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A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings

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DISCLAIMER

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 estimates of 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, this paper adds successive analytical filters to identify potential biases introduced to the estimates by different analytical approaches. Based on the meta-analysis, the best estimates of average energy savings potential are 24% for occupancy, 28% for daylighting, 31% for personal tuning, 36% for institutional tuning, and 38% for multiple approaches. The results suggest that simulations significantly overestimate (by at least 10%) the average savings obtainable from daylighting in actual buildings.

Key Words: 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 (U.S. Department of Energy). 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 an increase in source efficacies (U.S. Department of Energy 2011b). However, lighting controls are not incorporated in federal energy conservation standards and are only partially incorporated through state and local building codes.[1] 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 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% of lit commercial buildings in the United States have daylighting sensors and only 1% have an energy management and control systems for lighting, according to the U.S. Department of Energy 2003 Commercial Buildings Energy Consumption Survey (CBECS)—the potential for 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 the studies on controls has been done before. This makes it hard to understand the big picture of the opportunities of controls because the individual studies have been very diverse in their 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 (e.g. VonNeida et al 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 spaces and experimental spaces (e.g. Parker

[1] ASHRAE 90.1, the national model building code, is updated every three years and includes several controls requirements in ASHRAE 90.1-2010 including automatic shutoff controls and photocells in certain space types. However, states have until 2013 just to update their codes to meet ASHRAE 90.1-2007, and some states still meet only ASHRAE 90.1-2001 (U.S. Department of Energy 2011a).

et al 1996). Some studies separate the effects of controls from the effects of other lighting efficiency measures, while others do not. Some studies are designed to identify the influence of other factors, such as window glazing or orientation, on energy savings obtained from controls. Some studies focus on specific space types, while others report savings by buildings or across buildings without noting or reporting on savings by space types within buildings.

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 et al (2000) presented industry estimates of lighting energy savings for occupancy sensors by building space type, which ranged from 5% to 90%. The authors then presented results from their own study on 60 buildings with lighting savings ranging from 17% to 60%. 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% depending on the use of space. Guo et al (2010) reviewed the performance of occupancy-based control systems from seven previous studies, with energy savings ranging from 3% to 86%.

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 several 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 6% to 80%. 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% 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. 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 energy savings per control type based to the extent possible on all available data. While these studies do not generally use common parameters, we utilize a range of analytical filters to estimate the savings by control type and building type and to isolate the effect of controls from those of other lighting system modifications.

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 the National Electrical Manufacturers Association (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 lighting controls studies 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 are reviewed, and 48 were self-published reports or case studies. While not all of those papers classified as reviewed were technically peer-reviewed, we refer to them as such throughout this paper for simplicity.

Reviewed publications included conference proceedings of the American Council for an Energy-Efficient Economy (ACEEE) (8), conference proceedings and journal articles of the Illuminating Engineering Society of North America (IESNA) (6), and journal articles from *Energy and Buildings* (5), *Lighting Research and Technology* (4), *Leukos* (3), and *Solar Energy* (3). We also included several consultant reports. The most represented non-industry authors came from the Lighting Research Center (11), the National Research Council Canada (9), Lawrence Berkeley National Laboratory (LBNL) (9), the California Lighting Technology Center (CLTC) (6), the Florida Solar Energy Center (5), and the Heschong Mahone Group (3). The most represented industry case studies included those of WattStopper (11), Sensor Switch (2), and Lutron (2).

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 averaged over 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 (i.e. lights full on all day versus 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 1.

TABLE 1. Major lighting controls strategies

Strategy	**Definition**	**Relevant Technologies**
Occupancy	Adjusting light levels according to the presence of occupants	occupancy sensors, time clocks, energy management system
Daylighting	Adjusting light levels automatically in response to the presence of natural light	photosensors, time clocks[1]
Personal tuning	Adjusting 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

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

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 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). Report authors were not always clear about these important distinctions, but we used our best judgment to ascertain what each study represented. 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 think we had 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

By control type

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.

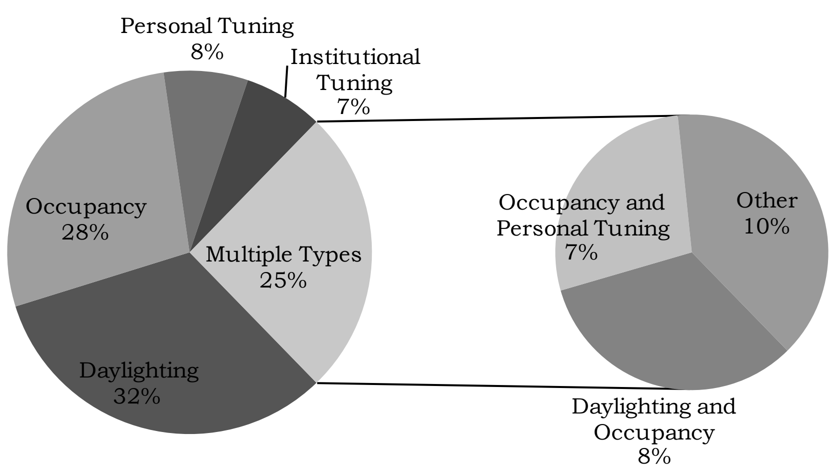

Fig. 1. Data by control type (n=240).

By building type

To obtain as complete sectoral coverage as possible, we made specific attempts to find studies in under-represented building types. Table 2 shows the coverage by building type with the building types ordered by their percentage of commercial lighting energy use, according to the 2003 Commercial Buildings Energy Consumption Survey (CBECS) (US Department of Energy). 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, occupancy is generally the only control strategy used in the lodging sector. While data are missing for five of the 14 categories, these constitute less than 20% of total lighting energy use in the commercial sector. On the other hand, a significant number of data points are available only for the top four categories, which together constitute an estimated 58% of commercial building energy use.

TABLE 2. Coverage by building type: number of rows for each control type (alone or in combination). (Percent commercial lighting energy use from CBECS 2003.)

Building Type (Reported by itself or in combination with other building types)	Percent Commercial Lighting Energy Usage (CBECS 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	-	-

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 removed data points that represented savings as a fraction of total building energy or included heating, ventilation, and air conditioning (HVAC) savings as opposed to lighting savings only. We also removed data points that represented a non-comparable 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% of lighting hours and there was no apparent change to 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 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% for occupancy to 41% 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.

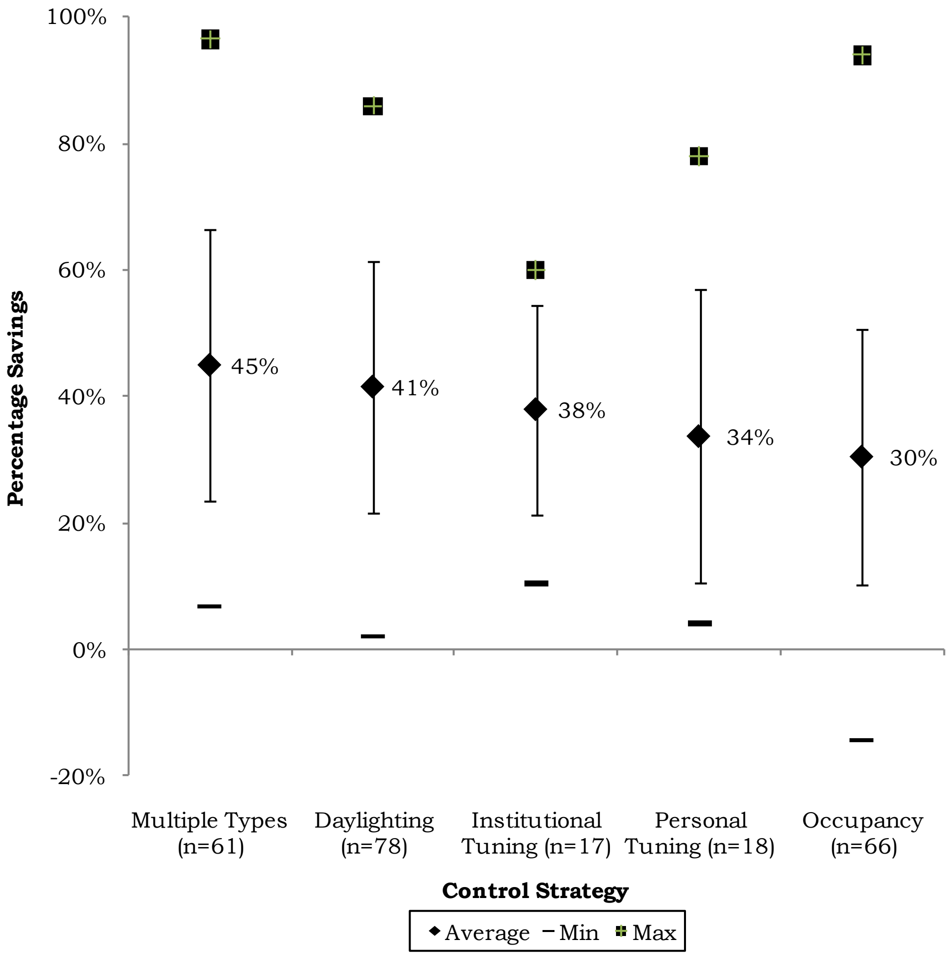

Fig. 2. Average savings (%) by control type – unfiltered; error bar shown represents one standard deviation.

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. We 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. However, we think 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 3. Because some studies provided data for multiple building types that we were unable to disaggregate, the table below 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.

TABLE 3. 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)	-	-	-

We checked for differences in savings between peer-reviewed and non-peer-reviewed papers to identify any possible quality issues in non-reviewed papers. Table 4 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.

TABLE 4. Average savings by control type for peer-reviewed and non-peer-reviewed papers

Control Type	Reviewed	Not 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%.

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 just attributable to the controls. 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% of all rows: 91% of peer-reviewed rows and 78% of non-peer-reviewed rows. Fig. 3 shows the average savings following this first filter. Savings range from 28% for occupancy to 39% for daylighting, representing a very small correction. Note that this filter does not remove many of the high outliers.

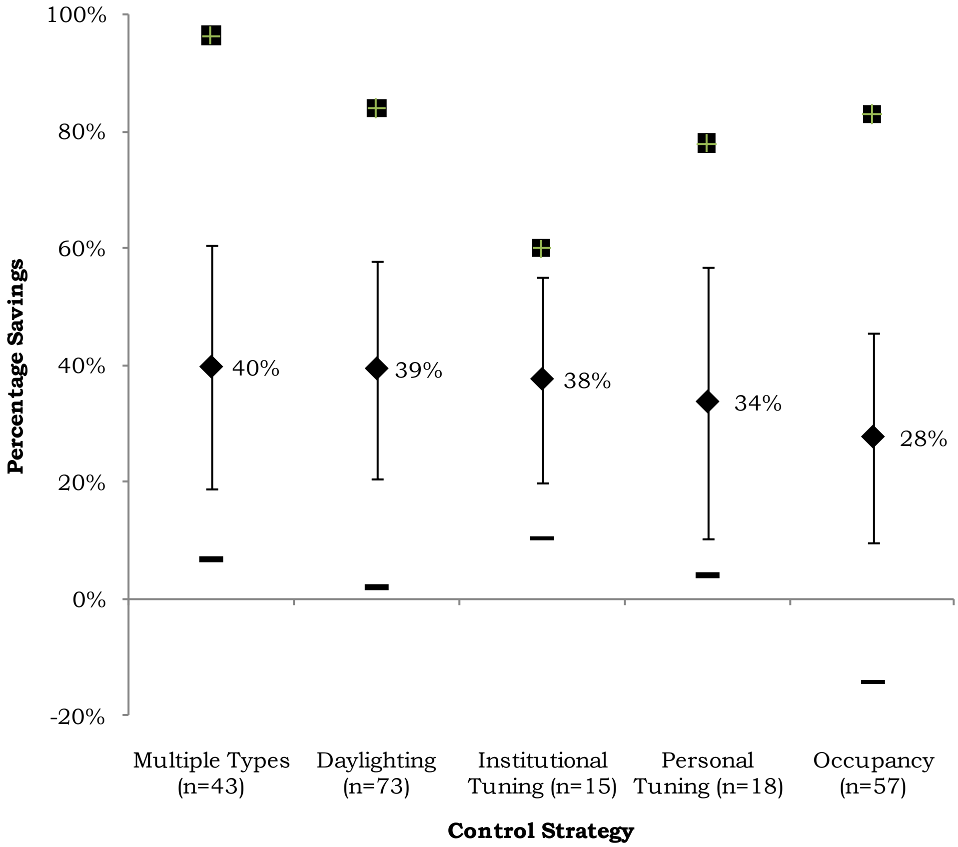

Fig. 3. Energy savings for lighting controls only – first filter; symbols as shown in Fig. 2.

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 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 (i.e. annual vs. daily, weekday core hours only vs. 24/7). 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 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.

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

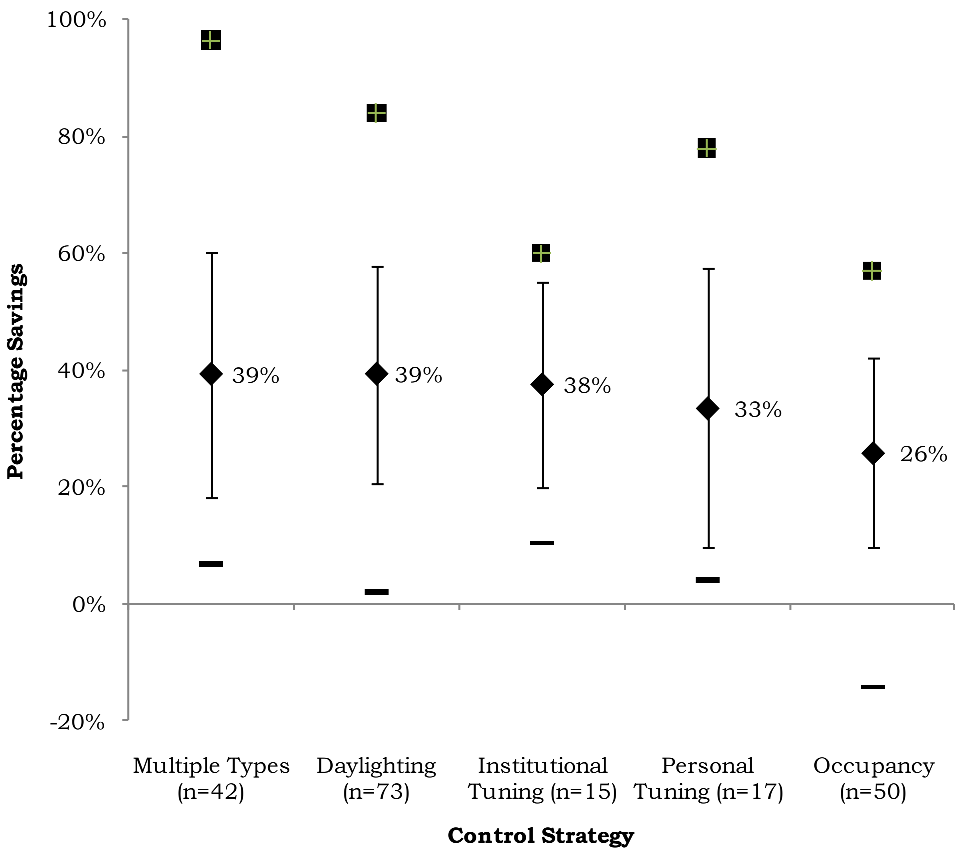

Fig. 4. Energy savings for lighting controls and lighting energy only – second filter; symbols as shown in Fig. 2.

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 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 5 shows the breakdown of savings estimates based on these parameters, categorized into the overarching themes of actual installations and simulations/calculations.

TABLE 5. 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 was estimated from a simulation rather than monitoring.

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

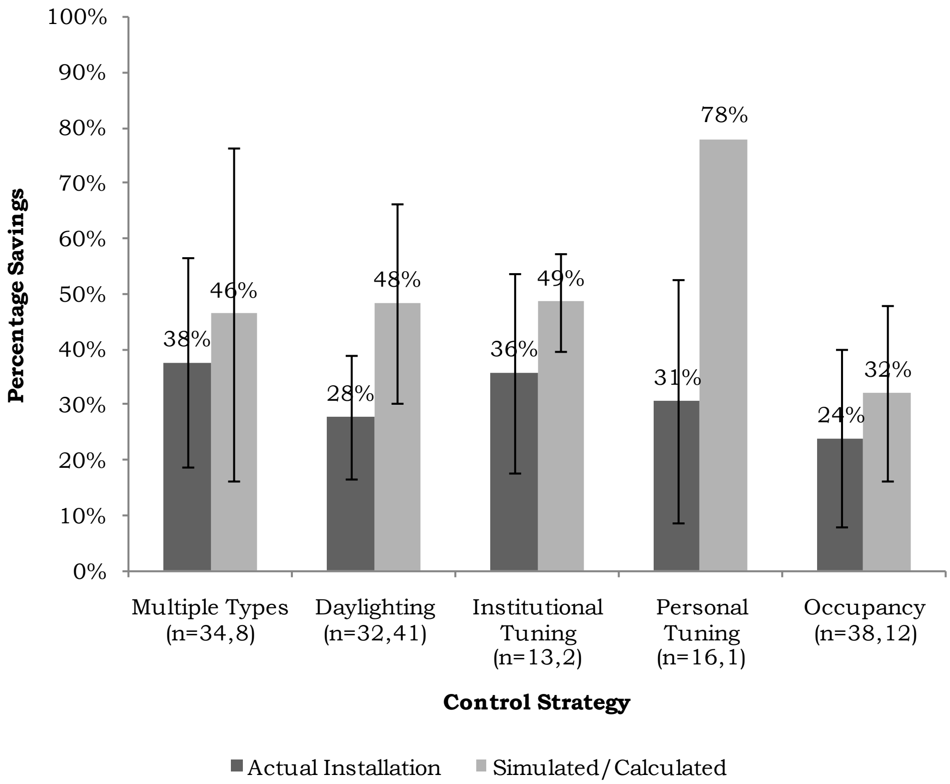

Fig. 5. Comparison of energy savings for actual installations and simulated or calculated installations.

For daylighting, savings from actual installations appear to be significantly lower than those from simulations ($p<0.0001$). Sample sizes may be too small for the other categories to identify significant differences. Because of the significant difference for daylighting and the strong possibility that simulated studies over-represent savings, we filtered on this variable. Fig. 6 shows the average savings and other statistics following this final filter. Note that the averages in this figure are equivalent to the average savings from actual installations shown in Fig. 5. Savings range from 24% for occupancy to 36% for institutional tuning. Most notable, this filter clearly reduced the savings for daylighting, down to 28%. The filter removed 40% of peer-reviewed rows and only 17% of non-peer-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.

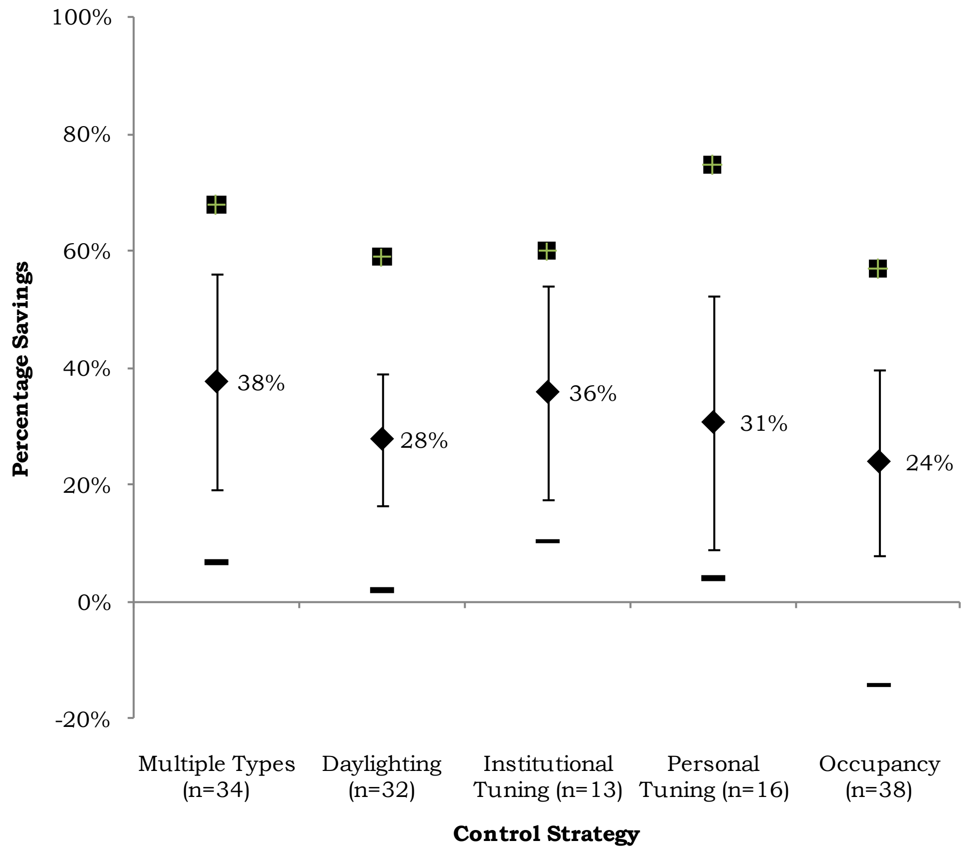

Fig. 6. Energy savings for lighting controls and lighting energy in actual installations – final filter; symbols as shown in Fig. 2.

In this final cut, we again checked for significant differences between savings from reviewed papers and savings from non-reviewed papers. Table 6 shows that the only significant difference was for multiple types (although note that sample sizes are small for all control strategies). Three very low non-reviewed data points for multiple types come from a single paper with a highly efficient lighting system as baseline. This, along with 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 6. Comparison of savings for reviewed and non-reviewed papers

Control Type	Reviewed	Not 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.

Table 7 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.

TABLE 7. Energy savings by building type – final filter

Building Type (Alone)	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)	-	-	-

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

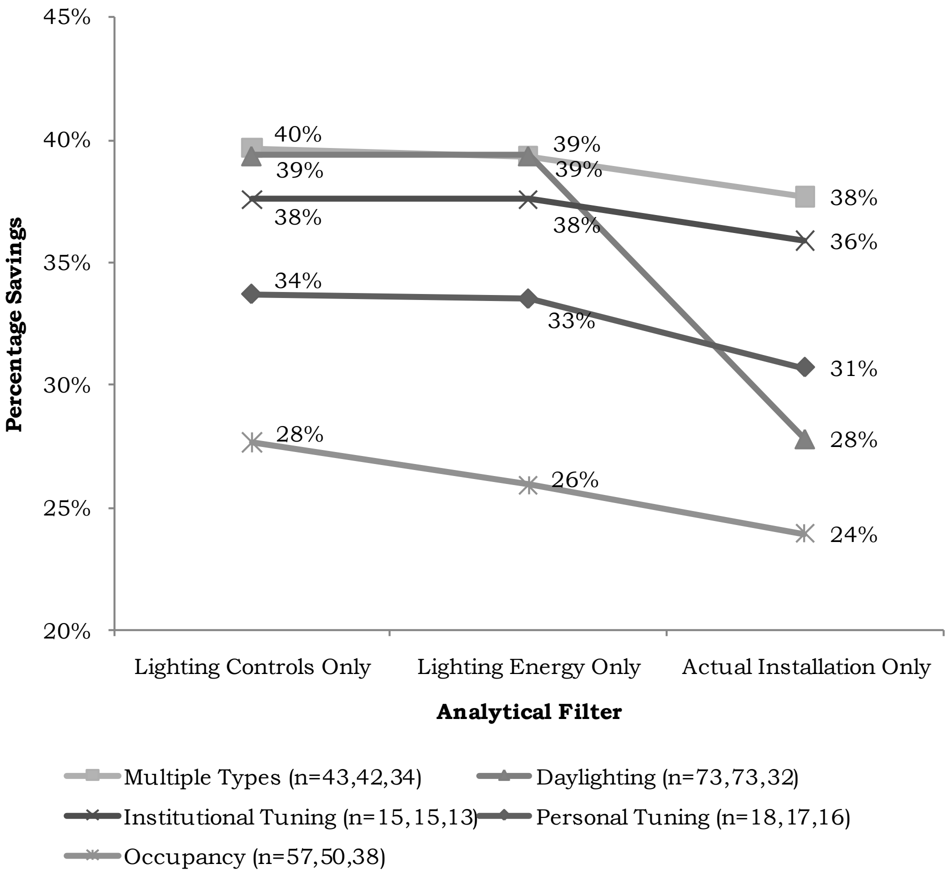

Fig. 8. Figure 8 highlights an especially strong downward trend for the daylighting savings estimates, which began with a filtered average of 39% and was reduced to 28% in the final filter. Savings from occupancy strategies also declined over the analysis, but only from 28% to 24%. In this case, savings declined steadily through each filter. We believe that the final filter represents the best conservative estimate of controls energy savings achievable in the field.

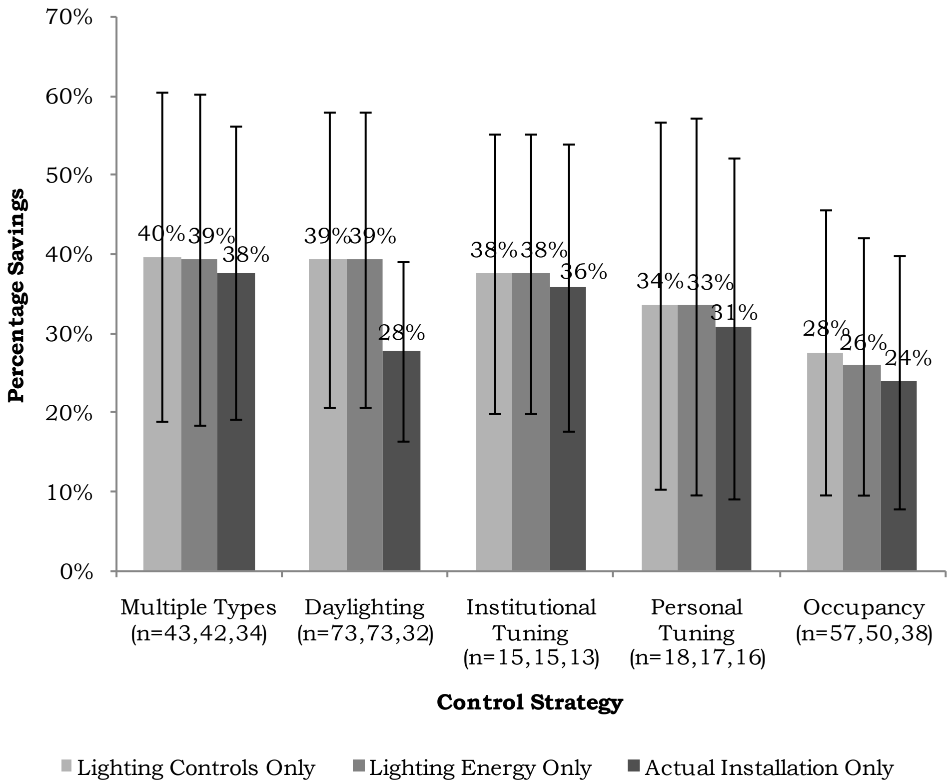

Fig. 7. Comparison of energy savings from first filter to final filter. (Note that we do not show the overall unfiltered results here; because it includes savings from non-controls-related measures, it is not relevant to the final analysis).

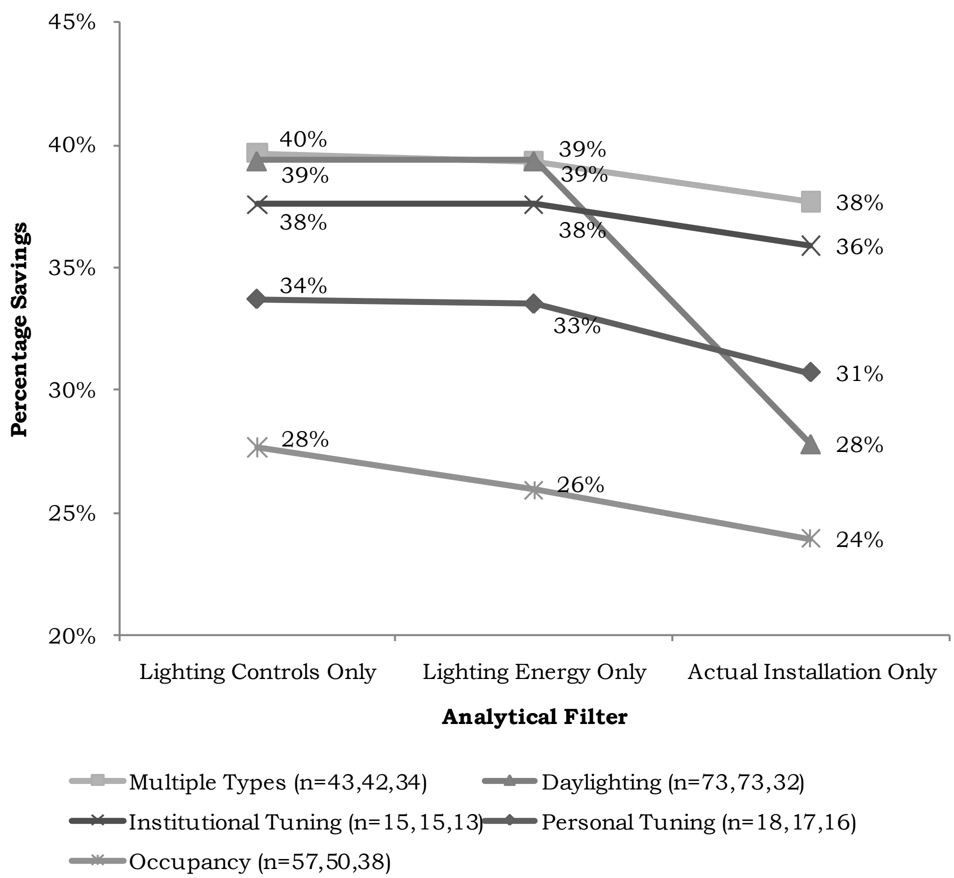

Fig. 8. Comparison of energy savings from first filter to final filter.

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 points with significantly different characteristics and to remove possible sources of bias in the data. Interestingly, we found no effect from peer-reviewed versus non-peer-reviewed literature and therefore did not filter on this variable. The first two filters we used screened out data points that include savings from non-controls lighting technology and 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 comprehensive meta-analysis provides strong evidence that lighting controls do on average capture significant energy savings—between one-quarter and one-third of lighting electric energy, depending on the individual control strategy, and up to nearly 40% for buildings in which multiple controls strategies are used. While these results may have limited value from a predictive standpoint, viewed in aggregate, they build confidence that lighting control strategies can and do provide significant 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 them. Our findings indicate that policies that increase the use of lighting system controls are among the most potent approaches to reducing U.S. energy use.

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