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Lighting Controls in Commercial Buildings

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Abstract—Researchers have been quantifying energy savings from lighting controls in commercial buildings for more than 30 years. This study provides a meta-analysis of lighting energy savings identified in the literature—240 savings estimates from 88 papers and case studies, categorized into daylighting strategies, occupancy strategies, personal tuning, and institutional tuning. Beginning with an overall average of savings estimates by control strategy, successive analytical filters are added to identify potential biases introduced to the estimates by different analytical approaches. Based on this meta-analysis, the best estimates of average lighting energy savings potential are 24 percent for occupancy, 28 percent for daylighting, 31 percent for personal tuning, 36 percent for institutional tuning, and 38 percent for multiple approaches. The results also suggest that simulations significantly overestimate (by at least 10 percent) the average savings obtainable from daylighting in actual buildings.

Keywords—Energy, daylighting, occupancy sensors, controls, tuning.

1 INTRODUCTION

Lighting systems have the largest potential of any known appliance to reduce United States energy use [Desroches and Garbesi 2011]. Lighting represents approximately one-third of electricity use in commercial buildings and more than one-half in lodging and retail [DOE 2003]. As a result, there is significant interest in reducing lighting energy use through more efficient lighting systems, including controls. The National Electrical Manufacturers Association (NEMA) has argued that controls have greater potential for energy savings in major applications than do increases in source efficacies [DOE 2011b]. However, lighting controls are not incorporated in federal energy conservation standards and are only partially incorporated through state and local building codes.[†] While energy savings from some system components, such as replacing T12s with T8s, can be fairly easily quantified and guaranteed, savings from controls that turn lights off or down when not needed depend on numerous factors

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including application, site orientation and occupation, building design,interior reflectances, occupant behavior, and tuning and configuration during installation and commissioning, making savings less easy to predict. With current estimates of the installed capacity of lighting controls systems very low—only 2 percent of lit commercial buildings in the United States have daylighting sensors and only 1 percent have energy management and control systems for lighting [DOE 2003]—the technical potential for energy savings appears large.

Researchers have been quantifying energy savings from lighting controls in commercial buildings for more than 30 years, but no comprehensive research review of controls studies has been done previously. This makes it difficult to understand the big picture of the opportunities of controls because the individual studies have had different goals, methods, coverage, and results. Some studies, such as those regarding U.S. Environmental Protection Agency programs, present data from monitoring of actual installations in numerous buildings all in one paper [for example, VonNeida and others 2000]. Other studies, such as those by the National Research Council Canada and Florida Solar Energy Center, present results from lab tests or experiments with just one or two control and test spaces [for example, Parker and others 1996]. Some studies separate the effects of controls from the effects of other lighting efficiency measures [for example, Birt and Newsham 2009; Jennings and others 2000], while others do not [for example, Deru and others 2006; The WattStopper, Inc. (date unknown)]. Some studies are designed to identify the influence of factors such as window glazing, blinds, or orientation on energy savings obtained from controls [for example, Galasiu and others 2004]. Some studies focus on specific space types [for example, Granderson and others 2010; Li and others 2009], while others report savings by buildings or across buildings without noting the building type or the space types within the buildings [for example, The WattStopper, Inc. 2007].

A few papers have provided limited overviews of lighting controls studies. Three of these reviews focused solely on occupancy sensors; the number of reports or individual energy savings estimates referenced by these papers range from seven to 35. VonNeida and others [2000] presented industry estimates of lighting energy savings for occupancy sensors by building space type, which ranged from five to 90 percent. The authors then presented results from their own study on 60 buildings with lighting savings ranging from 17 to 60 percent. The Lighting Research Center [2003] compiled 26 case studies and claims by manufacturers to recommend energy saving estimates for occupancy sensors for the U.S. Department of Energy. The recommendations based on the data were 25 to 40 percent depending on the use of space. Guo and others [2010] reviewed the performance of occupancy-based control systems from seven previous studies, with energy savings ranging from three to 86 percent.

The two reviews of savings from systems other than occupancy sensors provide only one to six savings estimates per control type. Southern California Edison [2008] produced a report on the “Office of the Future,” which referenced studies that provided energy savings for daylighting, occupancy sensors, and personal controls in open offices; vacancy sensors in private offices; and occupancy sensors in corridors. The overall range of savings was six to 80 percent. The Advanced Lighting Guidelines On-Line Edition [New Buildings Institute 2011] presents a table of lighting energy savings by space type (private office, open office, and classroom) and controls type (multilevel switching, manual dimming, daylight harvesting, and occupancy sensors); the range of lighting energy savings is 6 to 70 percent across 11 categories of space types and controls types.

These previous studies reported a very broad range of results for particular contexts using a subset of data existing in the literature. In contrast, this paper describes a comprehensive literature review and analysis of energy savings from all types of lighting controls studied in commercial buildings. The purpose of this meta-analysis is to derive average lighting energy savings per control type based to the extent possible on all available data. Because these studies have not generally used common parameters, we utilize a range of analytical filters to isolate the effect of controls from those of other lighting system modifications and to estimate the savings by control type and building type.

While we note that the applicability of controls strategies is nonuniform throughout a building, we do not address that issue in this paper. For example, occupancy controls have the greatest potential in spaces where occupancy varies throughout the day, and daylighting controls should only be applied in portions of the floor area where sufficient daylight exists. Similarly, personal tuning is primarily amenable to private offices or task lit areas used by single individuals at a time. Because the purpose of this study is to draw broad conclusions using as much data as possible, and because many factors significantly affect the energy saving potentials of the different controls strategies, we make no attempt here to analyze the relative potentials of the different controls technologies under different use scenarios within commercial buildings.

2 METHODOLOGY

2.1 LITERATURE SEARCH

Our investigation of lighting controls savings potential began with a literature search of consultant reports, research papers, professional organization publications, industry literature, conference proceedings, and report databases. The team also consulted with California utilities, lighting manufacturers, controls manufacturers, the California Energy Commission, and the lighting controls division of NEMA. We used the reference lists in the reports identified in this phase to find additional sources. If a paper presented only secondary data on energy savings from controls, as with some of the work cited in the introduction, we did not include it in our analysis. Instead, we expanded our search to identify the primary data sources and included them where available and appropriate.

To be included in the analysis, a paper needed to provide energy savings in percentage terms from studies of lighting controls in interior commercial building applications or present baseline and test case energy use from which we could calculate percentage savings. In total, we identified 88 papers that met these criteria. Of these, 40 were research papers published in a peer-reviewed journal or presented at a conference in which papers were reviewed, and 48 were self-published reports or case studies or presented at conferences without a review process. While not all of those papers classified as reviewed were technically peer-reviewed, we refer to them as such throughout this paper for simplicity.

The 88 papers were published in conference proceedings and journal articles of the Illuminating Engineering Society of North America (IESNA; including Leukos), conference proceedings of the American Council for an Energy-Efficient Economy (ACEEE), and journal articles from Energy and Buildings, Lighting

TABLE 1.
Studies Included in Meta-Analysis

Publication Venue	Number of Papers	References
IESNA	9	Granderson et al., 2010; Rubinstein and Enscoe, 2010; Galasiu et al., 2007; Jennings et al., 2001; Boyce et al., 2000; Jennings et al., 2000; VonNeida et al., 2000; Maniccia et al., 1999; Rubinstein et al., 1998
ACEEE	8	Koyle and Papamichael, 2010; Mukherjee et al., 2010; Page and Siminovitch, 2004; Figuerio et al., 2002; Reinhart, 2002; Floyd et al., 1996; Pigg et al., 1996; Schrum et al., 1996
Energy and Buildings	5	Roisin et al., 2008; Bourgeois et al., 2006; Lee and Selkowitz, 2005; Atif and Galasiu, 2003; Bodart and De Herde, 2002
Lighting Research and Technology	4	Newsham et al., 2008; Leslie et al., 2005; Moore et al., 2003; Moore et al., 2002
Solar Energy	3	Kapsis et al., 2010; Yang and Nam, 2010; Galasiu et al., 2004
Other journals	5	Li et al., 2010; Li et al., 2006; Chung and Burnett, 2001; Nilsson and Aronsson, 1993; Carriere and Rea, 1984
Other conference proceedings	8	Birt and Newsham, 2009; Galasiu and Newsham, 2009; Doulos et al., 2007; Deru et al., 2006; Floyd and Parker, 2005; Rubinstein et al., 2003; Parker et al., 1996; Rubinstein and Karayel, 1982
Consultant and government reports	30	LRC (2008, 2004a, 2004b, 2004c, 2003a, 1997a, 1997b, 1995); Herschong Mahone Group (2005, 2003a, 2003b); CLTC (date unknown; CLTC et al., 2010); California Utilities Statewide Codes and Standards Team (2011a, 2011b); Pacific Northwest National Laboratory (Jones and Richman, 2005; Richman et al., 1994); PIER (2008a, 2008b); ADM Associates Inc. (2002); Clanton & Associates (date unknown); Emerging Technology Associates Inc. (2010); Energy Solutions (2009); Energy Studies in Buildings Laboratory—University of Oregon (2006); Florida Solar Energy Center (Floyd et al., 1995); International Facility Management Association and Lawrence Berkeley National Laboratory (2005); Lawrence Berkeley National Laboratory (Rubinstein and Verderber, 1990); Sacramento Municipal Utility District (Bisbee, 2010); Southern California Edison (2009); Washington State University Extension Energy Program (2011)
Industry case studies	16	WattStopper (2010, 2008, 2007, date unknown a–h); Sensor Switch (date unknown a and b); Lutron (date unknown a and b); Encelium (date unknown)

Research and Technology, and Solar Energy, as well as other journals and various conference proceedings. We also included several consultant and government reports and case studies not published in journals or at conferences as well as industry case studies. Citations are provided in Table 1.

2.2 DATA ORGANIZATION

We compiled data from the 88 papers into a searchable database in an Excel spreadsheet format. Each row of the spreadsheet represented a unique estimation of energy savings from controls. Every paper was represented by at least one row, but multiple rows were used if the paper presented energy savings for more than one control configuration or space type. A single row often combined multiple data points from the source study to yield a representative average savings. For example, in some cases we entered a minimum and maximum savings from the source and calculated the average savings. In other cases, we

TABLE 2.
Major Lighting Controls Strategies

Strategy	Definition	Relevant Technologies
Occupancy	Adjustment of light levels according to the presence of occupants	Occupancy sensors, time clocks, energy management system
Daylighting	Adjustment of light levels automatically in response to the presence of natural light	Photosensors, time clocks*
Personal tuning	Adjustment of individual light levels by occupants according to their personal preferences; applies, for example, to private offices, workstation-specific lighting in open-plan offices, and classrooms	Dimmers, wireless on-off switches, bi-level switches, computer-based controls, pre-set scene selection
Institutional tuning	(1) Adjustment of light levels through commissioning and technology to meet location-specific needs or building policies; or (2) provision of switches or controls for areas or groups of occupants; examples of the former include high-end trim dimming (also known as ballast tuning or reduction of ballast factor), task tuning, and lumen maintenance	Dimmable ballasts, on-off or dimmer switches for non-personal lighting

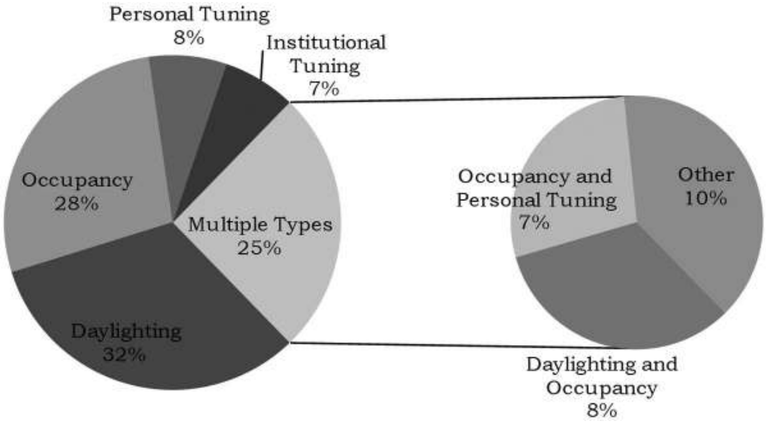
*Time clocks are often used for daylighting control in exterior applications, and while in theory they could be used in interior spaces, they rarely are. None of the 88 studies reviewed included interior time clocks for daylighting control.

averaged savings other variables such as window orientation, blind use, glazing, or time delay of occupancy sensors. A single control configuration might comprise multiple rows if the paper included savings based on significantly different baselines (for example, lights full on all day vs. occupancy profile). However if a paper presented two different savings numbers, one for core hours and one for 24 hours, we retained only the core hour value in order to avoid double counting savings from essentially the same scenario, while retaining arguably the most useful savings number. Ultimately this process yielded 240 rows of unique controls-related energy savings estimates from the 88 papers and a database that includes more than 40 independent columns. We based the primary data organization on the four major controls strategies defined in Table 2.

If a study tested multiple control strategies in combination, where possible, we presented data for each individual control strategy on separate rows. Depending on the study, this data might represent a fraction of the total savings, with all savings strategies totaling to the savings from the combination actually installed, or might represent the savings there would have been if the strategy had been implemented alone. We did not attempt to standardize this data. Some papers did not provide this level of data, so savings are presented for control strategies in combination on a single row. For a few studies that reported savings for controls both independently and in combination, we included the combination data on its own row in addition to the separate rows for each individual strategy. As we never calculate savings across control strategies, this does not result in double counting.

We included multiple additional fields to characterize the details of the control strategies. The most important fields include whether the control system used a clock or a sensor; whether the control was dimming, on-off, or both; and whether the control was automatic or manual. Any variation on these control strategies was determined to be a different control configuration and its results were presented on a different row. We also included a field for time delay for off

Fig. 1.
Data by control type ($n = 240$).



response; some studies varied this, and results are averaged from the minimum and maximum time delay tested and presented in a single row.

We also tracked building type, space type, and luminaire and lamp technology. As previously mentioned, we had savings fields available for minimum and maximum as well as average. We also recorded the energy savings determination method for both the baseline and the test case—monitoring, calculation, simulation, and so on—as well as a text description with more details. We also included a detailed description of the baseline.

We recorded additional details regarding the savings, including whether they were for lighting controls only (as opposed to including savings from luminaire or lamp retrofits), whether the savings were only of lighting energy use or total building energy use, and whether the savings were given in energy or another unit deemed equivalent to energy (such as power for a test case in which hours of use did not change). We also noted whether the data were from an actual installation (lab or field) or were estimated from a simulation or calculation.

For all studies we made our best effort to fill in all applicable variables. All reported variables were entered, and we made educated guesses based on other provided information for some variables not explicitly shown in a study. If we did not have enough information to determine a variable for a study with good confidence, we left that field blank. These database fields enabled us to identify unique control strategies and filter the data for desired characteristics.

2.3 COVERAGE

While we attempted to identify studies representing all available control types, the majority of the literature provided savings for daylighting and occupancy strategies. Figure 1 shows the percentages of the 240 rows of data that each control type represents. The smaller pie shows the most common groups of multiple strategies.

To obtain as complete sectoral coverage as possible, we made specific attempts to find studies in under-represented building types. Table 3 shows the coverage by building type with the building types ordered by their percentage of commercial lighting energy use, according to the 2003 CBECS [US DOE 2003]. Most of the studies cover office and education building types; we do have some coverage in most categories with a high percentage of lighting use. For some studies, the building type was difficult to classify based on the information provided, so we made our best guess. Some of the missing coverage is expected; for example,

TABLE 3.
Coverage by Building Type: Number of Rows for Each Control Type (Alone or in Combination). (Percent Commercial Lighting Energy Use from DOE, 2003)

Building Type (Reported by Itself or in Combination with Other Building Types)	Percent Commercial Lighting Energy Usage (DOE, 2003)	Occupancy	Daylighting	Personal Tuning	Institutional Tuning
Office	25%	76	70	18	31
Warehouse	12%	10	4	1	-
Lodging	11%	7	-	-	-
Education	10%	22	33	13	-
Retail (other than mall)	10%	2	4	2	3
Healthcare inpatient	7%	2	2	1	1
Service	6%	-	-	-	-
Food service	4%	-	-	-	-
Food sales	4%	-	-	-	-
Public assembly	2%	2	1	-	-
Healthcare outpatient	2%	5	-	-	-
Public order and safety	2%	-	-	-	-
Religious	1%	-	-	-	-
Other	5%	8	3	-	-

occupancy is generally the only control strategy used in the lodging sector. While data are missing for five of the 14 building types, these constitute less than 20 percent of total lighting energy use in the commercial sector. On the other hand, a significant number of data points are available for the top four categories, which together constitute an estimated 58 percent of commercial building energy use.

2.4 DATA ANALYSIS OVERVIEW

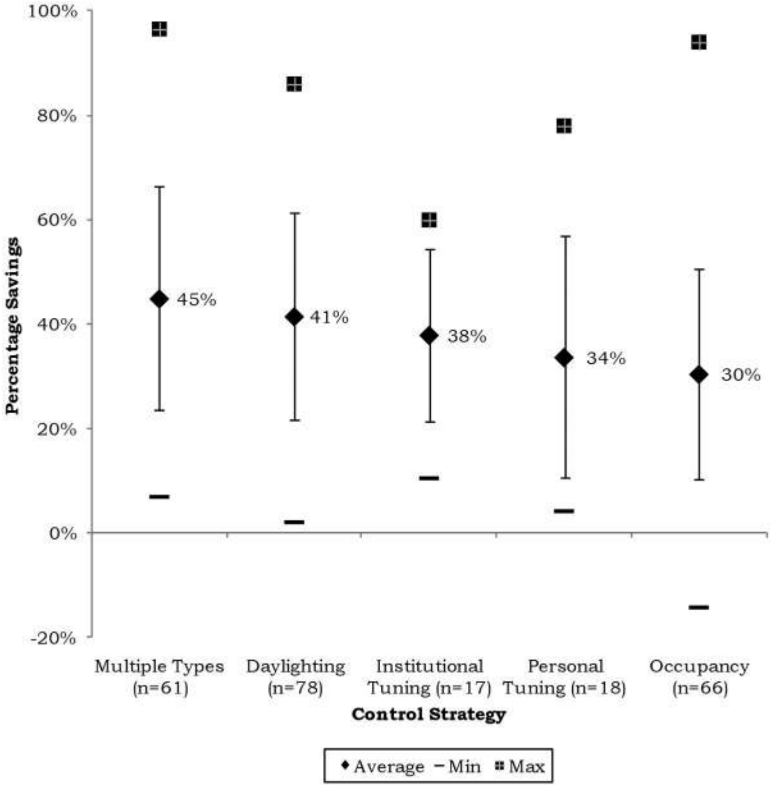
As a starting point, we calculated overall average energy savings by control type for all studies in the spreadsheet, irrespective of exactly what the savings represented. As mentioned previously, each row in our spreadsheet included an average savings either directly from the paper, calculated from a minimum and maximum provided in the paper, or calculated based on a range of other variables reported on, such as window orientation and occupancy sensor delay time. As such, we calculated the overall average savings for the meta-analysis as a simple average of the average savings in each row.

We then applied a series of progressive filters to the data, each building on the former, in order to screen out data points with significantly different characteristics. For the first filter, we screened out savings data that included not only savings from controls but also from lamp or luminaire retrofits. This filter left us with data points that represented savings from lighting controls only.

For the next filter, we examined what the savings represented, as we wanted to include studies that represented lighting energy savings only. We excluded data points that represented savings as a fraction of total building energy or included heating, ventilation, and air conditioning (HVAC) savings. We also excluded data points that represented a noncomparable savings type, such as wasted light hours and energy costs. In some cases we determined that the presented units were equivalent to energy; for example if occupancy sensors saved X percent of lighting hours and there was no apparent change in power, the savings were considered equivalent to energy savings.

Finally, we examined the remaining studies for significant differences between savings from actual installations and from simulations. We filtered out any

Fig. 2.
Average savings (%) by control type – unfiltered; error bar shown represents one standard deviation.



savings points that were not from actual installations—either lab or field. This last filter had the effect of removing outliers and likely provides more realistic savings. We also compared savings from each of the progressive scenarios—lighting controls only, lighting energy savings only, and actual installations only.

3 ANALYTICAL FILTERS AND RESULTS

3.1 OVERALL

As mentioned previously, we began by calculating an unfiltered, unadjusted average savings by control type for all data in our matrix. Figure 2 shows the average savings by control strategy as well as the standard deviation and minimum and maximum values. For individual control types, average savings range from 30 percent for occupancy to 41 percent for daylighting. Note that the institutional and personal tuning sample sizes are small. Throughout this paper, the savings figures for each filter will be shown with the control strategies in the same order to demonstrate changes between filters, while an overall comparison will be shown at the end of the paper.

The savings shown in Fig. 2 represent a wide range and include cases where the savings are negative. Throughout this analysis, we checked for outliers in the dataset in an effort to identify data that would not represent realistic potential energy savings and to narrow the range as appropriate. In the overall data, there appear to be outliers on the low end. However, these are generally from actual installations, and, in the negative case, occupants had previously been diligent about turning off lights but no longer did so after installation of controls. We

TABLE 4.
Average Savings for Each Control Type by Building Type

Building Type	Occupancy	Daylighting	Personal Tuning	Institutional Tuning	Multiple Types
Office	23% (n = 32)	38% (n = 42)	38% (n = 15)	38% (n = 15)	43% (n = 42)
Warehouse	35% (n = 6)	28% (n = 1)	-	-	63% (n = 3)
Lodging	48% (n = 7)	-	-	-	-
Education	31% (n = 9)	49% (n = 29)	6% (n = 2)	-	46% (n = 11)
Retail (other than mall)	5% (n = 1)	29% (n = 3)	-	60% (n = 1)	69% (n = 1)
Healthcare inpatient	-	-	-	-	55% (n = 2)
Public assembly	36% (n = 2)	36% (n = 1)	-	-	-
Healthcare outpatient	23% (n = 1)				
Other	7% (n = 1)	18% (n = 1)	-	-	-

believe this provides a legitimate potential result that may occur with occupancy sensor installation. Some other low savings numbers occur from strategies implemented in combination with other strategies, so that the savings attributed to any one strategy may be smaller than they would be if implemented alone. In addition, some low savings may result from less than ideal installations, such as daylighting in areas with little practical daylight illumination. However, we believe that many of the numbers on the high end are actually outliers, and we review the maximum savings after each filter to identify whether outliers have been removed. Note that we relied on the filtering process to remove outliers rather than removing any arbitrarily.

We also present savings by building type, as shown in Table 4. Because some studies provided data for multiple building types that we were unable to disaggregate, Table 4 only averages savings from building types reported alone. Therefore, this table is not comprehensive of all data in the study. Note that sample sizes are only robust for some control strategies within office and education.

We checked for differences in savings between peer-reviewed and nonpeer-reviewed papers to identify any possible quality issues in nonpeer-reviewed papers. Table 5 shows the results of the analysis. We did not find any significant differences between these categories. However, many of the sample sizes are low. Nevertheless, we do not believe sufficient evidence exists to filter on this variable, choosing instead to rely on other filters for our analyses.

3.2 SAVINGS FOR LIGHTING CONTROLS ONLY

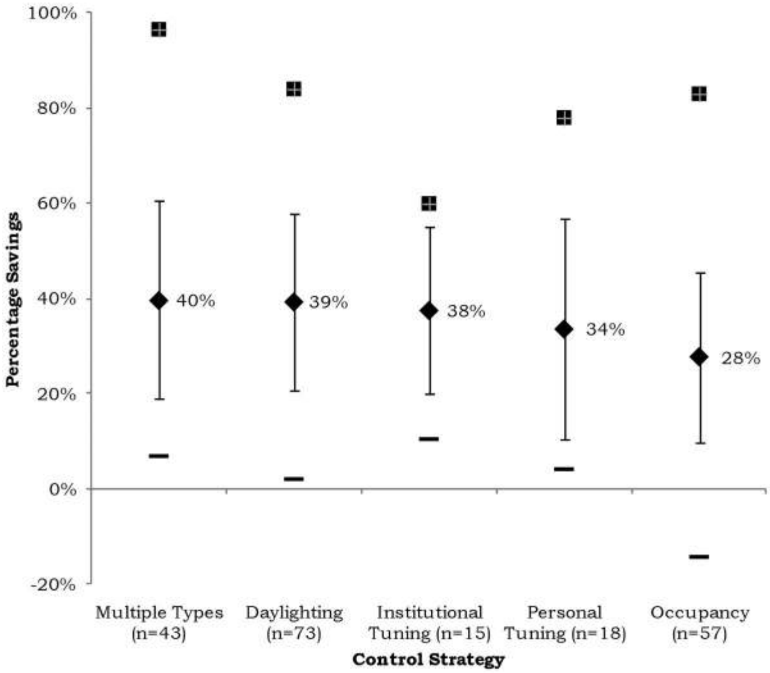
Many of the studies reported data for comprehensive lighting retrofits that included both lighting controls and lamp or luminaire replacements (or delamping, the removal of lamps from luminaires that remain in place). In many cases, the studies did not disaggregate the energy savings attributable to the controls.

TABLE 5.
Average Savings by Control Type for Peer-reviewed and Nonpeer-reviewed Papers

Control Type	Peer-Reviewed	Not Peer-Reviewed	Two-tailed *p* Value*
Occupancy	28% (n=31)	33% (n= 35)	0.3101
Daylighting	43% (n=63)	35% (n= 15)	0.1636
Personal tuning	36% (n=13)	27% (n= 5)	0.4727
Institutional tuning	43% (n=11)	28% (n=6%)	0.1407
Multiple types	50% (n=28)	41% (n= 33)	0.1006

*Values <0.05 would be considered statistically significant at 95%.

Fig. 3.
Energy savings for lighting controls only – first filter; symbols as shown in Fig. 2.



Because we wanted to focus on the savings potential that lighting controls provide, we filtered out all studies that did not disaggregate lighting controls savings from overall savings including other types of lighting retrofits. This filter retained 86 percent of all rows: 91 percent of peer-reviewed rows and 78 percent of nonpeer-reviewed rows. Figure 3 shows the average savings following this first filter. Savings for individual control types range from 28 percent for occupancy to 39 percent for daylighting, representing a very small correction. Note that this filter does not remove many of the high outliers.

3.3 SAVINGS FOR LIGHTING ENERGY ONLY

We next looked at what the savings numbers represented, attempting to identify all savings reported as lighting energy savings or as something equivalent. We originally believed that this would eliminate many data points, as only 150 of the original 240 records reported savings explicitly as lighting energy. Many studies used other descriptors such as lighting hours, power, or energy per area. However, we reviewed the reports to determine whether these data were equivalent to energy. For example, average power can be equivalent to energy if hours of use do not change. In the end, we determined that most studies reported in units equivalent to energy. Therefore with this filter, we removed only nine rows, including savings as a percentage of wasted light hours, energy costs, total building energy, or energy per workstation.

Note that within energy savings, savings may still represent different things (for example, annual vs. daily, weekday core hours only vs. 24/7, baseline of lights full on vs. occupancy profile). However, we did not attempt to filter or standardize further on this variable. Many of the papers did not provide clear information on all details, and many different hour ranges were used for core hours. In addition, in some building types, evaluating savings from core hours may account for nearly all the savings, while, in other building types, savings

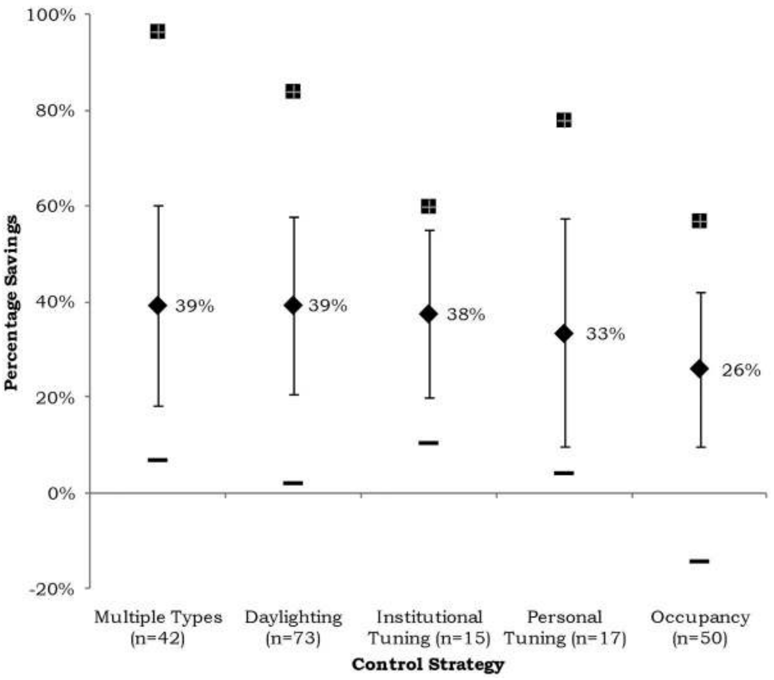


Fig. 4.
Energy savings for lighting controls and lighting energy only – second filter; symbols as shown in Fig. 2.

may accrue mostly after hours, making a 24-hour baseline important. With these examples, it does not seem critical to use only studies with certain definitions of energy savings, although standardization of some of these aspects in individual studies could lead to more robust conclusions in future meta-analyses.

The savings from the second filter are shown in Fig. 4. Savings for individual control types range from 26 percent for occupancy to 39 percent for daylighting, again representing only a small correction. This filter removes major outliers for occupancy only, but some high values remain in other categories.

3.4 SAVINGS FOR ACTUAL INSTALLATIONS ONLY

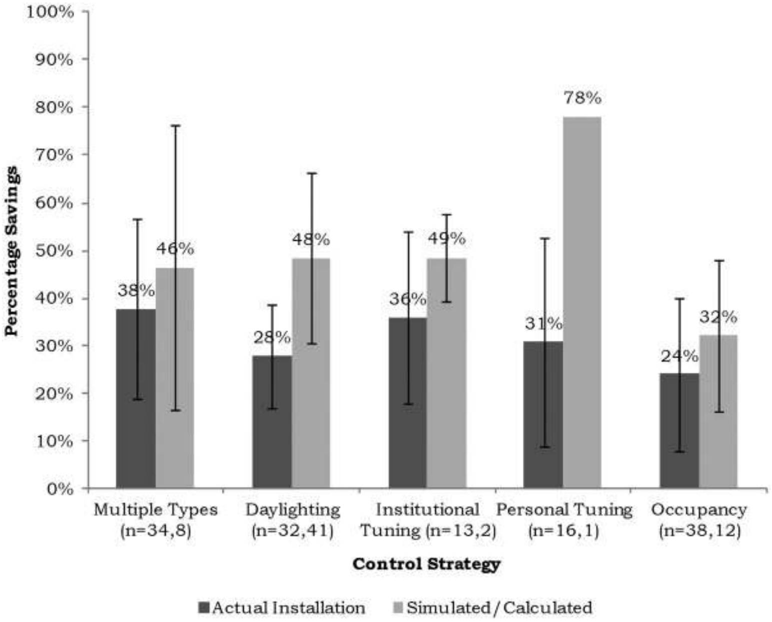
For the final filter, we wanted to address savings by how they were calculated. In theory, studies that monitor both the baseline and the test case should be most reliable. Studies that monitor only the test case and back-out the baseline may partially misrepresent savings by not capturing things like changes in behavior

TABLE 6.
Savings Basis for Actual Installations and Simulated or Calculated Installations

Savings Basis	Number of Rows—Actual Installation	Number of Rows—Simulated or Calculated
Monitored (with calculated baseline)	86	-
Calculated/simulated (from a monitored baseline)	-	26
Simulated (test case and baseline)	2*	33
Monitored/metered (test case and baseline)	37	-
Calculated (test case and baseline)	-	5
Unknown	8	-
Total	133	64

*These two data points represent actual installations for which the savings data were estimated from a simulation rather than monitoring.

Fig. 5.
Comparison of energy savings for actual installations and simulated or calculated installations.



after controls installation. Studies that monitor the baseline and calculate or simulate a test case may over-represent savings by reporting what are essentially theoretical (maximum potential) savings, as are estimates based on completely simulated studies. Table 6 shows the breakdown of savings estimates based on these parameters, categorized into the overarching themes of actual installations and simulations/calculations.

To simplify analysis and prevent reduction to small sample sizes, we looked at the difference between savings from the two major categories shown in Table 6:

Fig. 6.
Energy savings for lighting controls and lighting energy in actual installations – final filter; symbols as shown in Fig. 2.

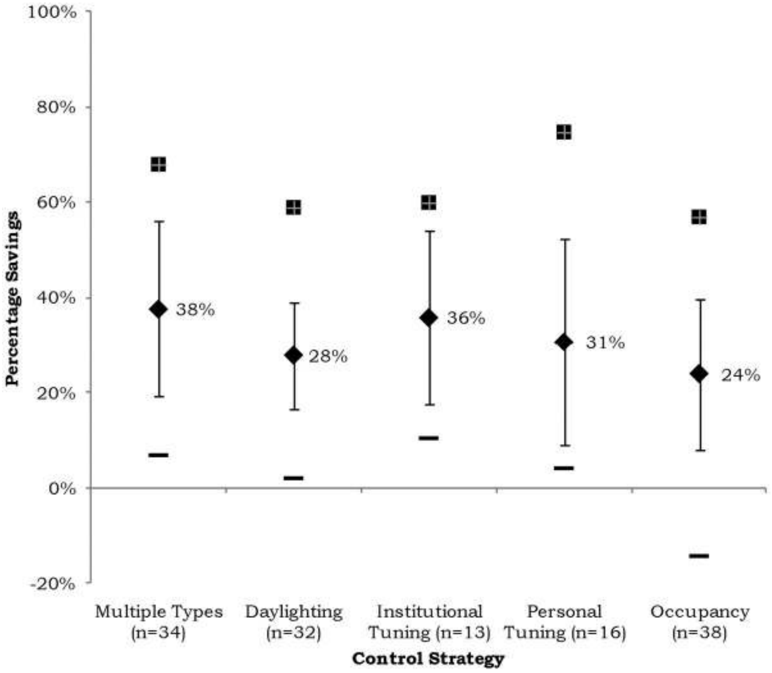


TABLE 7.
Comparison of Savings for Peer-Reviewed and Nonpeer-reviewed Papers

Control Type	Peer-Reviewed	Not Peer-Reviewed	Two-tailed *p*-Value*
Occupancy	24% (n=20)	23% (n=18)	0.8493
Daylighting	29% (n=20)	26% (n=12)	0.4687
Personal tuning	33% (n=12)	24% (n= 4)	0.4934
Institutional tuning	42% (n= 8)	26% (n= 5)	0.1268
Multiple types	43% (n=20)	30% (n=14)	0.0428

*Values <0.05 considered statistically significant.

actual installations of controls and scenarios in which the presence of controls was simulated or calculated. Figure 5 shows this analysis.

For daylighting, savings from actual installations appear to be significantly lower than those from simulations ($p < 0.0001$). We did not identify significant differences for the other categories, but sample sizes may be too small. Because of the significant difference for daylighting and the strong possibility that simulated studies over-represent savings, we filtered on this variable. Figure 6 shows the average savings following this final filter. Note that the averages in Fig. 6 are equivalent to the average savings from actual installations shown in Fig. 5. Savings for individual control types range from 24 percent for occupancy to 36 percent for institutional tuning. Most notably, this filter clearly reduced the savings for daylighting, down to 28 percent. The filter removed 40 percent of peer-reviewed rows and only 17 percent of nonpeer-reviewed rows, as simulations tend to be published in peer-reviewed literature. This filter removes many of the high outliers. Although some high values remain, because they come from actual installations, we believe that they represent real savings potential.

In this final cut, we again checked for significant differences between savings from reviewed papers and savings from nonpeer-reviewed papers. Table 7 shows that the only significant difference was for multiple types (although note that sample sizes are small for all control strategies). The disparate nature of combinations of control strategies may be the reason for this significant difference. We do not believe this indicates any quality issues, particularly since savings are higher for the reviewed papers.

Table 8 provides a final cut of savings by building type. However, note that with this filter there are not enough savings data left to provide reliable estimates for most building types.

3.5 COMPARISON OF ENERGY SAVINGS ACROSS FILTERS

Viewing the savings from all the filtered scenarios at once shows a general downward trend in energy savings as well as a reduction in the error band in some cases, as can be seen in Fig. 7. Daylighting savings estimates, which began

TABLE 8.
Energy Savings by Building Type—Final Filter

Building Type	Occupancy	Daylighting	Personal Tuning	Institutional Tuning	Multiple Types
Office	22% (n=23)	27% (n=18)	35% (n=13)	36% (n=11)	40% (n=24)
Warehouse	31% (n= 4)	28% (n= 1)	-	-	-
Lodging	45% (n= 2)	-	-	-	-
Education	18% (n= 5)	29% (n= 7)	6% (n= 2)	-	34% (n= 7)
Retail (other than mall)	-	29% (n= 3)	-	60% (n= 1)	-
Healthcare inpatient	-	-	-	-	35% (n= 1)
Public assembly	36% (n= 2)	36% (n= 1)	-	-	-
Healthcare outpatient	23% (n= 1)	-	-	-	-
Other	7% (n= 1)	18% (n= 1)	-	-	-

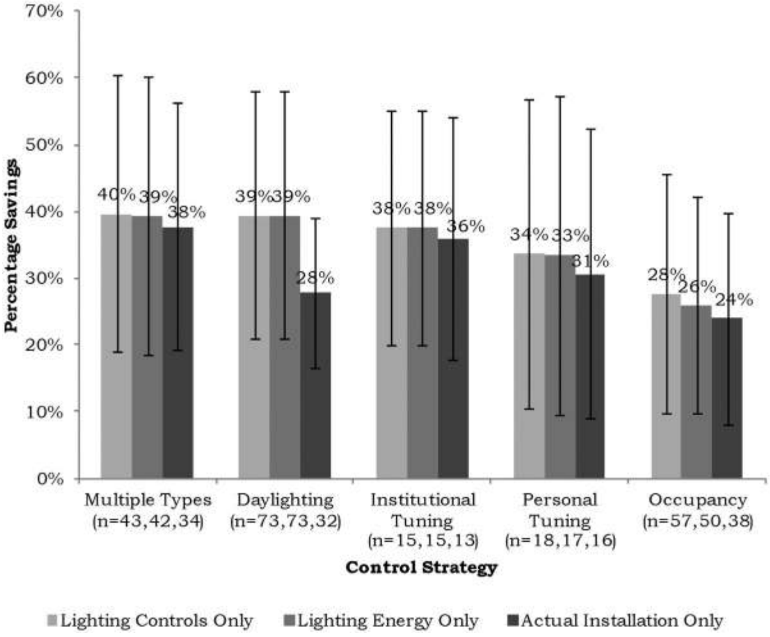


Fig. 7.
Comparison of energy savings from first filter to final filter. (Note that we do not show the overall unfiltered results here; because it includes savings from noncontrols-related measures, it is not relevant to the final analysis).

with a filtered average of 39 percent that was reduced to 28 percent in the final filter, show an especially strong downward trend. Savings from occupancy strategies also declined over the analysis, but only from 28 percent to 24 percent. In this case, savings declined steadily through each filter. We believe that the final filter represents the best conservative estimate of controls energy savings achievable in the field.

4 DISCUSSION AND CONCLUSIONS

This paper examined to the greatest extent possible the entire body of evidence on the energy impacts of lighting system controls used in commercial buildings. To arrive at the best estimates of the impacts of different controls, we applied a series of filters to screen out data with significantly different characteristics and to remove possible sources of bias. Interestingly, we found no effect from peer-reviewed vs. nonpeer-reviewed literature and therefore did not filter on this variable. The first two filters we used screened out data that include savings from noncontrols lighting technology and papers that report savings in something not equivalent to lighting energy. These filters did not create a large impact on overall savings.

The biggest single effect from filtering was the final filter, which screened out data points that were not based on actual installations: We found that simulations appear to overestimate savings achievable in the field, especially for daylighting. This result is not surprising, as daylight in a building is affected by so many factors (building orientation, location, use, weather, occupancy, blinds, reflectances, commissioning, etc.). This indicates that energy policy and savings estimates should not be based on simulations alone, but should include field measurement or at least downward adjustment of savings predicted from simulations.

This meta-analysis shows that individual control strategies save on average between one-quarter and one-third of lighting energy, and multiple controls strategies can capture up to nearly 40 percent savings on average. We acknowledge that this study may have a systematic bias towards higher savings as some included studies, particularly case studies, may focus on applications particularly suited toward controls. However, we believe that some of the low savings represented in the analysis may result from applications not amenable to controls. For example, one case of negative savings resulted from an installation in which occupants had previously been diligent about turning off lights and no longer did so after installation of occupancy sensors. For these reasons, we believe this analysis provides a reasonable estimate of average lighting energy savings.

In the future, light emitting diodes (LEDs) are expected to allow practitioners to capture additional energy savings. The vast majority of studies we examined used fluorescent lighting, which is less easy to control and dim than is the emerging LED lighting. LEDs are an inherently low-voltage source that can be more cost-effectively dimmed over a wider range than can incumbent technologies and are therefore more amenable to control strategies such as personal tuning. LEDs will not only allow capture of additional energy savings but also have the potential to enhance occupant comfort by improving control granularity, by allowing better occupant access to local lighting systems, and by the ability to control the light source spectrum according to automatic input and user preferences.

As mentioned previously, future research could develop more robust energy savings estimates through standardization of some aspects of individual studies, such as development of baselines for specific scenarios such as occupancy sensors in private offices. In addition, further examination of applications in which controls provide significant savings and applications in which controls provide very little savings could help to develop better specifications for how and where different controls strategies should be applied, thus helping to reduce uncertainty and guarantee savings at individual sites.

Despite these caveats, the results of this meta-analysis, viewed in aggregate, provide strong evidence that currently-available lighting controls strategies can and do provide significant lighting energy savings in commercial building applications. This finding has significant implications for energy policy. As mentioned previously, controls penetration is very low, federal energy conservation standards do not include lighting controls, and state and local building codes only partially address controls. Our findings indicate that policies that increase the use of lighting system controls can provide a potent approach to reducing U.S. energy use.

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*References marked with an asterisk were used as background only; as they are not primary sources of energy savings estimates, they were not included in the meta-analysis.