2021

Simulation-based Energy and Daylighting Impact Assessment of Integrated Shading Devices and Lighting Controls in Commercial Buildings

Niraj Kunwar
Oak Ridge National Laboratory, nirajkunwar@gmail.com

Mahabir Singh Bhandari

Simulation-based Energy and Daylighting Impact Assessment of Integrated Shading Devices and Lighting Controls in Commercial Buildings

Niraj Kunwar, Mahabir Bhandari*

Oak Ridge National Laboratory, Buildings and Transportation Science Division,
Oak Ridge, TN 37831, USA

* Correspondence: bhandarims@ornl.gov; Tel.: +1-865-574-0989; Fax: +1-865-574-3851

ABSTRACT

Fenestration systems are estimated to be responsible for 1,790 PJ of primary energy consumption annually in commercial buildings in the US and have significant impact on occupants' visual and thermal comfort. Window shading devices such as shades and blinds are cost-effective means to reduce energy losses/gains from fenestration systems and provide a comfortable environment in the buildings. Besides being cost effective, these products are less intrusive to install when retrofitting the buildings. To maximize the benefits, however, these products require integrated control strategies. Due to complex modeling process involved, existing control strategies used by shade automation industries, generally are not evaluated for energy and daylighting benefits. This paper presents the impacts of shading devices on various aspects of built environment using a comprehensive simulation study. The simulation is performed using a framework enabling automation of daylight and energy simulation and their interaction as well as result post-processing. The results from the simulation show that the control strategies enabled annual cooling and lighting energy savings of up to 40% and 25% respectively. The impact of different shading types, controls and climate conditions on the energy savings results is analyzed. The results of the impact of this technology on energy consumption, daylighting, and occupant comfort from this study will help building owners, designers, engineers, and utilities make informed decisions.

1 INTRODUCTION

Fenestrations in the United States attributes to 1,790 PJ of primary energy consumption in commercial buildings from heating and cooling loads (Sawyer, 2014). Generally, fenestrations have lower thermal performance compared to the opaque envelope. In addition, unlike the opaque envelope, windows also transmit daylight/solar radiation into the building and thus have significant impact on occupant's visual and thermal comfort (Kunwar et al., 2018). Solar gain from the windows is one of the most significant cooling loads in the buildings. While, high efficiency windows can control some of these parameters such as thermal transmittance and solar heat gain, the window retrofits might be disruptive and not be economically viable option (Ariosto & Memari, 2013). Also, even highly efficient windows such as electrochromic glazing are not able to control glare without use of shading devices (Fernandes et al., 2013). Window attachments/shading devices can achieve multiple objectives of energy savings, daylight provision and occupant comfort. However, the effectiveness of these systems depends on their properties and the strategies used to control. Most of the shading devices used currently are manually controlled and hence are not optimal in terms of achieving energy savings and daylight provisions in the space. Therefore, significant research efforts have been directed towards different types of shading devices and their automation in the past two decades.

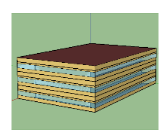
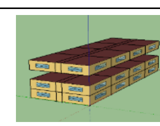
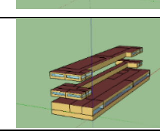
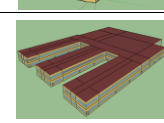
The studies on shading devices has been carried out both using simulation (Atzeri et al., 2018) and experimental studies (Kunwar et al., 2019). These studies have evaluated the energy savings potential and impact on daylighting and glare that occurs from shading control. Experimental testing was performed using a low cost camera to control the shading device to meet visual comfort requirements (Goovaerts et al., 2017). However, the qualification of the impact of general shading control strategies that are utilized by shade automation industries at present is missing. The quantification of impact of automated shading devices on various aspects of built environment is essential to enable adoption of such technologies in US building stock.

For addressing this gap of studies on general shading control strategies in office buildings, a comprehensive study of different shading devices and shading controls was performed in (Kunwar & Bhandari, 2020) by the authors. The paper modeled shading control strategies used by three shade automation industries and evaluated their impact in medium office prototype buildings (The U.S. Department of Energy (DOE), n.d.). In this paper, the analysis of the shading controls will be extended to 4 different types of buildings including medium office, secondary school, midrise apartment, and large hotel for new buildings vintage of 2016 (The U.S. Department of Energy (DOE), n.d.). Here, the medium office buildings used has a different window to wall ratio (WWR) than that used in (Kunwar & Bhandari, 2020). The control strategy for shading devices were chosen considering building type, occupancy, and the primary purpose of building. Combined occupancy and daylighting-based controls were used in medium office and secondary school buildings. While in midrise apartment and large hotel, the shading control was used only with occupancy-based lighting controls. In the next section, different control strategies used in different building types and their result in six different location in the US is presented. The conclusions based on the results and their analysis is presented in the subsequent section.

2 METHODOLOGY AND RESULTS

This section will first provide an overview of buildings and shading devices that were used for the simulations, Then, later for each building types, the different shading control strategies used and the results from their applications are provided in the sub-sections 2.1 to 2.4. The details of the 4 buildings that were used for the simulation is provided in Table 1. Among these buildings, both energy and daylight simulations were performed for the medium office building while for other three types of buildings only energy simulations were performed. Custom scripts were used to implement the different control strategies based on exterior illuminance by using the results from the daylight simulations, while some schedule-based control strategies were directly implemented in energy simulation. The shading and lighting state after implementation of control strategies were saved as schedules and used as text-based input into energy simulation. This framework of simulation has also been discussed in (Kunwar & Bhandari, 2020). Control strategies suitable to the different building types were used in the respective buildings as all shading control strategies are not suitable for all building types due to varying nature of occupancy and activities. The simulations were performed in six different climate zones/locations i.e., Houston (2A), Los Angeles (3B-CA), Washington DC(4A), Seattle (4C), Chicago (5A) and Minneapolis (6A).

Table 1: US DOE prototype building characteristics

Building type	**Building area (m^2)**	**No. of floors**	**WWR**	**Heating, ventilation, and air-conditioning system**	**Building image**
Medium office	4,982	3	48	Heating*:* Gas furnace and electric reheat Cooling: Packaged air-conditioning units	
Midrise apartment	3,135	6	20	Heating: Gas furnace Cooling: Split system direct expansion	
Large hotel	11,345	4	30	Heating: Gas-fired boiler Cooling: Air-cooled chiller	
Secondary School	19,592	2	35	Heating: Gas-fired boiler Cooling: Air cooled chiller	

Different shading devices used in these buildings are provided in Table 2. The properties of shading devices and secondary glazing are provided in the table along with the building type in which each of the shading devices are used for the simulation.

Table 2: Properties of shading devices and secondary glazing

Shade	Other Properties	Location	k (W/m-K)	VT (F/B)	T_{sol} (F/B)	R_{sol} (F/B)	Building types
Venetian blind	24 mm wide, 1.5 mm rise	interior	160	0.00	0.00	0.68	medium office, midrise apartment, secondary school
Roller shades A	light color, 1% OF	interior or exterior	0.3	0.12	0.18	0.74	medium office, midrise apartment, secondary school
Roller shades B	dark colored, 1 % OF	interior or exterior	0.12	0.00	0.00	0.04	large hotel
Secondary glazing (SG)	low e	interior	1.00	0.88	0.74	0.10	all

2.1 Medium office:

The medium office building used here is with increased WWR, i.e., from 33% of the US DOE medium office prototype building to 48% to cover the modern glass buildings with higher WWR. The control strategies in this case are the same control strategies which were used in (Kunwar & Bhandari, 2020) as provided below.

Baseline (B): No shading, no lighting control

Lighting control (LC): No shading, lighting dimming

Manual control (MC): Shading control based on different user type

Automated Control 1 (AC1): Roller shades closed to different heights based on exterior illuminance

- Exterior vertical illuminance > 53000 lux: Fully closed
- Exterior vertical illuminance <4300 lux: Fully opened
- Else shade deployed to at least 50% or greater height to prevent solar penetration depth of ~5 ft

Automated Control 2 (AC2): Roller shades open or closed based on cooling status or glare

- Daylight glare index >22 or zone in cooling mode: Fully closed
- Else: Fully opened

Automated Control 3 (AC3): Roller shades closed or opened based on exterior illuminance

- Exterior vertical illuminance > 20000 lux: Fully closed
- Exterior vertical illuminance <15000 lux: Fully opened

Automated Control 4 (AC4): Roller shades closed to different heights based on exterior illuminance

- Exterior vertical illuminance < 10000 lux: Fully opened
- Exterior vertical illuminance >50000 lux: 75% closed
- Exterior vertical illuminance > 30000 lux: 50% closed
- Exterior vertical illuminance >15000 lux: 25% closed

Secondary glazing (SG): Fixed secondary glazing

Venetian blinds (VC): Venetian blind controlled to block beam solar

- Blinds rotated to prevent direct sunlight from entering the space when external vertical irradiation on the façade is greater than 150 W/m^2

All the automated controls (AC1-AC4) and manual control (MC) used Roller shades A as shading device. Also, except the baseline case all the other controls strategies utilized lighting dimming controls to maintain a setpoint illuminance of 500 lux. The lights could be dimmed up to 30% of full power of the lighting device. The results from the application of the control strategies listed was then evaluated for energy savings and daylighting. The results for energy consumption for heating, cooling and lighting and the total energy savings from control strategies compared to B is shown in Figure 1. These results are provided for all the control strategies listed above for six different locations of

US. Here, the total energy savings refers to the sum of energy savings for heating, cooling and lighting. The total energy savings in the medium office buildings was in the range of 0.8 to 17.7 kWh/m^2-yr. From the figure it can be seen that higher energy savings is realized from use of roller shades (AC1-AC4, MC) and venetian blinds (VC) in cooling dominated climate of Houston and Los Angeles compared to heating dominated climate. The use of SG was able to achieve significant energy savings in all the climate zones. Among the automated strategies AC3 that uses exterior shades was able to achieve higher energy savings compared to interior shades. In all the climate zones, significant energy savings i.e., average of nearly 5 kWh/m^2-yr was from lighting control and reduction in lighting energy savings. The variation in energy savings was less for lighting energy consumption compared to cooling or heating energy across different climate zones as well as control strategies. The average lighting energy savings was approximately 25% which was lower than 50-75% savings from an experimental study (Shen & Tzempelikos, 2017). This difference comes from our assumption that the lowest dimming level for lighting was 30% of total lighting power, while in (Shen & Tzempelikos, 2017) the dimming capability was up to 1% of total power.

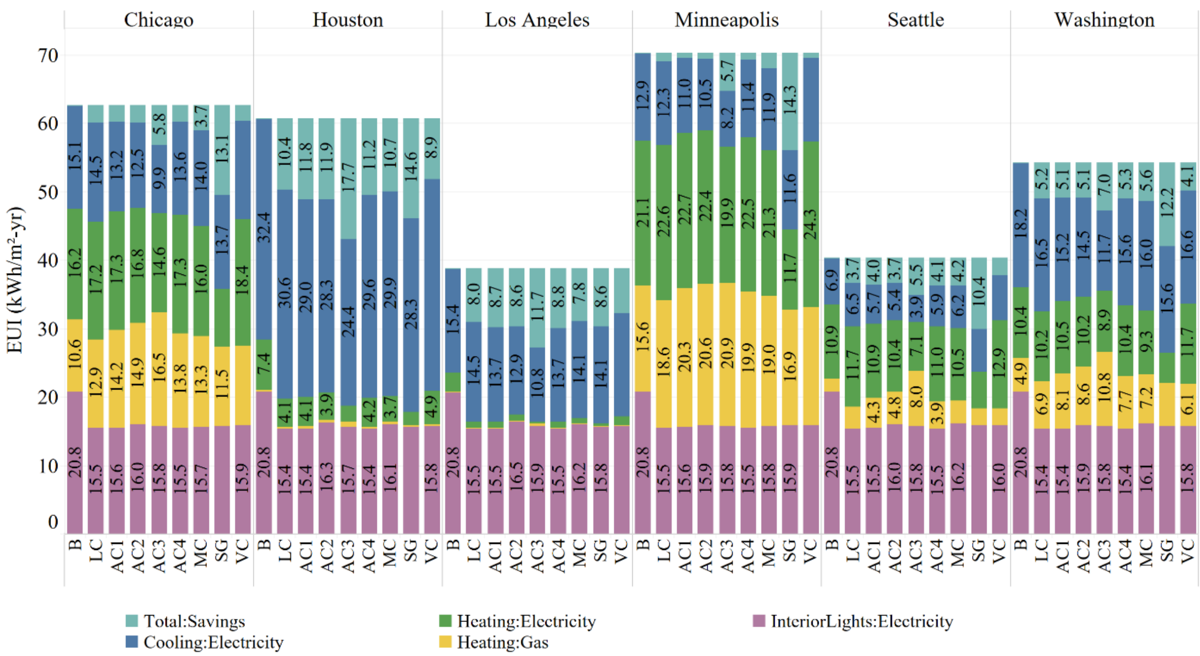


Figure 1: Energy consumption and savings in medium office building

The results for daylighting are provided for the four automated control strategies (AC1-AC4) and baseline (B) case. The results are provided in terms of spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) (IES Daylight Metrics Committee, 2012) calculated based on grid setup of work plane illuminance sensors shown in Figure 2. The results for $sDA_{300,50}$ i.e. percentage of floor area with illuminance greater than 300 more than 50% of the occupied hours and ASE i.e. percentage of floor area which receives direct illuminance greater than 1000x for more than 250 occupied hours are provided in Table 3. The results in the table show that generally from the use of shading device there is decrease in excessive illuminance that could cause visual discomfort reflected by reduction in ASE. There is also reduction in useful amount of daylight that could be utilized shown by reduction in sDA. AC2 which includes cooling status in the control strategy shows more variation in daylight across the location compared to other control strategies. While, using AC2 higher sDA and ASE is there in cold climate of Chicago and Minneapolis compared to other locations.

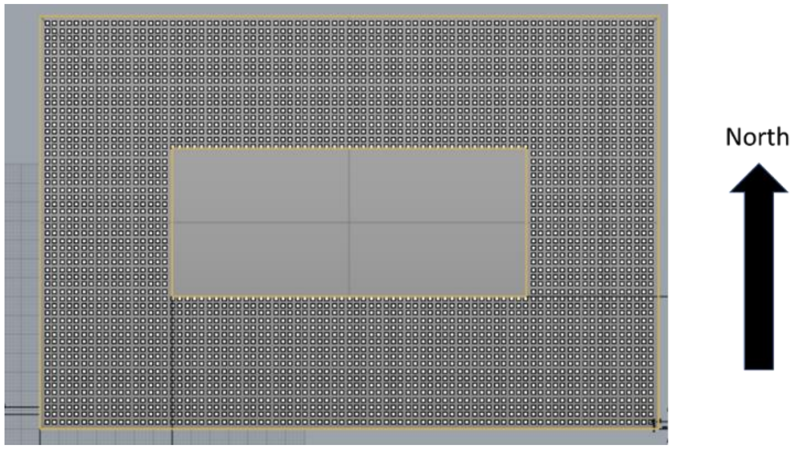


Figure 2: Grid setup for daylighting simulation in medium office building

Table 3: Daylighting results for medium office building using sDA and ASE

	ASE						$sDA_{300,50}$				
	B	AC1	AC2	AC3	AC4		B	AC1	AC2	AC3	AC4
Chicago	41	13	26	13	14		89	43	42	65	67
Houston	34	9	3	14	10		92	44	24	66	69
Los Angeles	38	13	7	10	15		93	46	21	67	69
Minneapolis	46	14	31	11	17		89	44	47	66	67
Seattle	40	9	7	11	14		83	40	30	62	65
Washington	35	11	19	12	14		91	45	39	66	68

2.2 Secondary School:

Secondary school has similar nature of occupancy as office building. Also, school building can utilize daylight and needs to ensure visual comfort for occupants' well-being and productivity like in the case of medium office. Considering this, the same shading devices and control strategies that were used for medium office were also used for secondary school. The results for the energy savings in secondary school from the use of those control strategies is provided in Figure 2. In case of the secondary school, the energy savings is in the range of 1.4 to 12.2 kWh/m^2-yr. There is less variation in energy savings across different locations compared to medium office buildings. However, the energy savings is higher from use of SG in secondary school like medium office buildings.

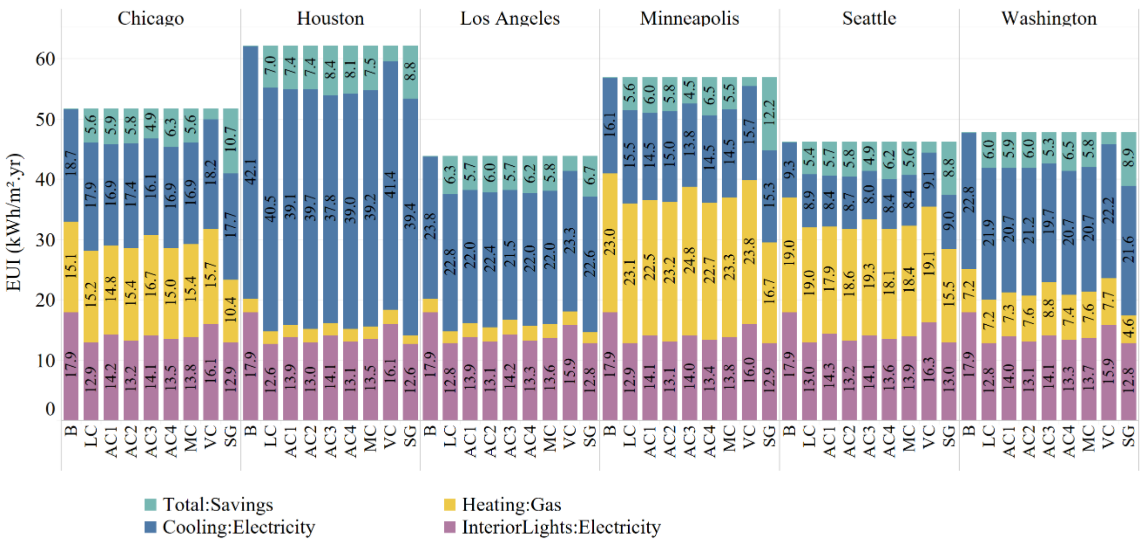


Figure 3: Energy consumption and savings in secondary school

2.3 Midrise apartment:

In residential buildings, the shading devices are mostly closed during the night-time for privacy reasons. Based on this control strategy "AC3" used for medium office was used in this building but the roller shades were closed completely after 6:00 pm in the evening until 8:00 am in the morning. Another strategy using same control strategy but using roller shades in the interior of the window "AC3-I" was tested in midrise apartment. Apart from this one case with secondary glazing "SG" and other two control strategy based on average schedule of shading state on residential building considering different time of day, day of week and season was applied for roller shades and venetian blinds namely "AER" and "AEV" respectively. This schedule was developed by (Peng & Curcija, 2017) based on a behavioral study of window and window attachments (DRI, 2013).Thus, not including the baseline case "B", five other scenarios of shading devices was tested. Since residential building are less likely to have lighting control and utilize daylighting, this building type was only evaluated for energy performance of shading device without using any lighting control. The results for energy consumption for midrise apartment are shown in Figure 4.

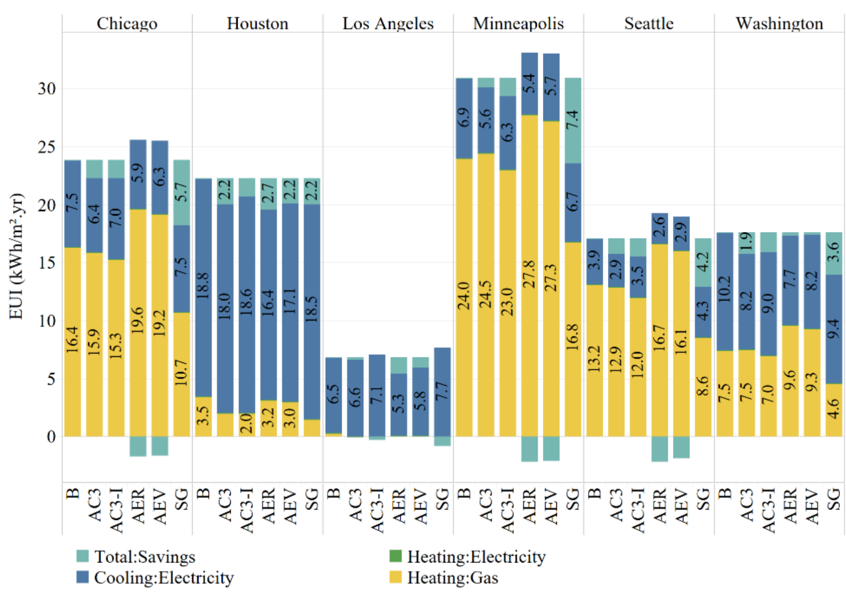


Figure 4: Energy consumption and savings in midrise apartment

As shown in the figure, for majority of the cases the shading control has contributed to energy savings while some of the cases also faced energy penalty while using shading device in mid-rise apartment without any lighting controls. The range of energy savings/penalty was -1.7 to 7.4 kWh/m^2-yr. Mostly the penalty is seen for control algorithms AER and AEV which provides the average representation of current operation of blinds by users in an area. Note that these two control algorithms cannot be directly applied in a household but can be used as average manual control and comparison with the automated shading control. In general, the energy performance of both AC3 and AC3-I was better than AER and AEV which represented weighted energy performance of manually operated roller shades and venetian blinds respectively. This also implies that the use of automated roller shades has a potential to reduce energy consumption in mid-rise apartment even without considering the influence on daylight, visual comfort, etc. compared to manually controlled shading devices.

2.4 Large hotel:

This is another building type where automated shading solution was utilized, and their performance was evaluated for energy consumption. Similar to residential building, large hotel was considered to have their shading devices closed during the nighttime after 6:00 pm until 8:00 am in the morning for all the control strategies. For the purpose of simplification one control strategy had shading devices always ON and another had shading devices ON during night (ON meaning closed) and open during the day. For each of these control, one case with interior shading device and other with exterior shading device was simulated in the large hotel building thus making up four different control strategies:
AOE- Always ON with exterior roller shades
AOI- Always ON with interior roller shades
NOE- ON during night with exterior roller shades
NOI- ON during night with interior roller shades
For all the four control strategies Roller shades B was used as the shading device. Other than these four control strategies one baseline case “B” and other case with secondary glazing “SG” was also simulated for large hotel. Although the closing of shading device during night is generally agreed upon there is potential of further research on operation of shading device during daytime and also based on the occupancy and other factors such as temperature, humidity etc. which would be area of future study. As for lighting, occupancy schedule-based weighting of lighting consumption was used for all the cases including baseline, but no daylighting dimming based control was used. The results for large hotel on energy consumption at six different locations are provided in Figure 5.

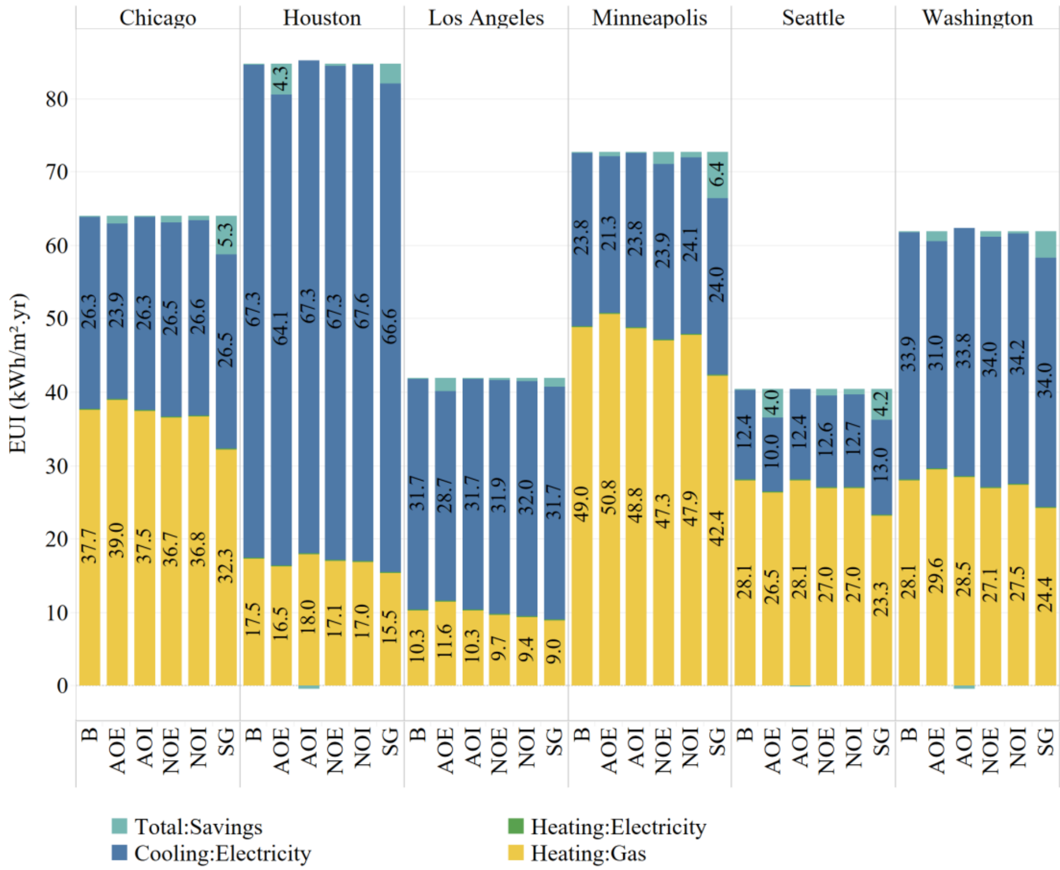


Figure 5: Energy consumption and savings in large hotel

The energy savings from heating and cooling ranges from approximately -0.5 to 6.4 kWh/m^2 in the large hotel. The results show that if left always ON, energy performance of exterior roller shades is better compared to the interior roller shades (i.e. AOE has higher savings compared to AOI). This is also seen for the shading devices closed only during night; the performance seems to be slightly better while using the exterior roller shades compared to the interior roller shades. Other than that, in large hotel, similar to medium office, SG provides the best energy savings in colder climate (Minneapolis, Chicago) and equivalent performance to exterior shades that is always closed (AOE) in hotter climate (Houston, Los Angeles). These results show that only using simple control strategy like closing the shading devices all the time some energy savings can be achieved. Further, if these are used to harvest solar heat gain during winter, considering the occupancy of each room then the energy savings could be higher.

3 CONCLUSIONS

Energy simulations were performed on 4 different types of commercial buildings at six different locations to evaluate the energy impact of different shading devices and control strategies. Daylight simulations were performed for the medium office buildings. Different control strategies were used in different building types considering the nature of their occupancy and activities in the buildings Energy savings up to 17.7 kWh/m^2-yr was seen in medium office buildings. Daylighting result showed that while use of automated shading devices enhanced visual comfort in the space by reducing excessive illuminance (shown by reduction in ASE), it also reduced some useful amount of daylight compared to the case without any shading device. The energy savings were higher in the buildings using both shading and lighting control compared to buildings using only shading control. This was seen by higher energy savings in medium office and secondary school buildings compared to midrise apartment and large hotel. The energy savings in secondary school was in the range of 1.4-12.2 kWh/m^2-yr while in case of midrise apartment and large hotel the energy savings was below 3 kWh/m^2-yr except for the case of SG. Without integration of lighting controls, it was seen that there could be some energy penalty if appropriate strategy is not used for shading control from results in midrise apartment and large hotel.

There are several limitations associated with this study. First, we use a single type of shading device for each of the buildings, thus the impact of shading devices on building from shading devices with different properties might vary than one presented in this study. Another limitation is that for midrise apartment and large hotel very simple shading strategy is used which does not consider the variation in climatic condition, occupancy, etc. More advanced shading control strategies and the integration of shading control with HVAC controls is an area that need more exploration in the future to tap the potential of integrated controls. Integrated controls that also includes properties of shading devices and fits the needs of the occupant in different building types, while providing energy benefits and grid service potential should be studied in the future.

NOMENCLATURE

F/B	Front and Back	(–)
k	Thermal conductivity	W/m-k
kWh	Kilowatt hour	(–)
m	meter	(–)
OF	Openness Factor	(–)
R_{sol}	Solar Reflectance	(–)
T_{sol}	Solar Transmittance	(–)
VT	Visible Transmittance	(–)
W	Watt	(–)
yr	Year	(–)

REFERENCES

Ariosto, T., & Memari, A. M. (2013). Evaluation of Residential Window Retrofit Solutions for Energy Efficiency. In *The Pennsylvania Housing Research Center* (Issue 111).

Atzeri, A. M., Gasparella, A., Cappelletti, F., & Tzempelikos, A. (2018). Comfort and energy performance analysis of different glazing systems coupled with three shading control strategies. *Science and Technology for the Built Environment*, *24*(5), 545–558. https://doi.org/10.1080/23744731.2018.1449517

DRI. (2013). *Residential Windows and Window Coverings : A Detailed View of the Installed Base and User Behavior*.

Fernandes, L. L., Lee, E. S., & Ward, G. (2013). Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort. *Energy and Buildings*, *61*(February), 8–20. https://doi.org/10.1016/j.enbuild.2012.10.057

Goovaerts, C., Descamps, F., & Jacobs, V. A. (2017). Shading control strategy to avoid visual discomfort by using a low-cost camera: A field study of two cases. *Building and Environment*, *125*, 26–38. https://doi.org/10.1016/j.buildenv.2017.08.030

IES Daylight Metrics Committee. (2012). IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Daylight Metrics Committee. Approved Method IES LM-83-12. *Illuminating Engineering Society of North America*.

Kunwar, N., & Bhandari, M. (2020). *A Comprehensive Analysis of Energy and Daylighting Impact of Window Shading Systems and Control Strategies on Commercial Buildings in the United States*. https://doi.org/10.3390/en13092401

Kunwar, N., Cetin, K. S., & Passe, U. (2018). Dynamic Shading in Buildings: a Review of Testing Methods and Recent Research Findings. *Current Sustainable/Renewable Energy Reports*, *5*(1), 93–100. https://doi.org/10.1007/s40518-018-0103-y

Kunwar, N., Cetin, K. S., Passe, U., Zhou, X., & Li, Y. (2019). Full-scale experimental testing of integrated dynamically-operated roller shades and lighting in perimeter office spaces. *Solar Energy*, *186*(February), 17–28. https://doi.org/10.1016/j.solener.2019.04.069

Peng, J., & Curcija, D. C. (2017). *Energy Performance Indices EPC and EPH Calculation Methodology and Implementation in Software tool*.

Sawyer, K. (2014). *Window and Building Envelope Reserach and Development: Roadmap for Emerging*

Technologies. http://library1.nida.ac.th/termpaper6/sd/2554/19755.pdf

Shen, H., & Tzempelikos, A. (2017). Daylight-linked synchronized shading operation using simplified model-based control. *Energy and Buildings*, *145*, 200–212. https://doi.org/10.1016/j.enbuild.2017.04.021

The U.S. Department of Energy (DOE). (n.d.). *Commercial Prototype Building Models*. Retrieved April 15, 2019, from https://www.energycodes.gov/development/commercial/prototype_models

ACKNOWLEDGEMENT

We would like to thank Amy Jiron and Cedar Blazek (Commercial Building Integration Program, US Department of Energy) for the project support and review. We would also like to thank Lucy Albin (Attachments Energy Ratings Council), D. Charlie Curcija (Lawrence Berkeley National Laboratory), Brent Protzman and Craig Casey (Lutron), Alen Mahic and Kevin Van Den Wymelenberg (University of Oregon), and John Crowley (formerly Rollease), for their input and feedback at different stages of the project.