to extrapolate the potential for daylighting control savings to the entire state of Minnesota. This information is useful for the utility efficiency programs operating in Minnesota (also known as Conservation Improvement Programs, or CIPs, there). This extrapolation contains significant uncertainty, but is worth some consideration as our sample includes fairly typical daylit buildings (see Table 1 and Table 2), and covers two of the commercial building types, office and public assembly, with the most daylighting according to CBECS. Schools would be the other primary type that we have not represented, so this extrapolation has inaccuracy to the level that school lighting systems perform differently than offices and assembly spaces. CBECS also shows a considerable number of daylit religious worship buildings, but in all our investigation we did not come across evidence of this in Minnesota. Our sample was unfortunately too small to make post-weighting of the sample feasible. We therefore simply relied on a qualitative comparison between our sample and the larger population of daylit Minnesota buildings that we identified. (see the *Extrapolation M* section for more assumptions and details).

First we examine the savings potential for daylighting controls in existing commercial buildings in Minnesota. We have estimated the annual lighting energy consumed in those spaces that have access to daylight⁴³ at approximately 826,000 MWh. Table 12 outlines how much of this energy could be saved if automatic daylighting controls were installed in these areas. The *technical potential* is listed first; this is the total potential for savings in the state. Next, the *annual achievable potential* is shown, which is the expected energy savings each year from targeted programs or other efforts. Due to higher upfront cost, it is difficult to determine what percentage of the annual lighting retrofit work in the state would be successful in including daylighting controls. Therefore two annual assumptions are shown, one for 5% of the retrofit market and one for 25% of the retrofit market.

⁴³ 'Access to daylight' is difficult to define with available information. Some estimates seem to account for areas which have some daylight, but not enough to necessarily achieve a high daylight factor. We therefore choose a fraction on the more conservative end of the literature.

Table 12. Technical and annual achievable potential for installing automatic daylighting controls in existing Minnesota buildings.

Savings Potential for Automatic Daylighting Controls (in MWh)

	Typical System	Fully Cx'ed System
Median energy savings (%)	23%	63%
Statewide Technical Potential	190,000	520,000
Annual Achievable Potential, 5% of retrofit mkt.	601	1,646
Annual Achievable Potential, 25% of retrofit mkt.	3,007	8,229

There is also potential for savings in recommissioning existing daylighting control systems in Minnesota buildings. The annual lighting energy consumed in those spaces that already have existing daylighting controls is approximately 56,400 MWh based on CBECS data and assumed growth in more recent years. Typical new construction rates were assumed, coupled with an assumed market growth rate (for an overall r_{exp} growth term). Resulting recommissioning savings potentials are shown in Table 13. In the “low” case we assume a 10% market growth and adoption of recommissioning at 50% of current lighting retrofit rates, albeit on that much smaller population.⁴⁴ In the “high” case we assume a higher 30% market growth and the same adoption as current lighting retrofit rates.

Table 13. Technical and annual achievable potential for recommissioning existing automatic daylighting control systems in Minnesota.

Savings Potential for Recommissioning of Daylighting Controls (in MWh)

	Low Case	High Case
Statewide Technical Potential	14,112	23,864
Annual Achievable Potential	447	1,511

The statewide technical potential for retrofitting buildings with automatic daylighting controls is, as we would expect, very large at hundreds of millions of kWh. This is because the current market saturation of daylighting controls is quite low, at a few percent. The technical potential for recommissioning of existing daylighting control systems is conversely quite small, at 10-20 million kWh, for the same reason. However, note that the *annual* achievable potential of retrofit and recommissioning are much more similar. This is due to an assumption, and perception from the market actors we’ve spoken with backs this up, that recommissioning would be more readily adopted due to lower cost. Though daylighting controls savings are most often achieved in new construction programs, it seems there are two separate measures with reasonable potential in the retrofit market.

⁴⁴ Market growth rate assumptions are arbitrary, so a significant range is tested. Adoption rate is assumed to be on the same order of magnitude as lighting retrofits (based on “Minnesota Statewide Electricity Efficiency Potential Study DSM Potentials Report,” Navigant Consulting, submitted to Minnesota Office of Energy Security, April 2010). We assume this because daylighting savings are similar to lighting retrofits, and the costs are potentially lower but the idea is new to most program trade allies.

STEPS TO MORE EFFECTIVE DAYLIGHTING CONTROL

In addition to learning from the quantitative data collected from these ten buildings and twenty spaces, we were able to learn lessons from speaking with occupants, managers, designers, owners, and manufacturers, as well as through commissioning the systems, and just observing the systems in operation across the data collection periods.

Operational Problems

First, through commissioning tasks, observation, and conversations with occupants we were able to determine the problems facing those systems that performed significantly less than optimally. When we add in the spaces that we visited but did not study, we looked closely at 43 systems, 24 of which had problems that left significant potential for improvement. These problems manifested themselves directly in our savings measurement and for spaces not studied in depth, were obvious through observation. The *primary* problems facing those 24 systems are listed in Table 14, with the number of times the problem was encountered and whether that problem could be addressed within a basic commissioning scope.

Table 14. Primary problems leading to less than optimal daylighting control along with the frequency of each problem. Also, whether or not the problem could typically be addressed within a basic commissioning scope of services (assuming that scope covered the lighting system of course). Some of these systems did have more than one problem; only the primary problem was tracked. For example, furniture and sensor orientation were *secondary* problems on a few other systems.

<u>Problem</u>	<u>Number encountered</u>	<u>In Basic Commissioning Scope</u>
Control calibration needed, major	8	Y
Control calibration needed, minor	5	Y
Zoning too large	3	Y
Glare, heavy shading applied	3	
Incorrect relay	2	Y
Furniture	1	
Sensor position	1	Y
Low deadband (disabled)	1	Y

CONTROLS CALIBRATION

To improve the daylighting controls in the majority of spaces to near optimal, we found that some amount of controls calibration was needed. Most often for a full dimming system this involved simply adjusting the setpoint or more accurately the controller *gain* of the system. On a couple systems it was other items such as a min/max setting or time delay. Where major adjustment was needed was generally an indication that no one calibrated or tested the controls. Where minor adjustment was needed, it appeared that the controls had been calibrated to some extent, but that too large of a safety factor had been applied, or controls were simply not calibrated well enough. Calibration and functional testing should be a primary step in any commissioning process. These tasks could be assigned to either the lighting contractor or the controls contractor depending on the scope of the control system, but could also be covered within the scope of the commissioning authority, to ensure they are completed properly. If spaces are sampled properly and a proper day with moderate light levels is picked, this can be a relatively simple task for fully dimming systems, and only requires a light meter as a tool. One potential cause for lack of full

calibration would be the contractor calibrating the system on too bright of a day. In this case, illuminance at the workplane is greater than design levels, making effective calibration impossible if additional shading is not available.

Additionally, on one of the systems we studied, a deadband was set too low on a switching system causing the system to switch on and off too frequently. This problem may be caught in functional testing by a careful commissioning authority, but is more likely to be noticed by occupants during the first cloudy days. If occupants notice this problem before the controls, electrical, or commissioning contractors have left the project, they could make additional adjustments, again with little time spent.

One setpoint that we did not consider part of our recommissioning scope was the maximum luminaire power. Reducing this setting, referred to as task tuning, would reduce the upper end of light levels and power at all times, even when it is dark. Therefore it is not purely a daylighting control adjustment, but has energy savings impact even during non-dimmed periods. It should be noted that where dimmable ballasts are purchased for daylighting control, they can also be used to modify the lighting levels in their full-power (i.e. night) condition so that they produce only the illumination required by design. This presents a significant additional opportunity for lighting savings, as many systems are installed with a level of safety factor for a variety of reasons that produces more light than is necessary. Where luminaires can be controlled differently by unit or by zone, this ‘tuning’ of light levels can occur at a high level of resolution, evening out the light levels in the space and at the same time saving energy. Hennepin County, one of the building owners in our study, enthusiastically mentioned they planned to incorporate this approach into many of their daylit buildings.

Finally, at times we also utilized shielding to create a more direct correlation between the sensor and workplane illuminances.

LIGHTING ZONES

A second type of problem that surfaced multiple times was zoning of the lighting controls. Three of the spaces had systems that attempted to control too large of an area in the building with a single sensor. This led to areas that had too little light even though the majority of the space was daylit adequately. This could be addressed as early as the latter half of the design process, and be reviewed by the commissioning authority. The designer should consider what area in the vicinity of the sensor will be receiving a uniform amount of daylight, and only control that extent with that sensor. Additional zones should be added as the façade or orientation changes. Additional control zones should be considered for deeper zones, especially if switching controls are used, or if the control zone penetrates further than 1.5× window height. Changes in furniture and interior obstructions should also be considered. For example, one building had a stairwell obstructing half of a zone. Of course adding zoning adds cost, so there is a balance to be reached.

In some systems, if it is not caught earlier, poor zoning could also be addressed after installation, during functional testing or even post-occupancy. For this to occur, the system would need to be on a central building automation system (BAS) that allows different sets of lights, and sometimes individual luminaires in the case of addressable ballasts, to be assigned to different sensors after installation. This was possible in half of the buildings that we studied. In some cases, reassigning luminaires was quite complex, so it would still be recommended that zoning be thoroughly considered prior to or during installation whenever possible.

INTERIOR DESIGN: FURNITURE AND BLINDS

Space design considerations like glare potential and obstructive furniture also caused systems to underperform. Unfortunately little can be done about these issues to recover energy savings once the spaces are designed. Office furniture (see discussion regarding cubicle walls in *Some Daylighting Design Conclusions*) is generally fixed after move-in. And glare is generally dealt with through shades/blinds, which create even less daylight savings. The designs for many of these buildings had addressed the bulk of glare through shading and orientation, but in many of the spaces there were still small portions of the year when direct sunlight entered the space and caused glare. This situation is very difficult to avoid entirely, so in these cases blinds were used to mitigate those issues.

Often these temporary periods of glare are concentrated during certain times of the year, such as near the winter solstice when the sun is low in the sky. Occupants will often pull the blinds at these times and then leave them down permanently. In our observations, we found that in the 12 spaces that utilized manually adjustable blinds, occupants in only 4 of the 12 spaces made some significant adjustment to the blinds over the entire six months of our study. If an annual blinds ‘reset’ were included in standard maintenance procedure, many of these systems would be able to operate and save energy. Adjustment should occur at the end of significant glare seasons. On south-facing facades this would occur when the sun’s azimuth reached the cut-off angle of exterior shades/glazing setbacks. More simply, blinds reset should occur once the daylight stops penetrating deep into the space.

INCORRECT CONNECTION

Two of the controls we studied were simply connected to the wrong relay. With hundreds of relays per building this should perhaps not be surprising. However this issue could easily be caught during functional testing, as it results in a photosensor that has no ability to modulate the lights in its zone. In the two misconnected spaces that we studied, it is likely that functional testing never occurred.

SENSOR POSITION

One of the systems that we identified had a sensor placed too far from the perimeter to accurately reflect the bulk of the luminaires being controlled. Sensor position should be an integral part of the daylighting design, and included explicitly on lighting layout drawings. Many daylighting simulation tools even allow for a near-optimal sensor position and orientation to be ascertained. However, in several of the buildings we studied, the placement of the sensor was never considered by the designer, did not appear in any design documentation, and was left to the contractor. There may be some advantage in allowing a contractor or manufacturer to position the sensor after the space is built and fit-out, for example furniture location and geometry will have been finalized. But to the extent possible some amount of guidance should probably be provided by the designer.

Lessons Learned: Controls Startup Process

As the above issues illustrate, the installation and startup process is pivotal in determining the performance of daylighting control systems. At the very least, an individual should be assigned to complete basic commissioning steps (installation and calibration checks, and functional testing) for the lighting controls in a significant portion of the building. Most of the systems’ problems that we encountered could be solved during that process. As we’ve pointed out, this is being addressed to some extent in the 2012 IECC, which will require some level of functional testing of these controls. However, the specific steps in that process, and the level to which designers/contractors will actually go to that end,

remains to be seen. Our study did turn up a few helpful observations and lessons learned for those looking to implement such a process to improve their performance.

A large majority of building managers and contractors we spoke with were not able to assist with startup because the controls interfaces were too complex. The manufacturer was needed to assist at this stage. This suggests that either manufacturers need to include startup in the cost of the system or, more usefully, simplify the user interface so that building managers and contractors can do it for themselves. This would also improve continual maintenance (see the next section). Specifically, personnel on some of these building projects suggested that they are now used to the more graphical approaches that most HVAC interfaces utilize with zones shown on plan view, rather than the codification used by many lighting control interfaces.

We did notice that some of the more complex functions in the daylighting control systems, such as networking, zoning of luminaires, and auto-calibration, were designed to try to improve performance, which is a positive step. However, our data shows that the small improvements that result from these innovations are dwarfed by the penalty that can be caused when a system is not tuned properly because no one is quite confident or capable enough to do so.⁴⁵

Another problem caused by these systems being complex and interdisciplinary in nature, is lack of accountability. Hennepin County, which operates the libraries that we studied, encountered and overcome this problem after considerable effort. They found initially that the luminaire manufacturer, controls manufacturer, and contractor all were unwilling to take ownership of problems that arose after occupancy. After the County initially had trouble making progress, they brought all these parties into the same room, discussed the specific system layout and corresponding problems, and effective solutions were found relatively quickly. This lesson suggests that sophisticated lighting control systems may benefit from their own focused construction meeting, before installation is complete, to identify these issues, assign ownership, and make the system work.

The problems, observations, and potential solutions that this research yielded in the area of controls startup are being compiled into a brief fact sheet to attempt to educate others.

Lessons Learned: Controls Maintenance

In addition to the design and startup considerations we have discussed, ongoing operation and maintenance (O&M) of all lighting systems is generally needed. Our conversations with building managers and our interactions with them during recommissioning uncovered some additional lessons regarding O&M.

Training of building staff is possibly the primary consideration we encountered. Training can take many forms, but at a minimum the daylighting controls should be mentioned in the training, and O&M documents transferred to the owner. In several of the spaces we studied the building manager knew daylight control was supposed to be occurring, but no training had taken place and no documents

⁴⁵ Interestingly, one simplification manufacturers have made is to eliminate scales and units from system interfaces, such that the operator cannot actually see a scale for light sensitivity/gain, or fractional power or fractional light output. Since the rest of the system is not simple enough for a non-expert to use, the experts that do end up calibrating and operating the systems are left without information that would've been useful.

transferred. A few of the staff were not even aware that daylight was a part of the control systems. Other staffs were trained, but self-focused the training effort on scheduling, which is a higher priority for many building managers because it can lead to more calls from occupants. Perhaps the importance of the daylighting controls and their benefits should be highlighted in this training, as obvious as it may sound.

At both the WECC and CEE spaces, the systems were actually a simple, integrated-fixture control that could have been taught to both building managers and occupants who could have adjusted their own systems if interested. However our interviews uncovered that such information was either poorly conveyed or not conveyed at all. Even when training does occur and is seemingly thorough, we found that owners still simply did not know what questions to ask or what items were important for daylighting. Many of them have never used a daylighting control system before. The problems, observations, and potential solutions that this research yielded in the area of controls startup, including training, are being compiled into a brief fact sheet to improve these processes.

Again, controls interfaces that were too complex hampered maintenance efforts. One user reported that the complicated ballast address system required more time to complete simple things like replacing a ballast and connecting it to the proper controls. Another user reported disabling the controls in a couple of the spaces because, though trained, the basic steps in tuning the controls were too complex for him to fix minor issues causing occupant complaints. If a manufacturer's solution to this problem is to provide this maintenance as a service—direction some prefer—this cost needs to be factored into the cost/benefit package that they sell the owner at the outset.

One final note on maintenance of these systems. Since the location and design of intermediate controls equipment such as controllers, power packs, and even relay boxes, is often left up to the contractor, it is often not shown on the drawings. This presents a problem in both calibration and maintenance of the systems because staff rarely knows where to find them. Controllers and relay panels should be located in the electrical room, or within sight of the luminaire junction box if in the ceiling. Better yet, intermediate equipment, controllers primarily, need to be shown on drawings, or at least wiring diagrams, with rough location noted.

Between complexity and lack of training, O&M of these systems is an issue that should be addressed as part of the commissioning process so that operation is seamless in the handover to the owner. Of course, as staff at CEE, an organization that runs lighting efficiency programs, pointed out to us, even a very motivated owner just doesn't have time to make operating their daylighting system a priority. So though maintenance is important, the importance of calibrating and testing that system to operate well on day one is not diminished.

Use of Alternate Control Methods

Of the 43 spaces that we considered for inclusion in the study, lights in the vast majority of spaces were controlled by an indoor, ceiling mounted sensor, independent of the luminaire, viewing the workspace. This has emerged as a successful approach. However, there are potentially times when other approaches are warranted, and some owners and designers that we encountered have had success with three alternative methods in certain space types. Owners of large buildings could potentially benefit from more than one different approach in their building.

FIXTURE-INTEGRATED CONTROLS

A few of the spaces that we studied utilized controls integral to the luminaire (fixture) — the photosensor and controller was factory installed in the luminaires. There are several benefits to this approach: it saves considerable cost in equipment, controls, and installation, and it is fairly simple to calibrate, requiring the turning of one simple knob. There were also drawbacks to this approach. The first is that it limits flexibility. The control is in a fixed location and has a fixed control sequence including a fixed minimum gain. Also, the calibration cannot be completed without reaching the luminaire with a ladder. This blocks the sensor and makes calibration more tedious. We found this approach in the CEE spaces. In these spaces we were not able to adjust the gain as low as the design setpoint for the space, so we did not achieve optimal results. At WECC we had the same problem, but to a lesser degree. Here the controls were near optimal after calibration and as a result performed very well. In both cases, the ease of calibration was very helpful. This type of control would be a great fit for smaller daylighted areas where the greater effort of executing a separate daylighting control system is simply not worth it. This would also be a good solution for projects where the resources, in terms of budget or personnel, do not allow for a very complex system to be installed and operated effectively. This system is so straightforward that the occupants could even make their own adjustments, if given a ladder.

OPEN LOOP CONTROL

One owner we spoke with, but were not able to study in depth, had a multi-building campus. He had gravitated towards a significant usage of open-loop control. With plenty of square footage to light and control, he was able to have one central open loop sensor used for specific area types in all of his buildings, saving on installation and maintenance. This approach was applicable and effective for all spaces which were transient—such as lobbies, general gathering areas, corridors, and stairwells—or spaces that had so much light that any amount of daylight could result in the lights being off or near off—such as lobbies with curtainwall glazing. Of course in continually occupied spaces where work is being done like offices or classrooms this approach has proven quite problematic. This is because the open loop sensor doesn't take into account any of the specific needs in each of those spaces, such as changes in blinds, furnishings, or sun path. One large space that we studied that should have taken advantage of this approach was Central Library N A. The controls in this system performed beautifully, but with a north facing space, a full curtainwall, and transient occupancy, a simpler approach such as open loop would have had similar results. Such spaces should be controlled aggressively through simpler, less expensive methods such as open loop, on-off control, or even an astronomical timeclock.

OCCUPANCY SENSORS

The perimeter open office in the WECC building included occupancy sensors. The *daylight* controls at this space saved a considerable amount of energy, partially due to the high ceiling and low workstation wall heights. For the same reason, the *occupancy* sensors were not as effective. There was not a sensor for each workstation, so in order to ensure they did not turn lights off on occupants, they had to be placed and tuned to be sensitive to a level such that the lights were nearly constantly triggered on by someone in the general area. We were able to completely filter out their effect within our energy saving calculation as they did not tend to control the lights except very early and late in the day.

However, we did find a few spaces that should have used additional occupancy sensing, in some cases instead of daylight controls. Private offices are one obvious candidate, but we also found that certain

infrequently used portions of the libraries would have been a good occupancy control application. The Labs building, though open office, had a much lower occupancy rate than most due to staff conducting much of their work in an adjacent laboratory; as a result this space would have been a reasonable occupancy sensor application (perhaps along with the daylighting controls).

FULL-OFF CONTROL

Most automatic dimming control systems dim to some minimum light level and power. We found that in some more transient or well-lit spaces (libraries), and any space where occupants are actively interested in energy savings (CEE, WECC), additional energy could have been saved if some mechanism existed to switch lights fully off (not just dim to a minimum). Manual switches or an automatic sequence could both work.

In short, automatic closed-loop controls with full dimming may be the best approach for many applications, but they are certainly not the best approach for all applications.

Regarding Occupant Comfort

We surveyed building occupants to determine how they react to and interact with the daylighting control approach in their space. Because impacts on comfort are naturally more important to owners and occupants than energy savings, the recommendations made for energy savings must not compromise comfort. Our recommendations for these systems could potentially be impacted by occupant comments.

In general, glare and heat from direct sun were the most common comfort problems. These are not problems with automatic daylighting control per se, but are indirectly related in that architects may choose to add glazing to improve daylighting, and potentially increase glare and heat as a result. Glare and heat were problems seen more often in the larger population than in systems that saved larger amounts of energy, suggesting that if these problems can be controlled, a control system stands a better chance of performing effectively. Properly orienting and massing a space, and using external glare control, are effective methods of dealing with direct sun. It is best for designers to 1) limit the amount of glazing as suggested by Figure 25, and 2) to include interior glare control such as blinds. Note the previous discussion on blinds operation.

The second largest problem was not enough light in spaces. This concern was generally voiced by a small minority in the space. This is consistent with our finding that in reality, only one of 20 spaces did not have enough light delivered to the critical workplane. One potential solution for this minority of occupants is increased use of task lighting. Only about half of the occupants complaining about low light levels reported using task lights. More task light awareness is needed; a few occupants were not even aware of the task lighting, and one respondent reported the realization that they should use their task light more.

At both the WPPI and CEE spaces, we also found that computer monitor placement had a big impact on both the glare and low light concerns. These users generally looked most often at their monitor and the spaces directly adjacent, and either indirect glare or shadows caused problems in these areas. Facing monitors away from the daylight, and placing the monitor between the occupant and the daylight or perpendicular to it, should mitigate these problems to some extent. In any case, this is one more area

where it could be helpful to involve the interior designer in more holistic design decisions for daylit spaces.

CONCLUSIONS AND FUTURE WORK

We successfully met our objective of testing the actual energy performance of automatic daylighting controls and measuring the additional impact of commissioning those controls. We have found that these types of controls can be complex, with potential for significant operational issues. However we see opportunities for substantial energy savings from multiple angles.

OPPORTUNITY #1

First, when installed, commissioned, and operated to perform as designed, daylighting controls can be an economically attractive solution for some building owners and managers. The systems we monitored typically exhibited substantial energy savings: median values were 23% savings prior to commissioning and 63%, or 1,976 kWh per kW, after commissioning. With these levels of performance we estimated that owners break even at a cost of \$1,000-2,200 per kW of controlled lighting for these systems, which is in line with current control system costs.

This opportunity is most promising in new construction or major renovation where daylighting can be included as part of the design from the beginning. Especially with regards to the availability of daylight in the space; all but one of the spaces we studied (CEE A) were designed with daylighting in mind. But there are certainly retrofit opportunities as well, in existing buildings with adequate daylight that are undergoing lighting retrofit. The daylight availability needs to be studied carefully in these existing building cases, and then the luminaires being retrofitted should include dimming ballasts. Stepped daylighting approaches are potentially applicable to a wider range of buildings, including simple retrofit with existing light fixtures, but have drawbacks beyond what we have explored in this study.

Some utility programs, or CIPs, in Minnesota take advantage of this savings opportunity already, in prescriptive and comprehensive programs for new construction. Those that do not could acquire additional savings with this measure. With the potential for savings in retrofit scenarios as well, general lighting retrofit programs should also take note (see discussion of utility incentive programs below).

OPPORTUNITY #2

Secondly, we have identified a significant amount of savings being ‘left on the table’ in systems that are designed for substantial energy savings but fall considerably short of optimal performance. The median improvement in system savings with our commissioning effort was 88%, or 690 kWh per kW. The opportunity is in improving the execution of these systems during their initial installation. A clear solution to this problem is a more robust, formalized commissioning focus on daylighting control systems. The demonstrated savings indicates that there is value to be captured in the commissioning process for building projects. As a result, the real opportunity here comes from contractors, commissioning agents, and utility program implementers to demonstrate this value to building designers and owners and ensure that these steps are completed.

The pieces of this commissioning effort that we found lacking and in need of formalization include:

- Establishment of clear illuminance targets prior to design
- Review of design documents to ensure that location, connections, and sequences of controls are explicitly laid out, and zoning and sensor location are appropriate

- Performance testing of controls as installed to ensure proper operation, including tuning of all available control setpoints⁴⁶
- Verification that proper training has occurred, and the importance of the controls to system savings is relayed to the owner

As modern daylighting control systems are generally increasing in complexity, this importance is only growing. The interdisciplinary nature of the systems makes commissioning even more beneficial. Such a system is influenced by almost all personnel on the project, and these individuals need to be coordinated. In theory commissioning of daylighting should already occur on projects with third-party commissioning authorities, but several of the buildings we studied had such an arrangement, and not all had effectively commissioned controls. The daylighting controls should be formalized into the commissioning scope and specifications, and this should occur early in design. Even if a third-party commissioner is not involved, a more thorough commissioning line item could appear in the contractor's (or vendor's) scope to ensure that the work is completed. Finally, commissioning could be offered as an added service by the manufacturer. If that is the case, it would be beneficial for manufacturers to make their systems and interfaces simple enough that the contractors and managers can be aware that their systems are not working properly, and be able to adjust them later if needed. This need is being at least addressed in the 2012 IECC, which will require some level of functional testing of daylighting controls. However, the specific steps in that process, and the level to which designers/contractors will actually go to that end, remains to be seen.

For utility program managers, this opportunity does not represent potential for new savings. Rather, it represents a risk mitigation strategy for the existing savings stream in daylighting controls. To ensure that savings are fully realized, our results suggest that perhaps commissioning should be required, and adequately demonstrated—even the 2012 IECC cannot ensure that—if incentives are to be paid for daylighting controls.

OPPORTUNITY #3

Finally, there is a substantial number of daylighting control systems already implemented that have room for improvement due to incomplete execution. We have identified the inadequacies that we found in such systems (see *Operational Problems*), and have quantified the potential savings that exist as a result. Again, recommissioning saved an additional 690 kWh per kW of lighting energy in the median case, and up to 2,420 kWh per kW in the worst case. This potential exists as an opportunity for consultants and contractors to offer a service in recommissioning of daylighting systems. This may work best coupled with other similar processes to take advantage of economies of scale, as the time taken to understand the lighting control system is generally a significant fixed cost.

This also represents an opportunity for Minnesota utility programs as a new program component. The service should certainly be, and likely already is, included in retrocommissioning program offerings for buildings that happen to have daylighting controls. In addition though, it could become a targeted program component for lighting retrofit programs, and even be coupled with work done on the other pieces of the lighting control system. Daylighting controls alone offer a substantial savings for such a

⁴⁶ Formally, in systems commissioning the contractor would run the test and the commissioning agent would simply verify that the test has occurred. Here we combine those tasks; the testing simply must be done.

program element in large buildings with such controls. When coupled with recommissioning of occupancy sensors and lighting scheduling (which, anecdotally, also present savings opportunities) they could be a nice addition to lighting retrofit programs needing to find new opportunities to pursue.

APPLICATION DETAILS FOR MINNESOTA UTILITIES

The opportunities above all require attention from Minnesota's CIPs. Though we were only able to study twenty examples of daylighting controls in practice, results here are robust enough to use in program design and implementation.

Demonstrating the savings from full commissioning was our primary focus, and our experiment was designed to that end. Therefore, those results are likely the most representative of the actual population. Utility program staff can use the results for savings from full commissioning to more readily include this measure in retrocommissioning programs. More innovatively, these results could be used as a basis for a more explicit recommissioning component within lighting programs. A prescriptive offering for a simple recommissioning of such systems is even possible. In implementing this offering, the challenge would lie in verifying that the recommissioning tasks have taken place. This would need more consideration from program personnel. A similar measure to consider as a model might be boiler tune-ups. In this type of program, third-party professionals (sometimes pre-certified) are required to complete a set of tuning tasks; upon completion an incentive is paid to the owner. As daylighting recommissioning is not likely to be a large program, further piloting may not be necessary beyond the results of this study.

There is considerably less certainty in the absolute savings metric being representative of daylighting controls in new buildings, because each commercial building is so different. However, for buildings of the type we studied, such as office or public assembly with closed loop control and primarily continuous dimming, the savings per kW of installed lighting are representative enough to be a good check on the more common calculation methods and deemed savings being used (which rely on assumptions such as typical daylight hours and perfect operation). Assuming commissioning is required as part of the measure, the larger results found for the post-commissioning period could be used, leading to an increase in measure savings. These results would be just as valid for retrofit as they are for new construction. In both cases they would need additional documentation demonstrating the daylighting autonomy of the spaces controlled. In addition to using the absolute savings, it is also possible that the post-commissioning *controls effectiveness* (we recorded an average of 75% and median of 86%) could simply be used as a factor to derate simple savings based on 'perfect' controls. Again, this assumes commissioning is actually completed as part of the program requirement.

Finally, the amount of savings being missed in systems that are not properly executed and started up is not an opportunity, but an area for risk to be mitigated in programs. Program personnel could mitigate this risk by requiring that projects seeking incentives for daylighting controls undergo the minimum commissioning steps discussed above. This requirement should be added in some capacity to new construction programs immediately, whether a third party is required or the contractor or designer simply completes documentation verifying that they have completed the tasks.

These opportunities apply to all utilities in Minnesota, as the only prerequisite is a commercial building, or potential commercial building for new construction, with adequate windows for daylight. The

technology has economies of scale like other sophisticated energy technologies. There is significant fixed cost in initial control installation and commissioning and as a result tends to be more cost-effective in large buildings. Therefore, there are likely to be territories in the state with a relatively minimal number of larger commercial buildings where these opportunities may not warrant a full program. These areas would be in contrast to the Minneapolis-St. Paul metropolitan area, where there are thousands of such buildings in place and under construction that have potential for the technology.

FURTHER WORK

There is certainly room to continue study of automatic daylighting control performance. We recognized a few specific issues during the course of our study.

A few of the owners mentioned that ballast failure was significantly higher among their dimming ballasts. A couple of these owners reported that failure was mitigated to some extent by more thoroughly ‘burning in’ the ballasts, which means running them at 100% power for the first several days of their lifetime (this is recommended by many manufacturers). We did not study the benefit of this specifically, and more importantly were not able to incorporate variance in ballast failure into our economics. It was not even clear from talking to owners that there was any well-established ballast burn-in process being followed, and certainly not whether the burn-in was mitigating the failures to the level of non-dimming systems.

It would also be beneficial to measure a broader data set of system performances. If metrics like controls effectiveness can be set aside, this type of study can be replicated on a wider scale using just simple electrical current measurement. Other space types such as schools, private office, and possibly religious worship, could be studied. Performance of newer daylighting control products could also be studied, as the changes in these products from year to year are substantial.

More information is also needed on implementation rates of this technology. Not only is the data in CBECS more than nine-years old, it is also not entirely clear. Are owners more willing to pay the cost of sophisticated, complex full building control systems? Are full dimming systems receiving the large majority of market share as our sample showed? Is penetration into the new construction market still increasing, and is there any substantial penetration into the basic retrofit (not major-renovation) market?

A final area for future study also came from discussions with owners and contractors, and that was the issue of controls complexity. While it was clear that certain things made controls manipulation easier, such as graphic interfaces, minimal control setpoints, simplified zoning and ballast assignments, there is definitely the need to investigate what controls solutions might be more readily operable by typical owners, operators, and contractors. It seems that this problem needs to be solved before these systems can become the control strategy of choice in the mass market, and perform robustly across the market. At the same time, if systems can be made less complex, the commissioning steps that we have outlined will become much easier for owners to incorporate and full savings will become much easier to realize.

GLOSSARY

Automatic Daylighting Control: see Daylighting Control; any daylighting control that is accomplished automatically without occupant input.

Building Automation System: a computerized network of electronic devices designed to monitor mechanical, electronic, and lighting in a building.

Closed Loop: a daylight control system in which the photosensor views the interior illuminance levels.

Coefficient of Performance: the efficiency of a piece of equipment expressed as the ratio of the useful energy provided to the amount of energy consumed.

Commissioning: as it pertains to lighting controls, this is a plan and process enacted to ensure that lighting control systems perform interactively according to the intent of the lighting design and control sequences.

Conservation Improvement Program: a category of energy efficiency programs in Minnesota, generally operated by utility companies, which provide incentives for improvements in energy usage.

Controls Effectiveness: the performance of a daylight control system expressed as the ratio of actual lighting energy savings to the energy savings achievable with perfectly operating controls.

Critical Workplane: the working surface within a daylight control system that is most likely to receive the least amount of light.

Curtainwall: a nonstructural outer covering, often transparent, of a building.

Daylighting Control: the practice of utilizing photosensors to reduce the electric light in a space when sufficient daylight is present.

Deadband: the area of a signal range where no action occurs.

DOE-2: a building energy analysis program capable of predicting a building's energy use and cost.

Dimming Ballast: a device that provides the proper operating electrical conditions to power lamps, allowing their lighting output to be lowered.

Extraterrestrial Radiation: the intensity of solar energy incident on a surface immediately outside the earth's atmosphere.

Functional Testing: a quality assurance process designed to verify a system's operation against design documents and specifications.

Glare: visual discomfort due to bright light or high contrast in light levels.

Glazing: the part of a building's envelope made of glass.

Global Horizontal Radiation: the intensity of solar energy incident on a surface after the light passes through the earth's atmosphere.

Illuminance: a measure of the amount of incident light on a surface per unit area.

Life Cycle Cost Analysis: a technique for determining the total cost of owning and operating a building over a specific time interval.

Luminaire: a device used to create artificial light from electricity (often called a light fixture).

Obstruction Factor: the fraction of light that reaches the workplane out of the total daylight available from building fenestration.

Open Loop: a daylight control system in which the photosensor views the exterior illuminance levels.

Photocontrol: the use of a photosensor to detect and adjust the amount of electric light provided to a space.

Photosensor: a device used for detecting the amount of light in a space.

Power Factor: the ratio of the real power flow to an electrical load to the apparent power in the electrical circuit.

Recommissioning: performing commissioning on a system that was previously commissioned but has undergone some modification(s); generally assumes a complementary process acting to improve upon any deficiencies found.

Reflectance: a surface property that expresses the fraction of incident light that the given surface bounces back into the space.

Startup: as it pertains to lighting controls, this is the phase of construction when the control settings are input, the lights powered for the first time, and any initial operating requirements of the manufacturer are completed.

Target Illuminance: the amount of incident light on a surface per unit area specified as necessary for performing a given task on that surface.

Typical Meteorological Year: a collection of weather data for a given location that reflects the location's annual averages while maintaining hourly variability within the location's expected ranges.

Visible Transmittance: a property of glazing that expresses the percentage of visible light that passes through it.

Workplane Illuminance: the amount of incident light per unit area on a working surface.

Zone: as it pertains to lighting controls, a zone encompasses the floor area lit by all the luminaires on a common controller.

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APPENDICES

A. SURVEY INSTRUMENTS

B. SITE INFORMATION COLLECTION CHECKLIST

APPENDIX A.

SURVEY INSTRUMENTS

Building Operator Interview Questions

What year was the daylighting system first operational?

On a scale of 1-5, how effective is the daylighting control system at saving energy? And how long has it been in this condition? (5 being fully effective)

On a scale of 1-5, what level of commissioning did the control system undergo? (1 being no Cx, 5 being full Cx)

Who is responsible for the energy management of the lighting? (could be a contractor)

Did that person receive any training for this lighting system?

How much have the staff adjusted the controls since the building was handed over?

On a scale of 1-5, how much maintenance does the system require? (3 being typical for a lighting, 5 being the most possible)

Do the lamps/ballasts need to be changed out more often than typical systems?

On a scale of 1-5, how satisfied are you and the occupants with the system operation? (5 being very satisfied)

If anything is unsatisfactory, please describe:

Describe the HVAC system for the building:

- System:
- Cooling plant / efficiency:
- Heating plant / efficiency:

Have you learned any other lessons about operating a daylighting system successfully?

Occupant Questionnaire

Building / company name:

Room number / floor number / location: _____

Is your workspace immediately adjacent to a window?: _____

1. Were you aware that the lights in your work area are controlled based on sunlight levels? If so, do you think that this system is effectively saving energy in the building?

2. On a scale of 1-5, how satisfied are you with the lighting in your area, and its control? (5 being very satisfied)

3. If there is anything unsatisfactory about the lighting and its control, please describe.
Responses could include: too much light, too little light, glare from sun, computer monitor visibility, heat from sun, or frequency of lights shutting on/off.

4. How often do you use a task light?

- never
- a small amount in the winter months
- a few hours a week most of the year
- most of the time all year

5. How often do you or someone else adjust the blinds / shades on the windows nearest to your work space?

- daily
- every few days
- every few weeks
- every few months
- practically never
- don't know

APPENDIX B.

SITE INFORMATION COLLECTION CHECKLIST

Site Name: _____

Date: _____

Address: _____

Site contact: _____

Contact Phone #: _____

Equipment Checklist

- | | |
|--|---|
| <input type="checkbox"/> Ladder | <input type="checkbox"/> Letter of Introduction |
| <input type="checkbox"/> Illuminance Meter | <input type="checkbox"/> Tape measure |
| <input type="checkbox"/> Phone with compass, watch | <input type="checkbox"/> Digital Camera |
| <input type="checkbox"/> Pens, Pencils | <input type="checkbox"/> Flashlight |
| <input type="checkbox"/> Writing Pads | <input type="checkbox"/> Laptop |
| <input type="checkbox"/> Graph Paper | <input type="checkbox"/> Screwdriver set |
| <input type="checkbox"/> Reflectometer | |

Questions for contact

- Ask for building plans
- Ask the first three questions on the interview questionnaire
 - What year was the daylighting system first operational? _____
 - On a scale of 1-5, how effective is the daylighting control system at saving energy? (5 being fully effective)
 - What level of commissioning did the control system undergo? (1 being no Cx)

Space Information

Candidate Space Name: _____

Space Type, Location	
Perceived Photocontrol Performance (1-5)*	
Total Area (ft²)	
Control Zone Depth (ft)	
Photocontrolled Area (ft²)	
Ceiling Height (ft)	
Window Head Height (ft), WWR	
Window T_{vis} (%)	
Description of Blinds	T _{vis} :
Fixture/Ballast/Lamp Info	
Auto. Control Description	<i>Stepped / Dimmed / Multi-step</i>
Auto. Control Location	<i>BAS / Ceiling / Fixture / Window / _____</i>
Location / access. elec. panel	
Man. Control Description	
Occupancy Schedule	
Reflectances	Floor: Walls: Ceiling: Partitions:

* 1 = no functionality, 5 = perfect functionality

Photograph

- Entire Room
- Window details
- Blinds
- Light switches
- Overhangs, light shelves, clerestories
- Partitions
- Light fixtures
- Photosensor (model number)
- Workplane

Light sensor mounting: _____

Sketch space: area, general fixture layout, general furniture layout, control zone depth; include:

- Light fixtures and circuits, with sensor placement and orientation
- Furniture and logger location
- Shading devices (incl. blinds and ext. devices)
- Wall and glazing

Other Modeling inputs

- Approx. window u-value _____
- Wall construction:
- List exterior surfaces:
- Number of occupants _____
- Number of computers _____
- Other equipment: