HIGH PERFORMANCE BUILDINGS: INTEGRATION OF SMART WINDOWS IN COMMERCIAL BUILDINGS

by

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ABSTRACT

RUSHANG SHAH. High performance buildings: Integration of smart windows in commercial buildings. (Under the direction of Dr. NAVID GOUDARZI)

Energy Efficiency Measures (EEM) are increasing to bridge the gap between energy supply and demand scenarios. About 70% of the electricity generated in the US is consumed by buildings alone. HVAC and lighting consume about 74% of electric load demand in a commercial office building. People, -equipment and lighting- load contribute major portion of internal load in office buildings. Building envelope of typical office building consisting of 40% window to wall ratio and meeting the minimum ASHRAE design guidelines contribute to around 33-35% thermal load except topmost floor which may be higher due to exposed roof. Except roof, windows contribute 70% of thermal load due to building envelope. Hence, need for energy efficient windows which have good thermal property for all environmental condition yet allow enough daylight in the space is important. Two types of smart windows, electrochromic glass and transparent solar glass, when used in optimum combination has potential of both, energy saving and energy generation with help of renewable energy source. The thesis focuses on reducing thermal load of the building by optimizing the window selection for building envelope based on building orientation and providing a stepping stone to smart plugin for integration of smart windows in existing energy simulation software.

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Chapter 1: INTRODUCTION

Energy has been an important part of human life. A traditional believe for basic human needs were food (including water) clothing and shelter, but humans depend on energy from the beginning[1]. Energy dependence has greatly increased over last hundred years[2], and it is estimated that electricity, demand will rise by 40% 2040[3]. “Necessity is the mother of invention” ~ Greek philosopher Plato, growing energy needs led to find new methods of energy generation and focus on renewable energy increased rapidly. In past 15 years as seen in Fig. 1[4], coal contributed to 40% of energy production in 2015[5].

Figure 1 Energy production share. Source: BP (2016) Statistical review of world energy 2016 workbook

In North America, the share of renewable energy in electricity production has from 24% to 27.7% over a period of 2005 to 2015 respectively. Thus, more efforts are necessary either to fulfill growing electricity demand or to focus on an area with higher electricity consumption and make them energy efficient.

Energy is used in many forms in various sectors of human activities. International Energy Outlook classifies energy consumption data by end use sector in three major categories[6]:

1. Buildings
2. Transportation
3. Industrial

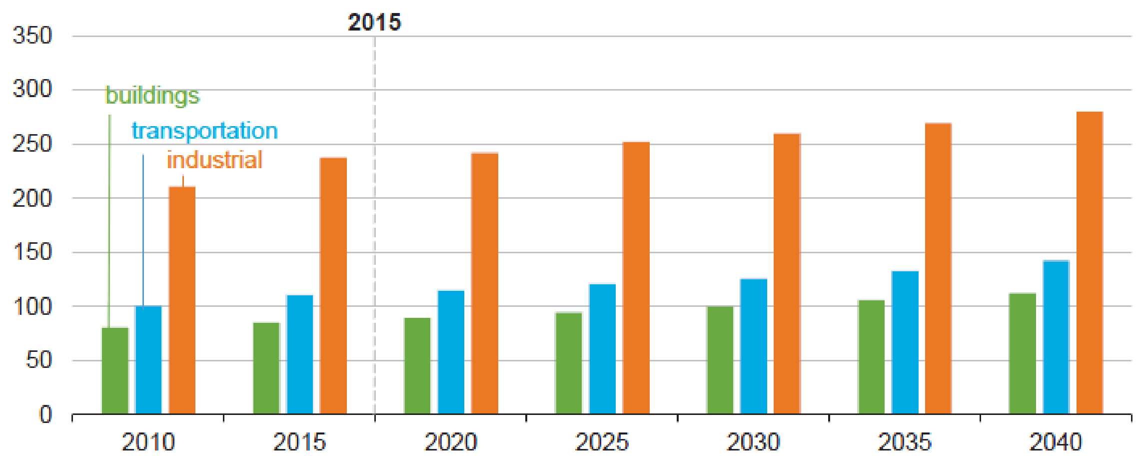

Figure 2: World energy consumption by end-use sector (Units in quadrillion BTU). Source U.S. Energy Information Administration

It is seen that projection of energy consumption by the building is around 50% for a period of 30 years. Also in 2010, 32% of total global final energy use and 19% energy-related greenhouse gas emissions[7]. Looking at sectors consuming electricity is much more consumption as efficiency in power generation and transmission is around 40% and between 8-15% respectively[8-10]. The survey conducted by U.S. Energy Information

Administration (EIA) suggests that commercial building sector consumes about 61%, office building, being major share in it as seen Fig. 3 and Fig. 4.

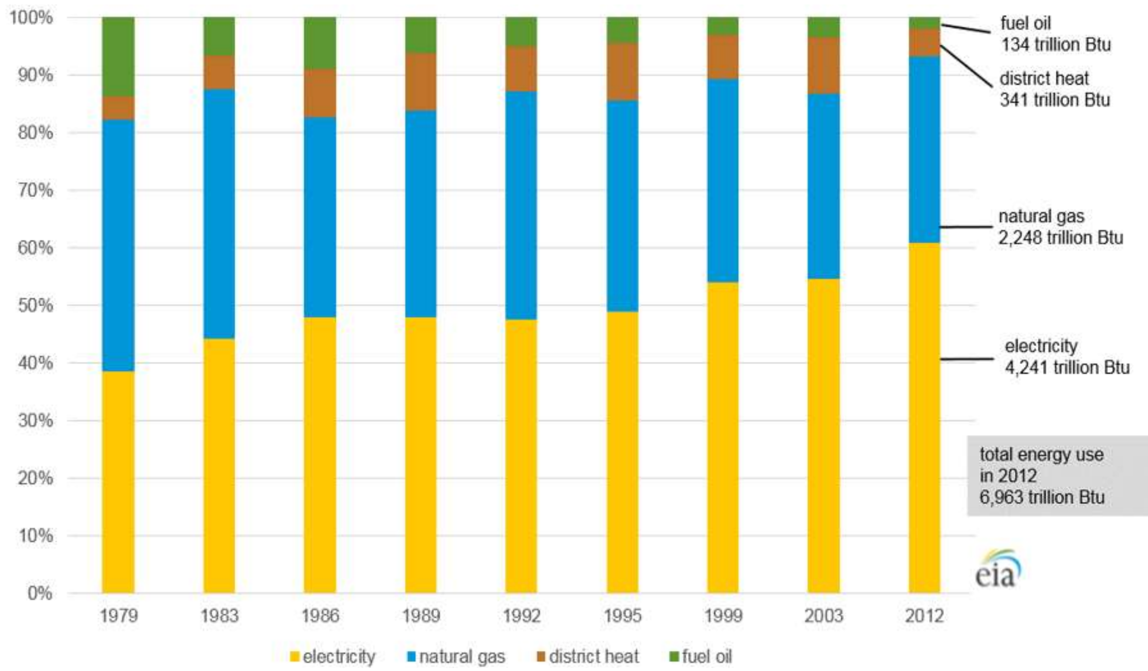

Figure 3: Commercial building consumption share, 2012. Source: U.S. Energy Information Administration (EIA)

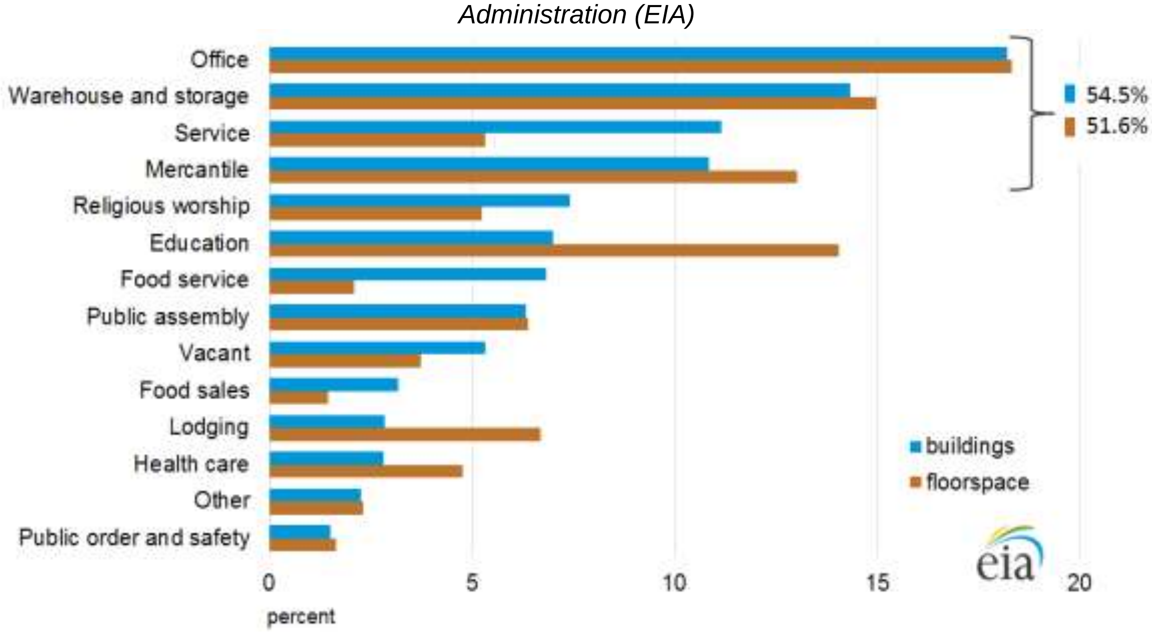

Figure 4: Building floor space share, 2012. Source: U.S. Energy Information Administration (EIA)

Commercial building data trends also suggest office space is growing larger in recent years[11] which can be seen in Fig. 5. Hence, this paper focuses research area on commercial office space.

Figure 5: Trend in commercial office space, 2012. Source: U.S. Energy Information Administration (EIA)

Energy consumption, especially electricity, by the buildings in the U.S have grown rapidly form 1950s being 25% to recent statics of 2012 shows consumptions levels as high as 76%[12]. Electricity consumption in office space are greatly varied on depending on the type of offices such as sales, designing, mixed-use, data storage, warehouses, and manufacturing yet typically Heating, Ventilation and Air Conditioning (HVAC) and Lighting are major sources of electricity consumption[12]. HVAC system is responsible for maintaining the inside thermal comfort irrespective of the varying environmental conditions. Hence, identifying the major source of heat flow will help in making the buildings, more energy efficient. According to U.S. Department of Energy (DOE), about 60% of the energy flow in the buildings occurs through the building envelope, i.e. wall, windows, roof, and foundation[12]. Table 1 shows the average heat flow for residential and commercial through the different building envelope components. From Table 1, it is observed that windows play a major role in heat flow through the building envelope.

Table 1: Energy flow in the building shell. Source: U.S. Department of Energy (DOE)

Building component	**Residential**		**Commercial**	
	Heating	**Cooling**	**Heating**	**Cooling**
Roofs	1.00	0.49	0.88	0.05
Walls	1.54	0.34	1.48	-0.03
Foundation	1.17	-0.22	0.79	-0.21
Infiltration	2.26	0.03	1.29	-0.15
Windows (conduction)	2.06	0.03	1.6	-0.3
Windows (solar heat gain)	-0.66	1.14	-0.97	1.38

(Unit: Quadrillion British thermal unit)

The heat transfer from the window affects both heating and cooling process significantly than any other building envelope entity. Hence, research on reducing the heat flow from the buildings will significantly help in reducing the HVAC load on the building system, indirectly helping in lowering the electric consumption of the buildings.

Windows is an important part of the building envelope. The purpose of the windows is not only to allow sunlight enter the building interior but also to have sufficient daylight for the occupant to keep them healthy and efficient[13]. The benefits and design guideline for proper placement and orientation of window in the buildings are also been carried out by architects[14, 15]. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has conducted numerous on building performance and after through design and actual data of building performance, the minimum standard for efficient building performance was set by them which gets updated every three years.

Geographical location and surrounding climate directly impact the heat flow into the buildings. Thus, ASHRAE has specified eight climate zone for the U.S. and the building design standards, especially for the building envelope are specified for each zone to optimize the building performance. The ASHRAE standard was used as the baseline model for these paper and further details are explained in the next chapter. The work aims at investigating the performance of smart windows in commercial buildings with an innovation of integrating renewable energy within the windows.

An Extensive literature review was conducted on software and tools capable of energy modeling and simulation of the buildings. Understanding the advantages and disadvantages of the software [16, 17] and hands-on experiences and direct contacts with experts in the field of HVAC during seminars and conferences on some of the popularly recognized software [18, 19] it was found that integrating renewable energy isn't easy or rather inaccurate to account their effect. Thus there is a need to develop a smart tool that will act as a bridging tool to integrate renewable energy into energy simulation software. Smart windows are part upcoming technology that would help in reducing the building energy consumption data. The working principle of the smart windows makes it difficult for the simulation software to conduct out energy simulation throughout the year. Hence, an integration of smart window as renewable energy to the buildings is a stepping stone for developing the smart tool. Also, list of most commonly used energy modeling software along with their advantages and disadvantages is been provided in Appendix B.

Understanding the impact of different building design on the heat flow process helps to identify the potential design changes applicable to make the buildings more energy efficient. Building energy modeling and simulation play vital role in identifying the effect of different building system variable. The first computer-aided tool for the building energy simulation was developed by ASHRAE in the early 1960s and at present, there are more than 20 different simulation packages available in the market. A brief comparison of the advantages and disadvantages of the simulation tools are been researched over past decade to help the user understand which can be suitable for them to carry on their research. This paper makes use of Carrier Hourly Analysis Program (HAP) as energy simulation tool has it is third most used software for energy simulation for Leadership in Energy and Environmental Design[18]. MATLAB and System Advisor Model (SAM) by National Renewable Energy Laboratory (NREL) were also used to cross-reference the results obtained from Carrier HAP and data from smart window manufacturer. The research aims at providing a novel solution for the building envelope design especially for windows, run a virtual simulation on energy simulation tools, and provide a stepping stone for developing an interactive plugin to incorporate the novel solution to existing simulation software.

Chapter 2: Methodology

Energy modeling and simulation can be identified as one of the key steps in making buildings efficient[20, 21]. As mentioned in the earlier chapter, building envelope design is largely affected by the geographical results. Hence, building energy codes vary from each location to location. Majority of Building energy codes are followed standards specified by ASHRAE. Energy simulation software is helpful in carrying out simulation according to building energy codes with help of inbuilt library and thus also validates and verifies that energy simulation satisfies the local energy code requirement. ASHRAE fundamental handbook also specifies the ways in which heat transfer process should be evaluated by simulation tools. Fig 6. explains different methods which can be used by simulation tool in order to perform heat transfer or energy load estimation for the buildings. It is seen that, higher accuracy also increase the complexity and thus demands higher processing capabilities for running energy simulation. Since this research concentrates on heat flow through windows, only equation pertaining to windows is been studied in depth. The ASHRAE fundamentals handbook specifies the heat flow through the window as:

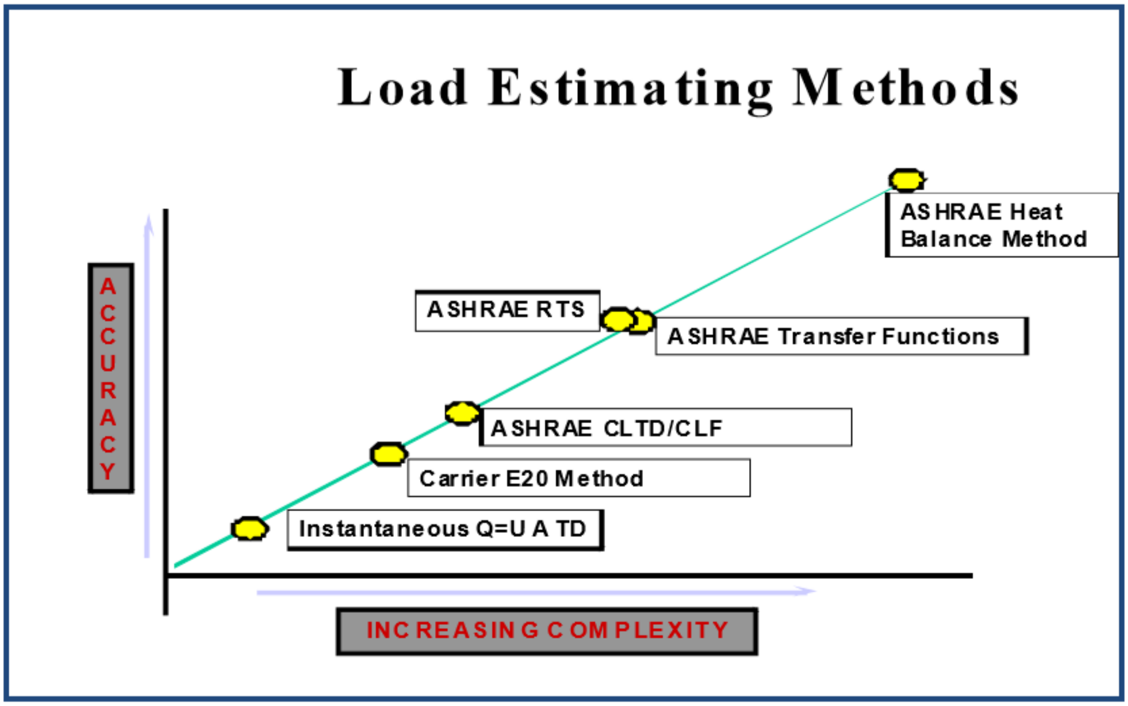

Figure 6: Different load estimation methods used by simulation software

$$Q_i = UA_{pf}\,(T_{iout} - T_{in}) + (SHGC)A_{pf}\,E_t + (AL)A_{pf}\,(\rho)C_p(T_{iout} - T_{in}) \qquad (1)$$

where,

Q_i	Instantaneous energy flow	W	(Btu/hour)
U	Overall coefficient of heat transfer	W/m^2-°K	(Btu/hour-ft^2-°F)
A_{pf}	Total projected area of fenestration	m^2	(ft^2)
T_{iout}	Indoor air temperature	°K	(°F)
T_{in}	Outdoor air temperature	°K	(°F)
SHGC	Solar Heat Gain Coefficient	-	-
E_t	Incident total irradiance	W/m^2	(Btu/ ft^2)
AL	Air leakage at current condition	1/ second	(1/hour)
ρ	Air density	kg/m^3	lb/ ft^3
C_p	Specific heat of air	J/kg-°K	(Btu/hour-lb-°F)

It is seen from Equation 1 that heat transfer through the window is through conduction, convection, and radiation as well. Also, though Equation seems to be steady state equation, it is as good as the transient equation, especially when used by simulation software. One of the main reason is that most of the heat transfer process is largely dependent on outside temperature and solar irradiance. The hourly weather data provided by NREL and Weather Bureau Army Navy (WBAN) is sufficient enough to monitor the transient changes and thus help to determine heat flow through the window into the building accurately. The Carrier HAP calculates the heat transfer through the window in two processes and they are as follows:

$$Q = UA_{pf}(t_{out} - t_{in}) \tag{2.a}$$

$$\text{TSGH} = [\text{TSGHb}(1 - \text{Fs}) + \text{TSGHd}](\text{SC})(A_{pf}) \tag{2.b}$$

$$\text{ASGH} = [\text{ASGHb}(1 - \text{Fs}) + \text{ASGHd}](\text{Ni})(\text{SC})(A_{pf}) \tag{2.c}$$

$$\text{SHG} = \text{TSGH} + \text{ASGH} \tag{2.d}$$

where,

TSGH	Transmitted component of solar heat gain	W	(Btu/hour)
TSGHb	Bean component of transmitted solar heat gain	W	(Btu/hour)
TSGHd	Diffuse component of transmitted solar heat gain	W	(Btu/hour)
Fs	Fraction of window area directly shaded from sunlight	-	-
SC	Window overall shade coefficient	-	-
ASGH	Absorbed component of solar heat gain	W	(Btu/hour)
ASGHb	Bean component of transmitted solar heat gain	W	(Btu/hour)
ASGHd	Diffuse component of absorbed solar heat gain	W	(Btu/hour)
Ni	Fraction of solar radiation absorbed by reference glass which is conducted to interior of the building. A standard value of 0.267 is used	-	-
SHG	Total solar heat gain for window	W	(Btu/hour)

It is seen that the Eq. 1 specified by ASHRAE is been split into two equation for calculation purpose. Eq. 2 is similar too as the first term of Eq. 1 which calculates heat transfer through conduction. The heat transfer through the solar component is calculated a bit differently. The simulation software used the material property and in-built library weather data set for solar radiation to calculate heat transfer process. This calculated heat transfer may vary from the results obtained from Eq. 1 because of many other variables involved and use of transfer function equations.

The paper focuses on using smart windows to replace an existing or upcoming commercial office buildings. There are many smart windows techniques available [7, 22-24] and selecting one for the purpose of research depends on understanding how different smart windows work. They are as follows:

1. <u>Electrochromic Windows:</u> Window with electrochromic glass which darkens or lightens itself when applied with an applied potential difference to it.[12, 24-28] as seen in Fig 7.
2. <u>Thermochromic Windows:</u> Windows with thermochromic glass which changes its state when coming in contact with heat i.e. layer that activates when a certain amount of temperature rise occurs in it.[26, 29-31] as seen in Fig. 8
3. <u>Thermotropic Windows:</u> Windows with thermotropic glass which works similar to thermochromic glass the only difference is it diffuses the light transmitted by glass completely rather than turning glass to semitransparent state [32-34] and the difference between both the glasses can be seen in the Fig. 8 and Fig. 9.
4. <u>Photochromic Windows:</u> Windows with photochromic glass that changes from clear state to colored state when exposed to light[24, 35] automatically and it cannot be controlled.
5. <u>Liquid Crystal Device Windows:</u> Windows with liquid crystal layer which turns translucent milky white when applied with electric current.[23].

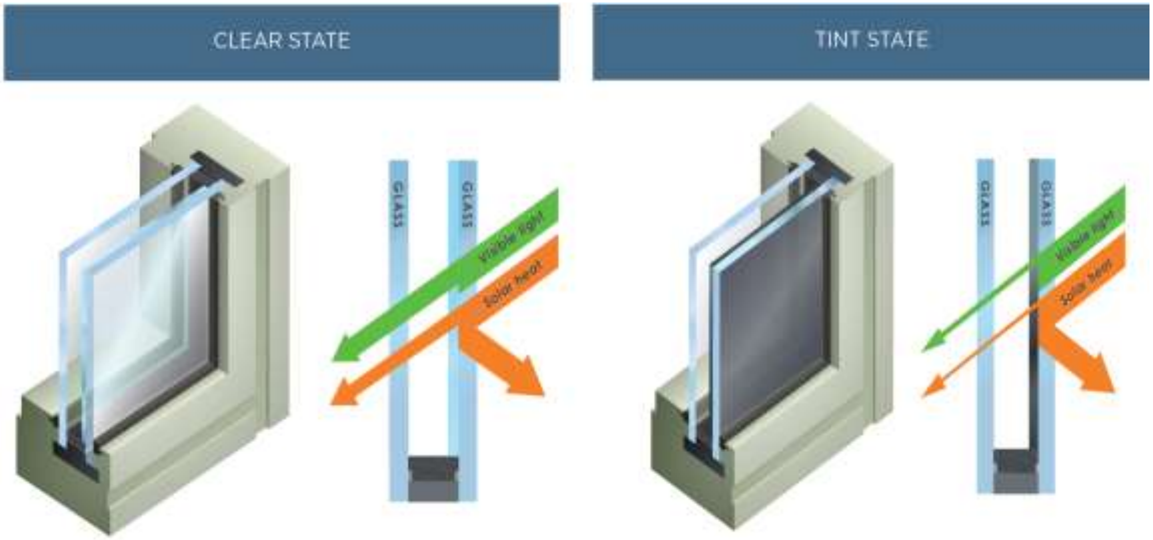

Figure 7: Window with electrochromic glass. Source: VIEW Dynamics Glass Inc. datasheet

Figure 8: Effect of temperature on the thermochromic glass[23]

Figure 9: Effect of temperature and light diffusion through thermotropic glass[23]

There is another type of smart window which uses solar glass layer [36-40]. The solar cell layer is semitransparent and can generate electricity like a photovoltaic cells. As this research is focused on making building more efficient and integrating solar windows seems plausible choice. The experimental results of solar windows [39-46] that replacing solar glass in the windows could not only generate power but also result in reducing thermal load inside the space by as high as 30%. Also, from the above list of smart windows, thermochromic and thermotropic diffuses the light based on temperature difference hence cannot have human control. Similarly, photochromic windows are light dependent with no proper means of controlling its state. Liquid crystal display windows allow better control capability then thermochromic, thermotropic and photochromic window, though their translucent state transmission of daylight in the interior space of the building. As mentioned in chapter 1, about the importance of daylight and health and productivity of the occupant, and the window being a vital part in bringing daylight, constant fluctuation of liquid crystal windows will decrease the efficiency of the windows in transmitting daylight through them. Electrochromic windows, on the other hand, are able to transmit the daylight through its tint state in a diffused manner yet more efficiently than liquid crystal window. Thus, this paper's research concentrates more on solar glass windows and electrochromic windows and how to efficiently integrate them into commercial office buildings.

Solar glass windows: The working principle is of a solar glass is similar to photovoltaic cell except it allows sunlight to transmit through itself rather than blocking it completely a seen in Fig. 10. The details of the different layers of the solar glass windows are described in Table 2. The topmost row in Table 2 is the layer which is directly in contact with outside environment and subsequent rows are inner layers with the last row to be inside the building space. The use of iron glass has increased greatly after an increase in photovoltaic cells use as an alternate source for generating electricity[47, 48]. Reducing initial green tint and providing ultra-transparency than clear glass helps to direct maximum sunlight to inner photovoltaic layer, thus indirectly making power generation process efficient. It can be seen how different material composite the solar windows and provide and the translucent photovoltaic cell capable of generating power and reducing the thermal load on the building.

Table 2: The different layers of solar glass window manufactured by Solaria[49].

Description	**Thickness (in mm)**
Low Iron Glass	5
Interlayer (acts as a spacer)	0.5
Solaria PV String	0.5
Interlayer (acts as a spacer)	0.5
Clear glass	5
100% Airspace gap	11
Clear glass	5
Total	**27.5**

Figure 10: Solar glass with regular glass in the window[49]

<u>Electrochromic windows</u>: The concept of using of electrochromic glazing was developed more than two decades ago yet technology lagged commercial large-scale use of electrochromic glazing[50]. As seen in Fig. 7 right side is outer most layer in direct contact with outside environment. Most of the times clear glass are used as opposed to low iron glass in the solar window. This is to the fact that, electrochromic windows main purpose

is to reduce thermal load transmitting through it thus, having less transparent outer layer is more advantageous. The inside of outer layer glass is been coated with electrochromic materials. This organic material is transparent in a normal state and when the potential difference is applied to it, they change from transparent to semi-transparent or colored state depending on the material composition and amount of current passed through it. There is a gap between two layers of glass similar to the solar window with the difference being, this gap could be with numerous transparent, low conductivity fluids. Recent research and experimental analysis of electrochromic glass in the windows have shown to reduce the thermal load inside the building by a significant amount [51, 52].

By analyzing the different types of solar windows and aim of the research to be making building more energy efficient and also to integrate renewable energy in an effective manner, discovering a method to optimize the use of both solar and electrochromic windows serves the methodology and results of this work. Electrochromic window alone, being effective, still increases the building electric consumption has it needs constant current flowing through it to perform thermally better. Solar windows are similar to other photovoltaic cells available in the market, i.e. a large number of photovoltaic cells are needed to implement their positive impact on energy generation thus increasing not only the initial capital investment but also demands rigorous changes in the building design to accommodate space usage by them. Hence, this work puts forward a novel solution to integrate both solar and electrochromic windows in an optimum manner and serve the main objective of achieving saving energy consumption by employing alternate power generation source.

WINDOWS software by Lawrence Berkeley National Laboratory (LBNL) helps to find the U-value and SHGC for the whole window which may not be available all the time for the window manufacturer. The two smart windows used in this paper were been modeled in WINDOWS software layer by layer and their U-vales and SHGC are been documented by manufacturers[49, 53]. Different types of double pane windows too were modeled in WINDOWS software in order to refer exact same values as specified by ASHRAE standards. The research paper about the impact of building orientation system loads[19], the effect of windows in heat transfer was clearly demonstrated and served as a reference for choosing the energy modeling environment. Some of the assumptions followed by simulation process are as follows:

- The location for simulation is Charlotte, North Carolina, United States.
- The location falls under ASHRAE climate zone 3A. Thus the building envelope was modeled by reference to specification related to climate zone 3A[54, 55].
- Latest weather file TMY3 available from NREL website is used for simulation.
- All the factors account for building thermal load were modeled as specified in the standards[54, 55], but only load contribution from windows is taken into focus in the following chapter.
- The office building was distributed in core and perimeter zone with perimeter zone depth of 4.5m (15 feet) as specified in ASHRAE standards.[56].
- The occupied cooling set point is at 75℉ and heating set point is at 70℉ whereas unoccupied cooling set point is at 80℉ and heating set point at 65℉ respectively.
- Thermostat and lighting schedules were adopted from ASHRAE 90.1 which is available default in the Carrier HAP library as well.

Following procedure followed for in different software to analyze the impact of smart windows in the office buildings.

A. Carrier HAP

As stated earlier load estimation results for the window in Carrier HAP are analyzed. The electrochromic window having dynamic properties does not allow proper load estimation when the simulation occurs for the whole year. Thus each hour of each month was analyzed individually. The SHGC of the electrochromic window was altered manually in such a way that overall heat transfer through the window is minimized. Verification of heat load estimation will help to automate the SHGC value of electrochromic glass by calculating each value and select a value such that the heat transfer would be minimum. Carrier HAP provides and average hourly load estimation for each month. Though it also provides detailed results, average load estimation was accounted.

B. MATLAB

Load estimation carried out in MATLAB is based on the heat transfer equation defend by ASHRAE in Eq.1. Carrier HAP equation could not be used as they are dependent on many other inputs from various building envelope and such information is not available from software programmer. Thus, MATLAB code calculates the heat transfer through the window as an independent component. The solar irradiance data acquired from NREL website for different orientation is a monthly average. The above two mentioned difference is the main reason for obtaining different output result from the MATLAB and Carrier HAP. Nevertheless, if potential energy saving is similar in both the cases, it indicates that the MATLAB code works in a similar way for load estimation and hence can be used to program to perform the overall energy simulation with smart windows.

C. SAM

The datasheet from solar glass manufacturer provides details for the photovoltaic cell in the window. This data was used in SAM to calculate the actual energy generation that is possible from the solar window. All the windows in the floor are assumed to be connected to single module and have a common inverter. The inverter size was selected based on maximum power that can be generated from the window under normal test lab conditions. The efficiency of inverter and losses occurring the power generation were set as default in the SAM and monthly energy generation was results were analyzed. Below is the flow chart for the methodology which is applied for the research.

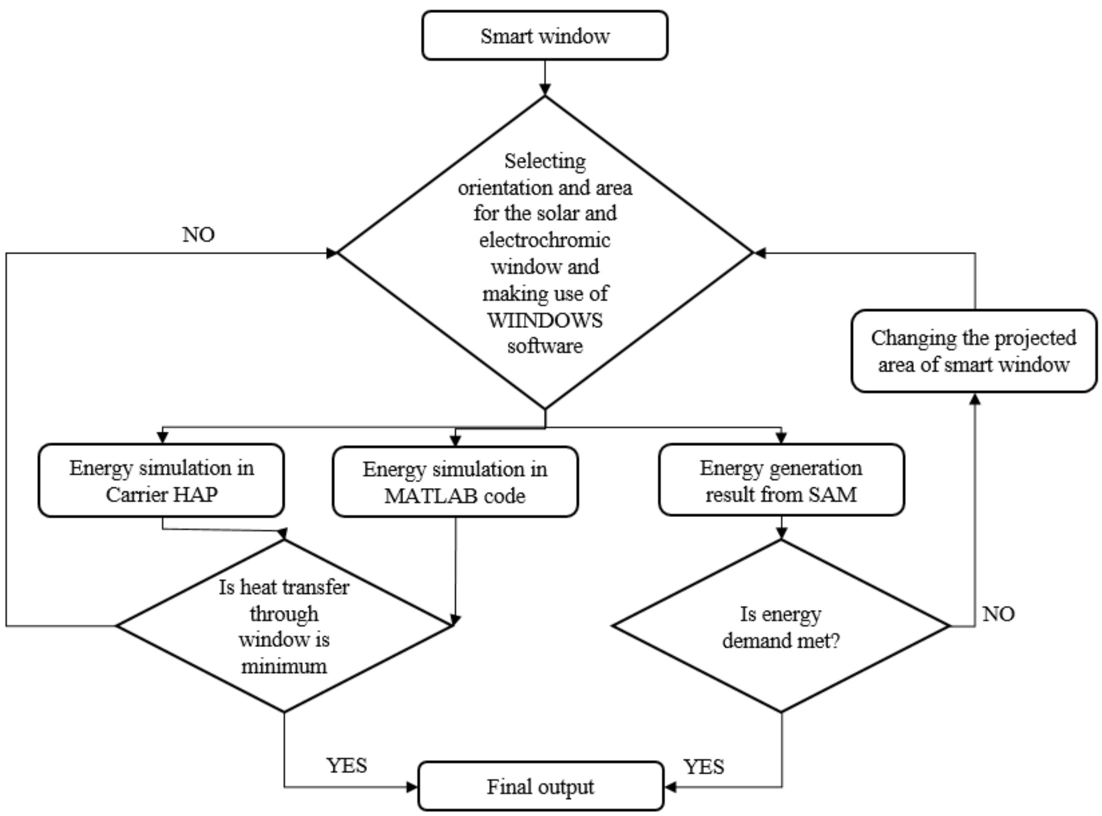

Figure 11: Flow chart for simulating smart windows into the building energy simulation software and plugin tool

As we discussed earlier, electrochromic window and solar window are selected as a smart window. They are been designed in WINDOWS software layer by layer to obtain its thermal property. These property is required by energy simulation software to estimate heat load calculation through the windows. The heat load estimation is also carried by MATLAB code to verify and help develop plugin tool for the smart windows. Optimum heat transfer process is calculated through the code and verified by the software. If it does not matches the selection process is carried out again by changing window area and orientation and checked again until the target is achieved. Similarly, energy generation through the solar window is run through SAM and based on energy consumption need of electrochromic window and/or desired by the user, the area of the solar window can be optimized to achieve targeted energy generation rate. Finally, the results from both the software will provide estimated energy reduction and generation achieved through a smart window and help towards modeling plugin tool to integrate smart window into the simulation software.

Chapter 3: Results and discussion

The results obtained from the Carrier HAP were analyzed to detail of heat transfer through each and every component of building envelope of the virtual office building. Since the performance of smart windows needs to be compared with ASHRAE recommended window, only south and west orientation results are thoroughly diagnosed. Graphs of only four months, i.e. January, April, August, and October are displayed further in this section while tables for all the months is provided in the Appendix B. These four months are selected based on the variation of different heat transfer occur throughout the monthly cycle. January and August show maximum heat transfer during winter and summer season respectively whereas month of April and October shows characteristic of change in season during the year. This analysis helps in analyzing the year round as well as seasonal impacts on the smart windows. The values seen negative in the graphs indicate heat transfer from the office space to the outside stating that HVAC systems need to be operated in the heating mode whereas positive values indicates heat entering into the office space stating that HVAC systems need to run on cooling mode in order to maintain the indoor conditions.

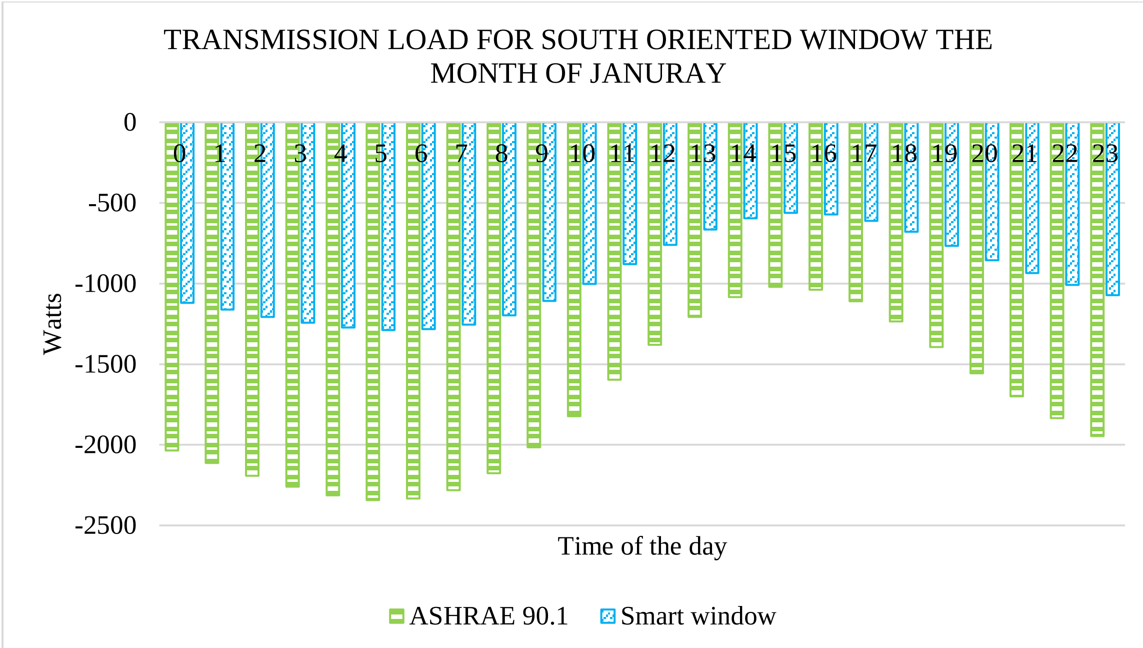

Figure 12: Average transmission load for the month of January for south oriented window

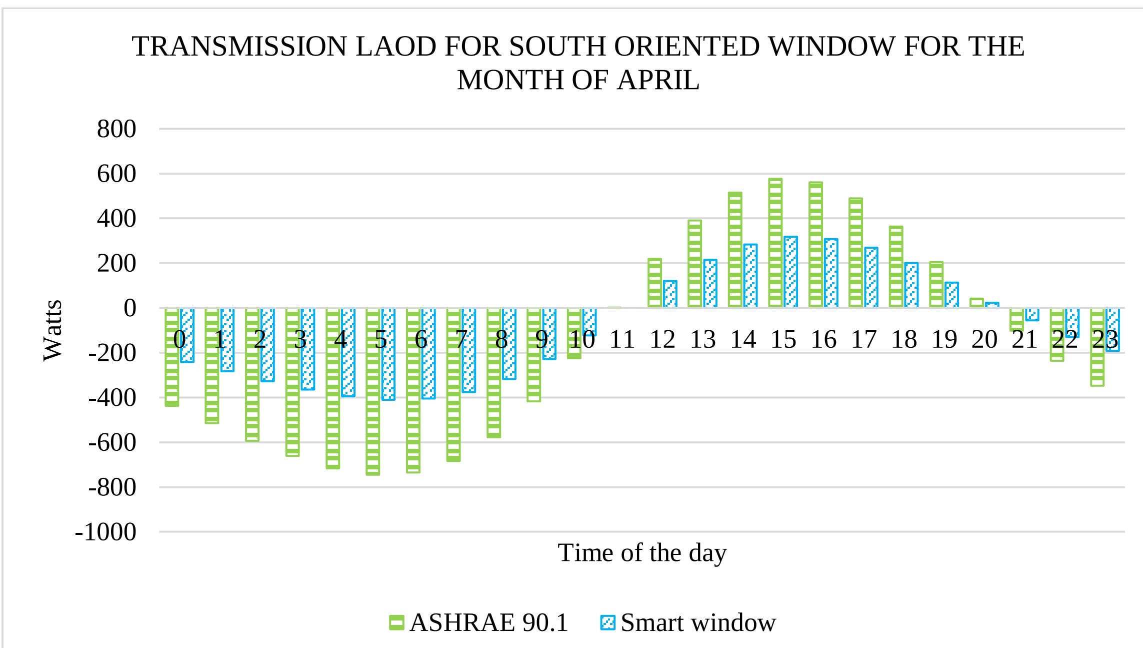

Figure 13: Average transmission load for the month of April for south oriented window

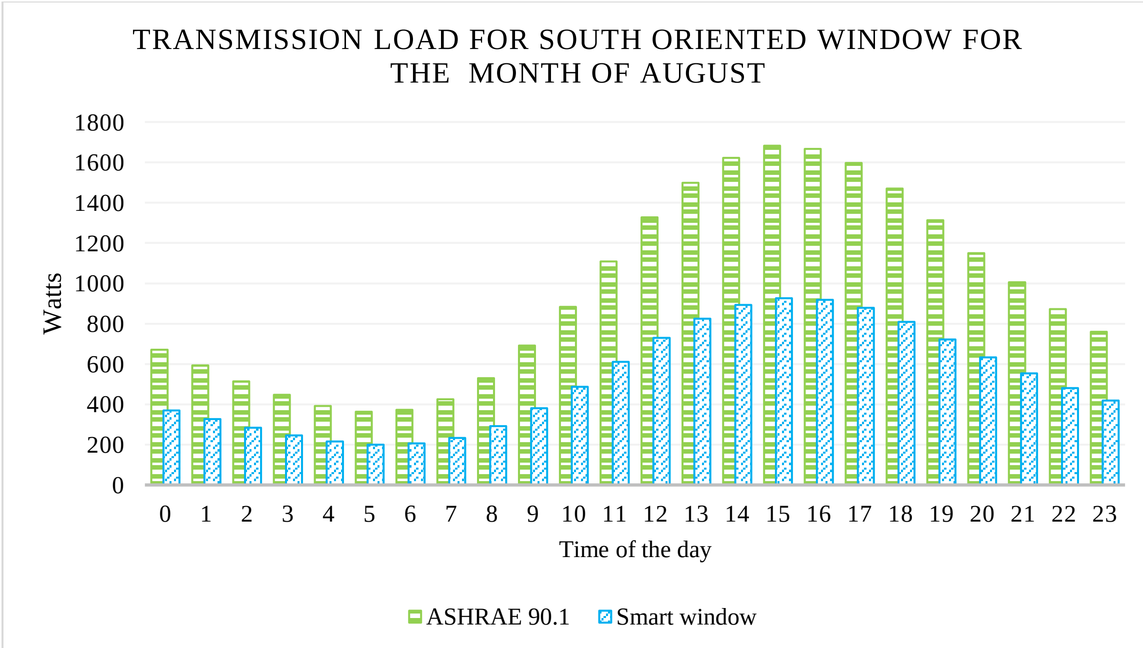

Figure 14: Average transmission load for the month of August for south oriented window

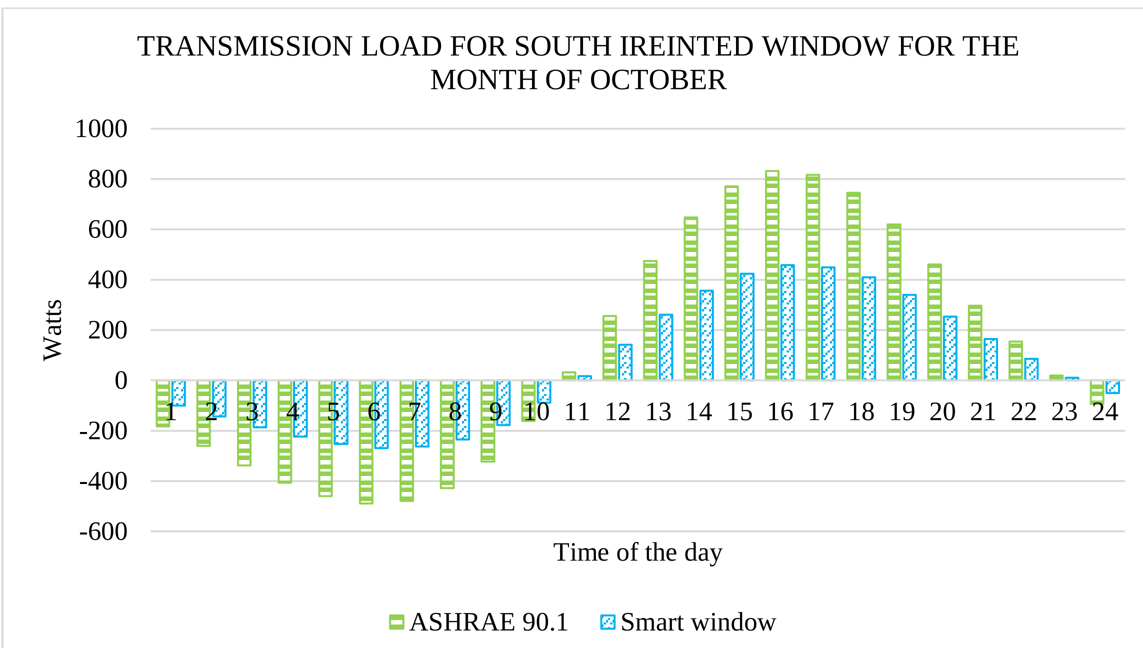

Figure 15: Average transmission load for the month of August for south oriented window

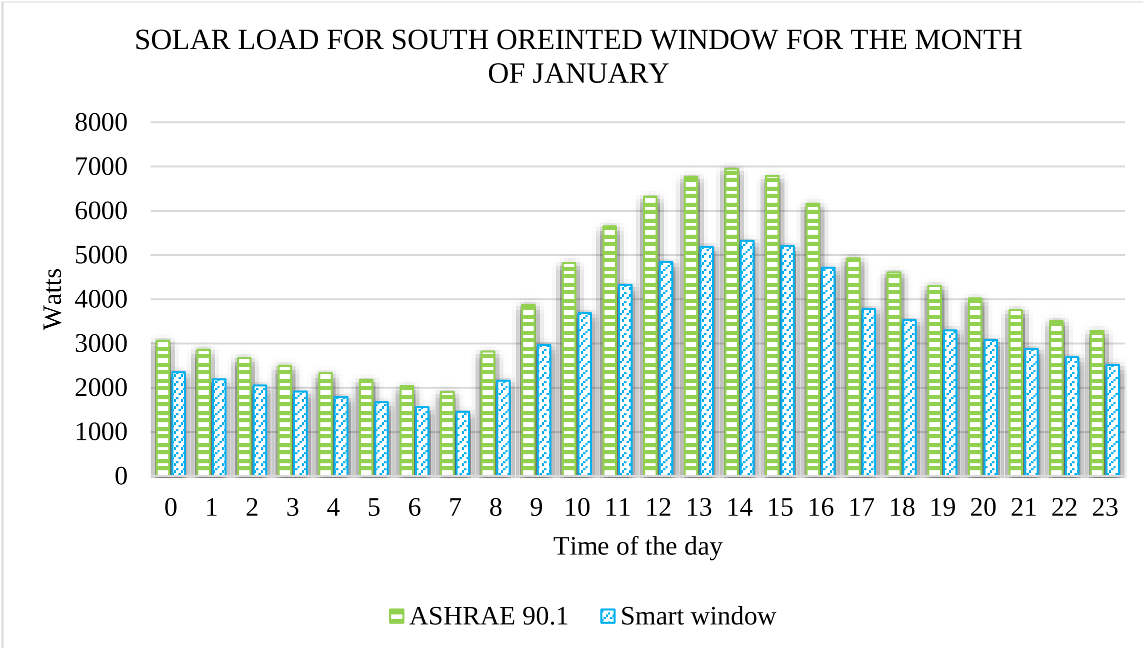

Figure 16: Average solar load for the month of January for south oriented window

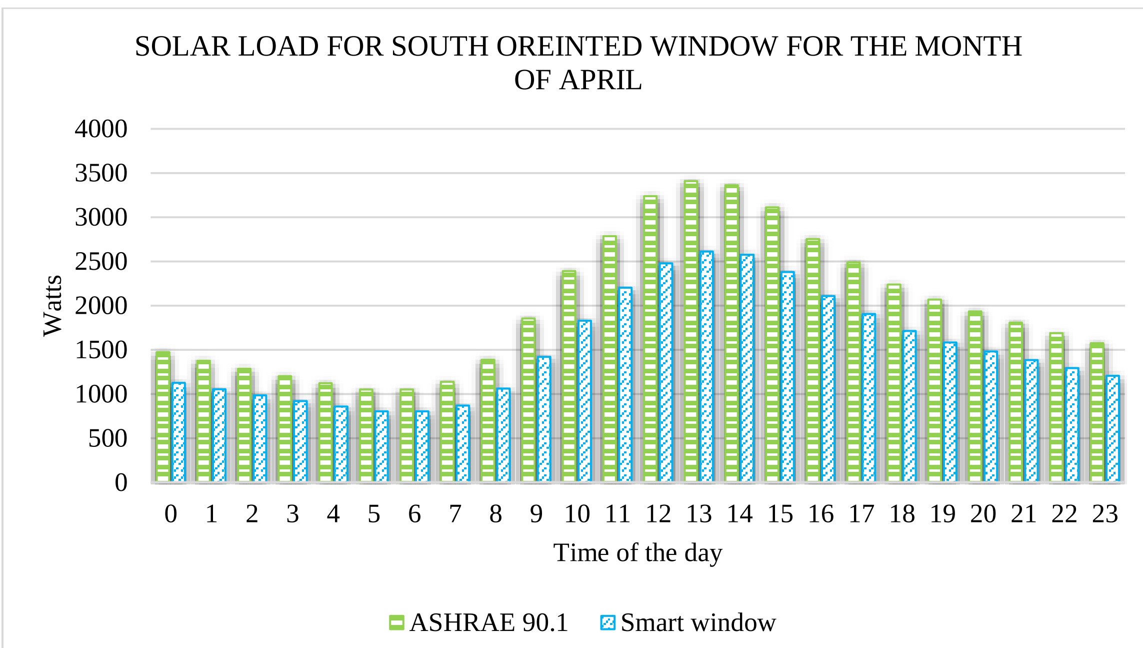

Figure 17: Average solar load for the month of April for south oriented window

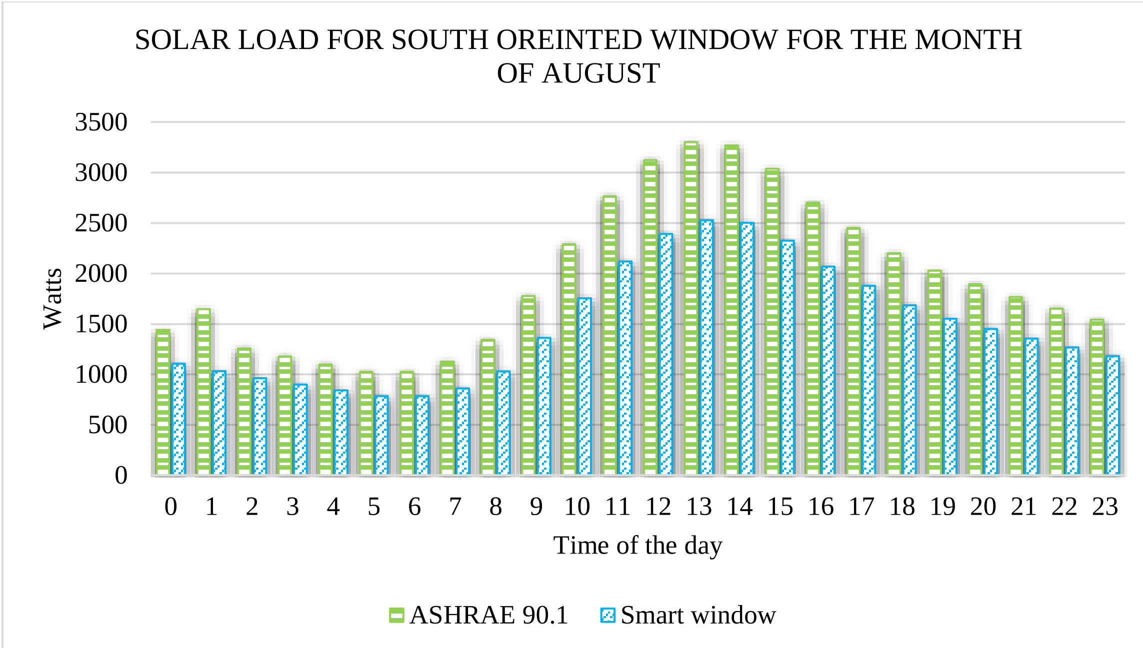

Figure 18: Average solar load for the month of August for south oriented window

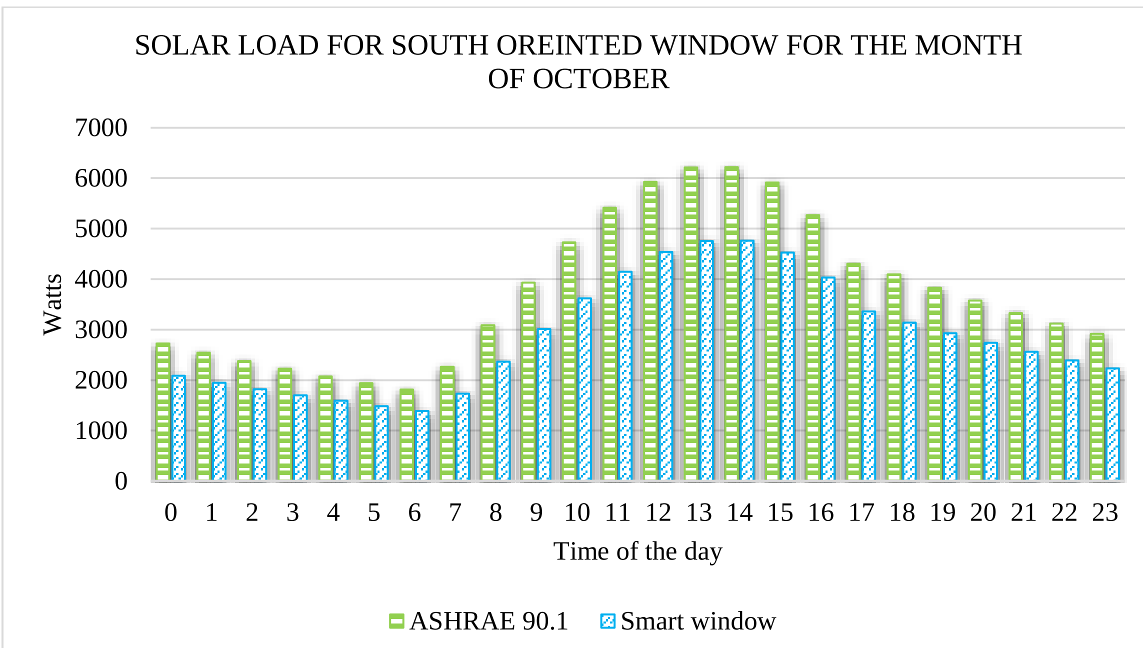

Figure 19: Average solar load for the month of October for south oriented window

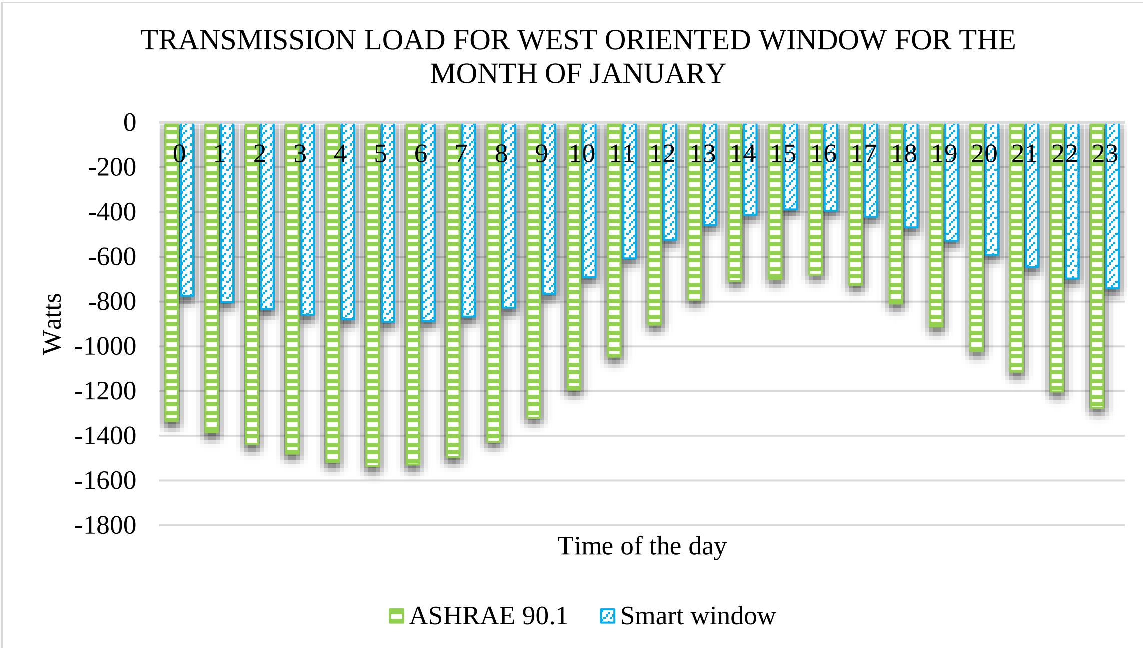

Figure 20: Average transmission load for the month of January for west oriented window

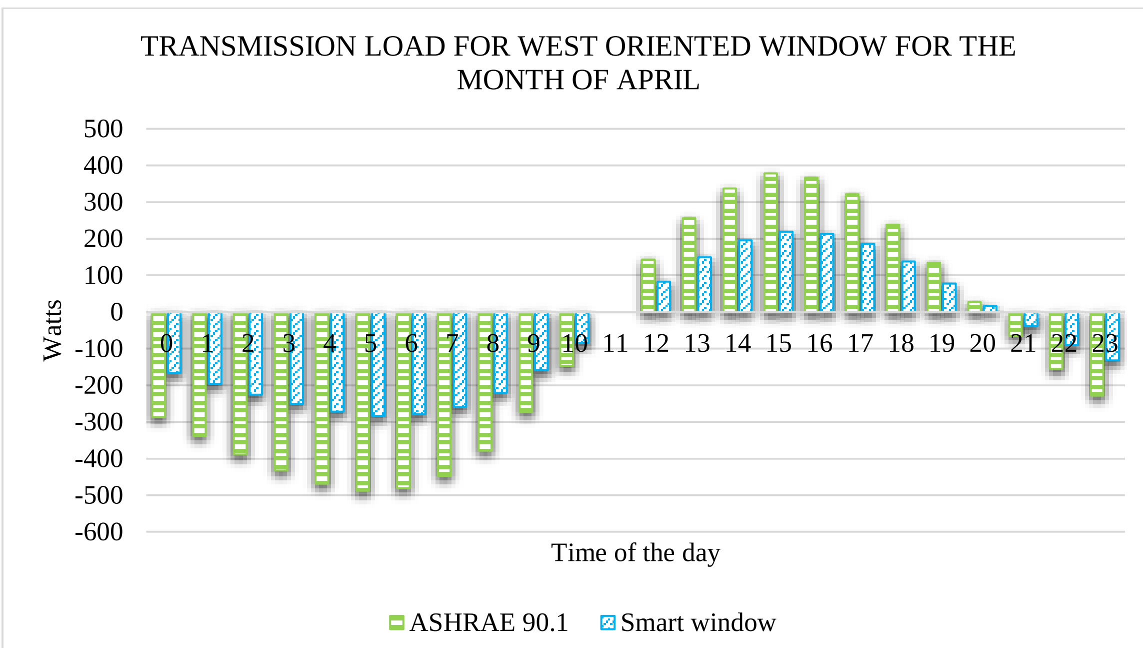

Figure 21: Average transmission load for the month of April for west oriented window

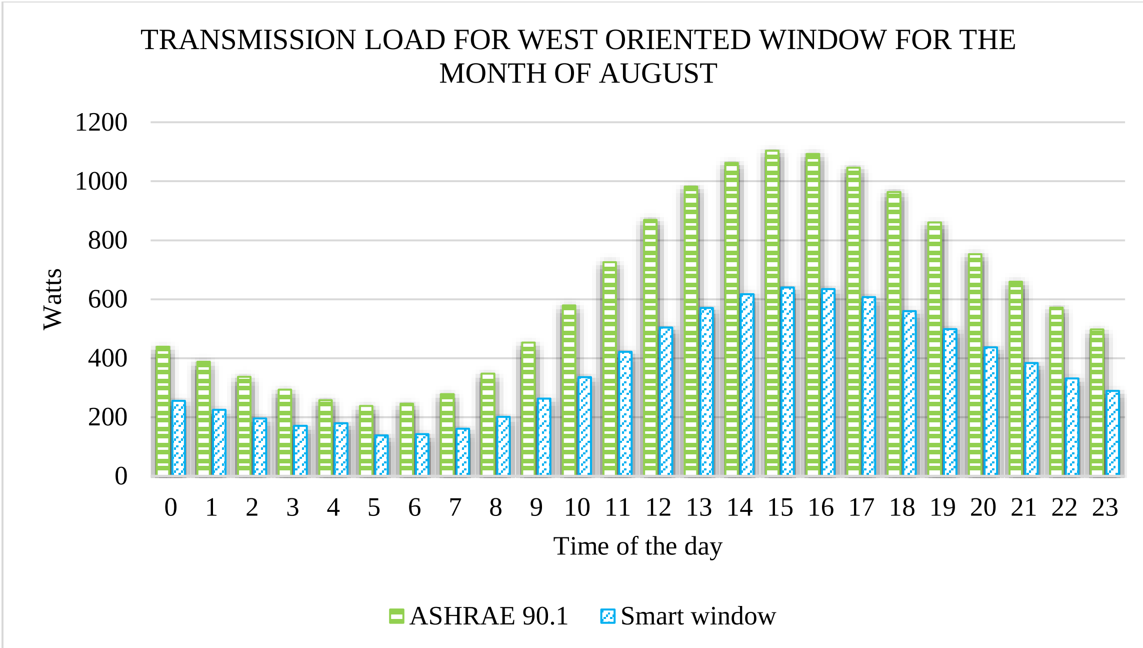

Figure 22: Average transmission load for the month of August for west oriented window

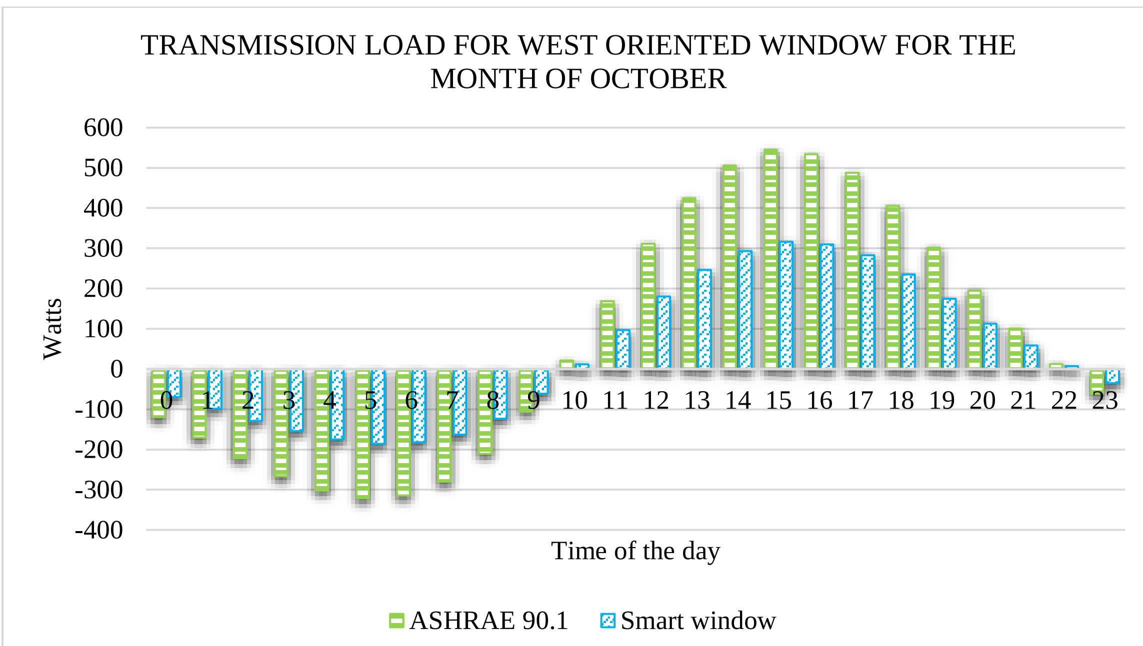

Figure 23: Average transmission load for the month of October for west oriented window

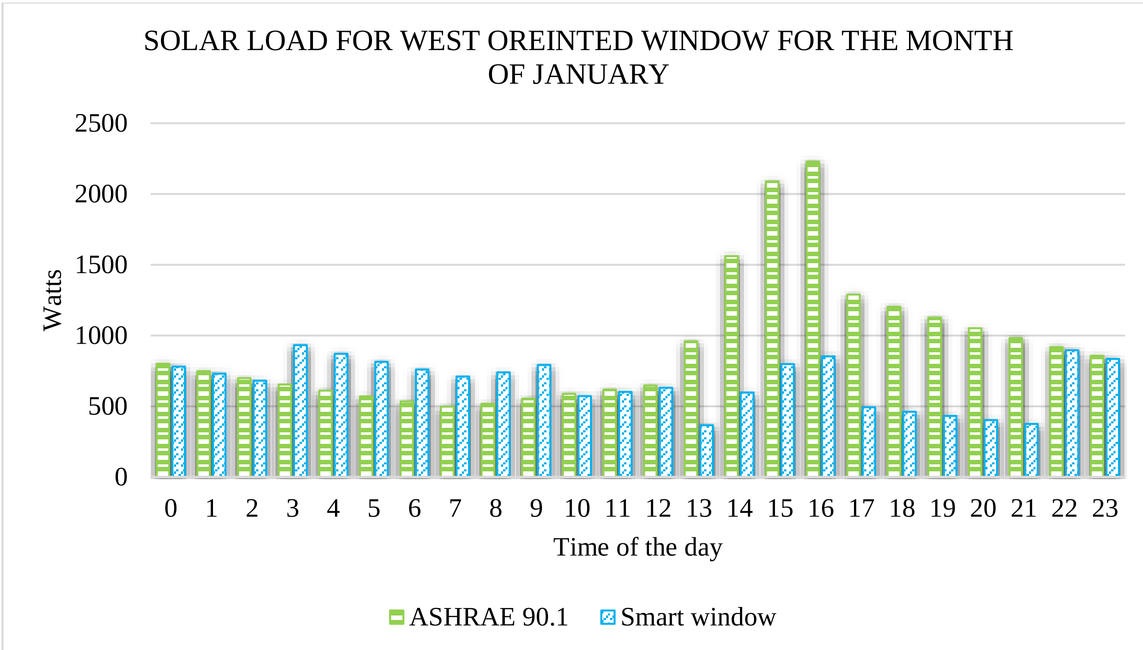

Figure 24: Average solar load for the month of January for west oriented window

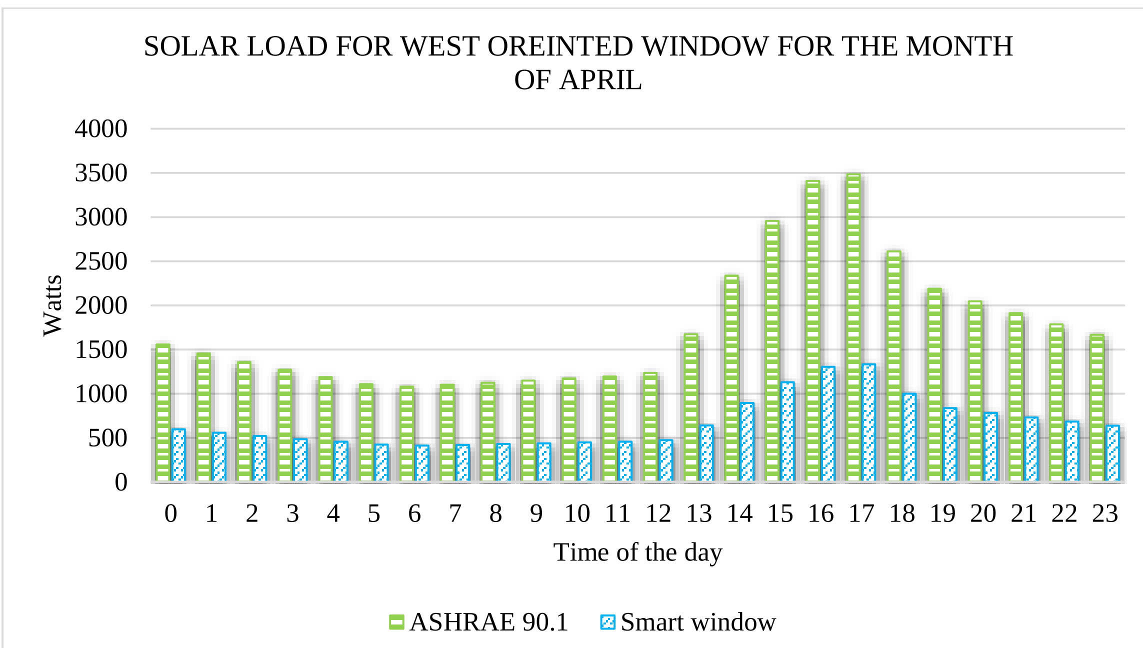

Figure 25: Average solar load for the month of April for west oriented window

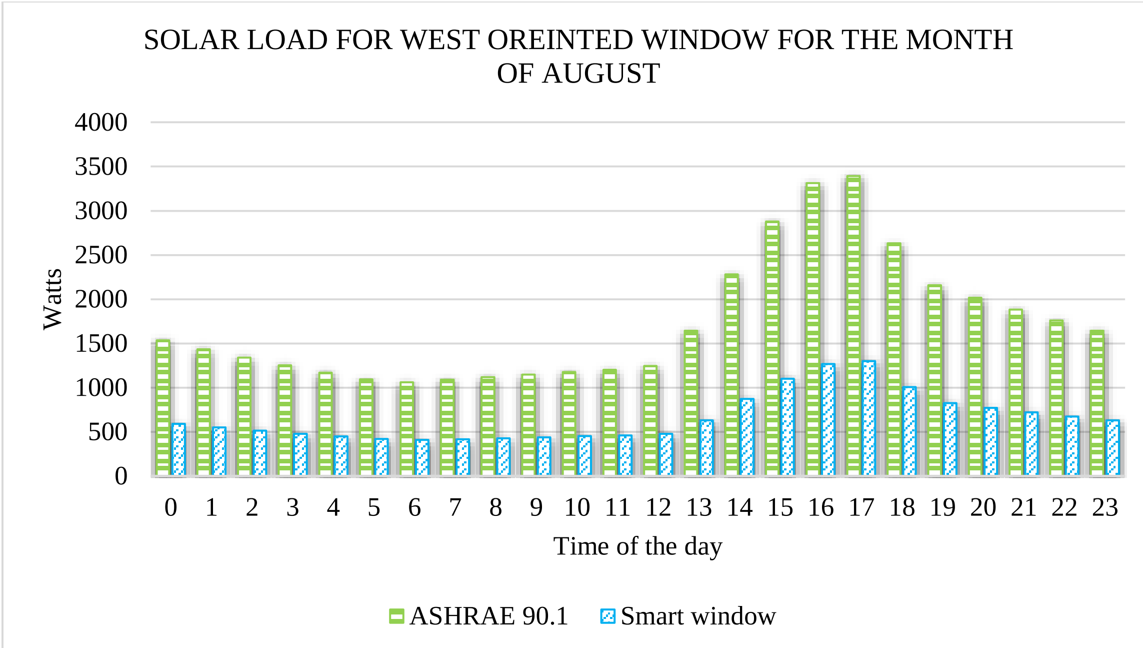

Figure 26: Average solar load for the month of August for west oriented window

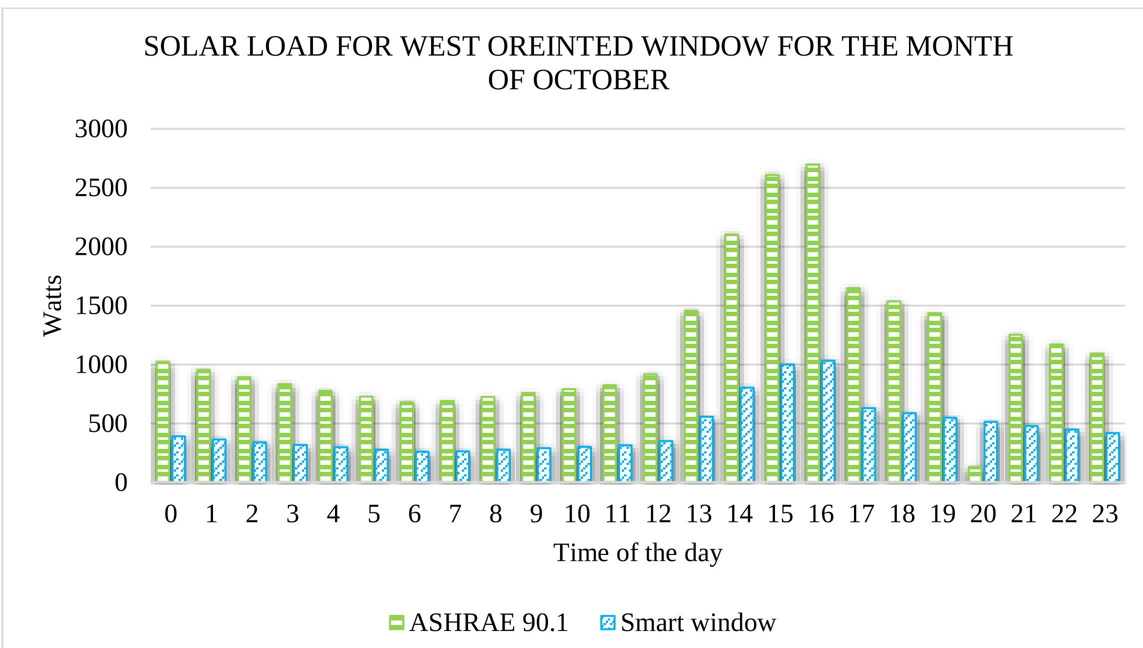

Figure 27: Average solar load for the month of October for west oriented window

From the graphs, we can certainly see that significance of U-value and SHGC on the glass of the window. The U-values impact lost during winters or HVAC heating mode while SHGC plays a vital role in blocking heat in the summers or HVAC cooling mode as described in *ASHRAE Fundamentals Handbook*[56] and verifies by the pattern of the graph. The table below summaries the overall heat transfer for the south and west oriented windows. The heat loss or heat gain were separated by summing up the average heat gain per hour of each month. The actual values may be referred by referred from the table listed in the Appendix B. Note that, heat transfer through the solar load is always positive even in winters.

Table 3: Overall average hourly simulation of heat transfer through the window of the virtual office building

Orientation	**Transmission Load**		**Total**	**Solar Load**	**Overall Total**
Unit (watts)	**Heat loss**	**Heat gain**		**Heat gain**	
ASHRAE 90.1					
South	-151076	93274	-57802	805401	747599
West	-99401	61101	-38300	415510	377210
Smart Windows					
South	-83651	51316	-32335	644506	612171
West	-57642	35431	-22211	181522	159311

The data shows that even just by comparing the average hourly data, smart windows are able to reduce the at least **40%** of transmission load of the window. While for solar load, south orientation shows about **18%** saving while, west orientation indicates around **56%** heat load reductions. The heat load reduction is less in the southern orientation because heat transfer is needed for photovoltaic cells to generate energy. One thing to note is that the results are design results. That is it does not perform actual simulation but calculate heat transfer based on design day conditions. This means Carrier HAP have simulated this results with assuming worst case scenario and we can be positively sure that the actual simulation will also result in a similar pattern. The results from MATLAB code also shows a similar pattern. The whole purpose of MATLAB code is to verify the heat load distribution pattern with existing simulation software and hence can be further developed to use as a smart plugin. Note that, both MATLAB and Carrier HAP results are based different temperature profile. This is because of the fact that, Carrier HAP uses inbuilt temperature data from its library for Charlotte location during design load calculation for each hour of the month by following transfer function equation and uses weather file only during simulation estimation. The MATLAB code extracts data from the TMY3 weather file for Charlotte obtained from DOE website and calculates heat transfer for each hour of each month of the year by following ASHRAE method described in Eq. 1. Thus there will be the difference in actual numerical value but if the pattern of heat transfer is same it proves that MATLAB code can be further modified by integrating it with software calculation method and thus help in integrating smart window in energy simulation estimation.

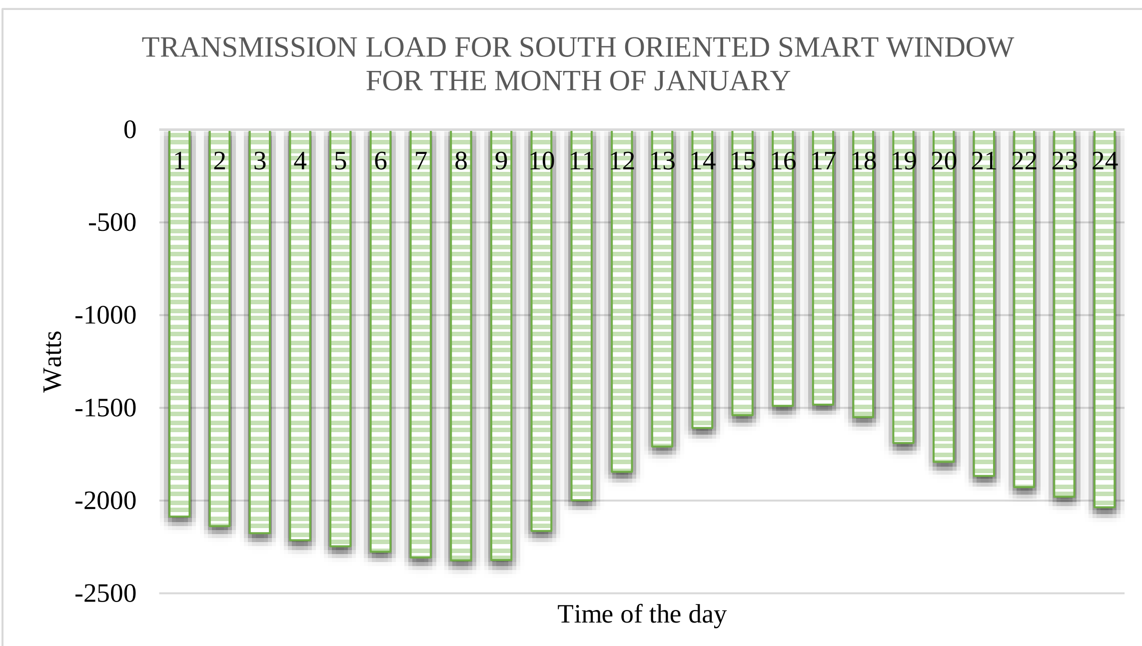

Figure 28: Average transmission load for the month of January for south oriented window. Results are generated using MATLAB code

From Fig. 11 and Fig. 27 we can see that load transmission profile is similar. This verifies that MATLAB code can be successfully used to integrate smart window with energy simulation software. The part of the research aimed at verifying whether the combination of solar window and the electrochromic window can self-sustain themselves without any need of external power demand. The results from the SAM for energy production for the solar window for each floor can be seen in the graph and table below.

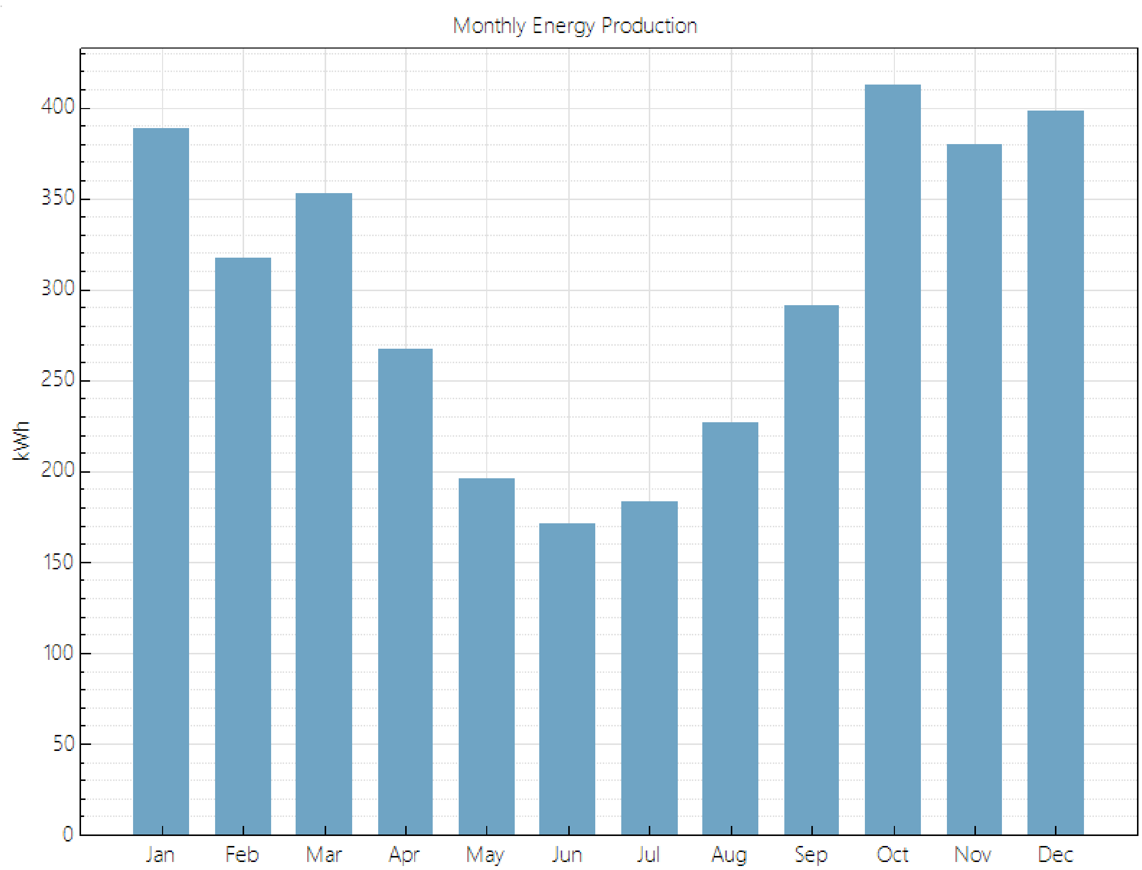

Figure 29: Monthly energy production for a solar smart window for each floor of the window

The energy production is maximum during winters rather than summer which is a usual trend in photovoltaic cells. This is because the solar window is mounted on the wall of the office building thus giving fixed tilt angle of 90° and provides such energy production pattern. The amount of energy consumed by the electrochromic window yearly assuming active all year round which makes it maximum energy case. Thus total amount energy consumed my electrochromic window for each floor of the window of the office building and shown in Table 5.

Table 4: Monthly energy production from all the solar windows for each floor of the building.

Month	PV array DC energy	System AC energy
(Unit)	kWh/month	kWh/month
January	411.52	388.59
February	336.60	316.98
March	375.46	353.11
April	287.01	267.60
May	213.79	195.97
June	188.10	171.08
July	199.65	182.83
August	244.77	226.51
September	311.00	291.09
October	436.52	412.25
November	402.42	380.07
December	421.25	398.02

Table 5: Energy requirement for the electrochromic window

Description	Value	Unit
Area of the window on each floor	44.37	m^2
	478	ft^2
Energy requirement for the window	33	mW/ft^2
Total energy requirement for each floor	15.77	W
Total energy for the overall year	138.15	kWh

From Table 4 and Table 5, it is seen that amount maximum amount of energy consumption by the electrochromic window is still lower than minimum energy generated by solar windows. Thus, the energy consumption can be completely fulfilled by the year round.

Chapter 4: Summary

Understanding the importance of energy, its current and upcoming needs and major end usage in different forms, the research aimed at reducing the energy consumes in the commercial office building. The major two purpose was to establish a method to integrate renewable energy and smart windows in order to reduce energy consumption. The results from energy simulation software Carrier HAP shows the combined use of two smart windows and potential overall load reduction of **10%-25%** depending on its use. The research also verified that MATLAB code will initiate development of a smart plugin for renewable energy and smart windows into the simulation software. It also possible to program it in such way that use of a number of solar window and the electrochromic window can be optimized in both, technical data and power generation as well as economic variable as well. Possibility of obtaining proper weather information will give more insight about the actual comparison between energy simulation software and MATLAB code and help us make necessary changes if possible to make code closer to actual estimation results. These are the future work of the research that needs to be further explored and to benefit the idea of integrating smart window in commercial office and expand it to all building types. This is with the bigger aim of achieving overall energy consumption by the building sector.

Appendix A: Simulation results

The following tables summarize the result of heat transfers form south and west orientation for an average hour of each month from Carrier HAP. The negative sign indicates heat transfer from the office building to the surrounding and positive sign indicates heat transfer into the building from the surroundings. The nit of heat transfer is watts and time displayed in 24-hour clock.

ASHRAE 90.1 recommended window on south orientation						
Time	July		August		September	
	Transmission Load	Solar Load	Transmission Load	Solar Load	Transmission Load	Solar Load
0	670	1035	670	1443	330	2196
1	593	967	593	1648	252	2051
2	514	904	514	1259	173	1916
3	447	844	447	1177	106	1791
4	392	789	392	1099	51	1673
5	363	737	363	1027	22	1563
6	373	804	373	1026	32	1468
7	424	914	424	1127	83	1728
8	530	1033	530	1343	189	2292
9	691	1241	691	1777	350	2987
10	884	1577	884	2291	543	3683
11	1109	1916	1109	2767	768	4290
12	1327	2169	1327	3123	986	4744
13	1499	2280	1499	3301	1158	4989
14	1623	2231	1623	3269	1282	4985
15	1684	2068	1684	3038	1344	4714
16	1668	1927	1668	2704	1327	4215
17	1597	1808	1597	2453	1256	3645
18	1471	1640	1471	2202	1130	3301
19	1313	1454	1313	2027	972	3084
20	1150	1359	1150	1894	809	2882
21	1006	1270	1006	1769	666	2692
22	872	1186	872	1653	531	2515
23	760	1108	760	1544	419	2350
Total	**22960**	**33261**	**22960**	**46961**	**14779**	**71754**

ASHRAE 90.1 recommended window on south orientation						
Time	April		May		June	
	Transmission Load	Solar Load	Transmission Load	Solar Load	Transmission Load	Solar Load
0	-437	1473	159	1036	521	923
1	-515	1376	81	968	444	862
2	-594	1286	2	905	365	805
3	-661	1201	-65	845	298	753
4	-716	1122	-119	790	243	703
5	-745	1049	-148	738	214	662
6	-735	1051	-138	820	224	758
7	-684	1138	-87	327	275	867
8	-578	1387	18	1044	381	988
9	-417	1854	180	1296	542	1146
10	-224	2390	373	1656	735	1419
11	1	2787	597	2000	959	1703
12	219	3237	815	2242	1178	1909
13	391	3409	988	2331	1350	1986
14	515	3363	1112	2255	1474	1930
15	576	3110	1173	2070	1535	1806
16	560	2752	1157	1927	1519	1728
17	489	2489	1086	1798	1448	1624
18	363	2237	959	1621	1322	1476
19	205	2069	802	1456	1164	1296
20	42	1933	638	1360	1000	1211
21	-101	1806	495	1271	857	1131
22	-236	1688	361	1187	723	1057
23	-348	1577	248	1109	610	988
Total	**-3630**	**47784**	**10687**	**33052**	**19381**	**29731**

ASHRAE 90.1 recommended window on south orientation						
Time	**October**		**November**		**December**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-182	2724	-1034	2940	-1758	2992
1	-260	2545	-1112	2747	-1836	2796
2	-338	2378	-1191	2567	-1915	2612
3	-406	2222	-1258	2398	-1982	2440
4	-460	2076	-1312	2240	-2037	2280
5	-489	1939	-1341	2093	-2066	2130
6	-479	1812	-1331	1956	-2055	1990
7	-428	2263	-1280	2034	-2005	1859
8	-322	3088	-1175	3186	-1899	2877
9	-161	3933	-1013	4175	-1738	3983
10	32	4731	-821	5069	-1545	4941
11	256	5416	-596	5837	-1320	5789
12	475	5927	-378	6420	-1102	6417
13	647	6209	-206	6762	-930	6828
14	771	6218	-81	6804	-806	6937
15	832	5915	-20	671	-744	6657
16	816	5269	-37	5575	-761	5739
17	745	4306	-107	4732	-832	4816
18	619	4096	-234	4421	-958	4499
19	461	3827	-391	4131	-1116	4203
20	297	3576	-555	3859	-1279	3927
21	154	3331	-689	3606	-1422	3669
22	20	3121	-833	3369	-1557	3428
23	-93	2916	-345	3147	-1669	3203
Total	**2507**	**89838**	**-17340**	**90739**	**-35332**	**97012**

ASHRAE 90.1 recommended window on west orientation						
Time	**January**		**February**		**March**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-1333	801	-1138	1143	-677	1375
1	-1384	749	-1189	1067	-728	1284
2	-1436	699	-1241	997	-780	1200
3	-1480	654	-1285	932	-824	1121
4	-1516	611	-1321	871	-860	1048
5	-1535	570	-1340	813	-879	979
6	-1528	533	-1333	760	-872	914
7	-1495	498	-1299	724	-839	922
8	-1426	519	-1230	753	-770	945
9	-1320	555	-1125	781	-664	971
10	-1194	588	-998	810	-538	996
11	-1046	617	-851	834	-390	1021
12	-903	647	-708	861	-247	1049
13	-791	960	-595	1176	-135	1434
14	-709	1562	-514	1836	-53	2123
15	-699	2088	-474	2463	-13	2777
16	-680	2229	-485	2848	-24	3237
17	-726	1290	-531	2469	-70	3196
18	-809	1205	-614	1718	-153	2067
19	-912	1126	-717	1605	-256	1931
20	-1020	1052	-824	1500	-364	1804
21	-1113	983	-918	1401	-457	1686
22	-1202	918	-1006	1309	-545	1575
23	-1275	858	-1080	1223	-619	1472
Total	**-27532**	**22312**	**-22816**	**30894**	**-11757**	**37127**

ASHRAE 90.1 recommended window on west orientation						
Time	**April**		**May**		**June**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-287	1558	104	1677	342	1692
1	-338	1456	53	1566	291	1581
2	-389	1360	2	1464	239	1477
3	-433	1271	-42	1367	195	1380
4	-469	1187	-78	1278	159	1289
5	-488	1109	-97	1194	140	1208
6	-481	1080	-90	1201	147	1220
7	-448	1100	-57	1218	180	1238
8	-379	1122	12	1239	249	1260
9	-273	1147	118	1264	355	1286
10	-147	1173	244	1289	481	1312
11	0	1194	391	1309	629	1334
12	143	1235	534	1359	772	1376
13	256	1675	647	1780	884	1745
14	337	2338	728	2404	966	2341
15	378	2957	769	2992	1006	2917
16	367	3407	758	3433	995	3366
17	321	3485	711	3584	949	3565
18	238	2610	629	3106	866	3270
19	134	2189	525	2355	763	2377
20	27	2045	418	2201	655	2221
21	-66	1911	324	2056	562	2075
22	-155	1785	236	1921	474	1938
23	-228	1668	163	1795	400	1811
Total	**-2380**	**42062**	**7002**	**45052**	**12699**	**45279**

ASHRAE 90.1 recommended window on west orientation						
Time	July		August		September	
	Transmission Load	Solar Load	Transmission Load	Solar Load	Transmission Load	Solar Load
0	439	1664	439	1535	213	1316
1	388	1554	388	1435	165	1229
2	337	1452	337	1340	113	1149
3	293	1357	293	1252	69	1073
4	257	1268	257	1170	33	1003
5	238	1184	238	1093	14	937
6	245	1182	245	1062	21	879
7	278	1204	278	1090	55	909
8	347	1228	347	1118	124	938
9	453	1255	453	1148	229	969
10	579	1283	579	1178	356	999
11	726	1306	726	1203	503	1028
12	869	1346	869	1245	646	1088
13	982	1690	982	1643	759	1587
14	1063	2290	1063	2280	840	2255
15	1104	2876	1104	2879	880	2834
16	1093	3333	1093	3313	869	3157
17	1046	3531	1046	3393	823	2799
18	964	3194	964	2631	740	1979
19	860	2337	860	2157	637	1849
20	753	2184	753	2015	530	1727
21	659	2040	659	1883	436	1614
22	570	1906	571	1759	348	1508
23	498	1781	498	1644	274	1408
Total	**15041**	**44445**	**15042**	**41466**	**9677**	**36234**

ASHRAE 90.1 recommended window on west orientation						
Time	**October**		**November**		**December**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-119	1021	-677	806	-1152	710
1	-170	954	-728	753	-1203	663
2	-222	891	-780	709	-1255	620
3	-266	833	-824	657	-1299	579
4	-302	778	-860	614	-1334	541
5	-321	727	-879	573	-1353	505
6	-314	679	-872	536	-1347	472
7	-280	691	-839	511	-1313	441
8	-211	726	-770	550	-1244	463
9	-106	759	-664	585	-1138	499
10	21	791	-538	616	-1012	531
11	168	822	-390	647	-865	558
12	311	915	-247	720	-722	594
13	424	1455	-135	1202	-609	981
14	505	2104	-53	1794	-528	1550
15	545	2609	-13	2199	-488	1965
16	534	2695	-24	1967	-499	1772
17	488	1648	-70	1296	-545	1143
18	405	1535	-153	1211	-628	1068
19	302	1434	-266	1132	-731	998
20	195	130	-364	1057	-838	932
21	101	1252	-457	988	-932	871
22	13	1170	-545	923	-1020	813
23	-61	1093	-619	852	-1094	760
Total	**1640**	**27712**	**-11767**	**22898**	**-23149**	**20029**

Smart window with photovoltaic layer on the south orientation						
Time	January		February		March	
	Transmission Load	Solar Load	Transmission Load	Solar Load	Transmission Load	Solar Load
0	-1120	2344	-956	2245	-569	1761
1	-1162	2190	-998	2098	-612	1645
2	-1206	2046	-1042	1960	-655	1537
3	-1243	1912	-1079	1831	-692	1436
4	-1273	1786	-1109	1711	-722	1342
5	-1289	1669	-1125	1598	-738	1253
6	-1283	1559	-1119	1493	-732	1171
7	-1255	1456	-1091	1505	-704	1282
8	-1197	2158	-1033	2130	-646	1677
9	-1108	2964	-944	2793	-557	2210
10	-1002	3686	-838	3442	-451	2765
11	-879	4324	-715	4028	-328	3265
12	-759	4839	-595	4503	-208	3658
13	-664	5187	-500	4821	-113	3898
14	-596	5322	-432	4943	-45	3949
15	-562	5197	-398	4839	-11	3792
16	-571	4718	-407	4479	-20	3438
17	-610	3772	-446	3832	-59	2985
18	-679	3524	-515	3376	-129	2647
19	-766	3293	-602	3154	-215	2473
20	-856	3076	-692	2947	-305	2311
21	-935	2874	-771	2753	-384	2159
22	-1009	2685	-845	2572	-458	2017
23	-1071	2509	-907	2403	-520	1885
Total	**-23095**	**75090**	**-19159**	**71456**	**-9873**	**56556**

Smart window with photovoltaic layer on the south orientation						
Time	**April**		**May**		**June**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-241	1128	88	793	287	706
1	-283	1054	45	741	244	660
2	-327	984	1	693	201	617
3	-364	920	-36	647	164	576
4	-394	859	-66	605	134	538
5	-410	803	-82	565	118	507
6	-404	805	-76	628	123	580
7	-376	871	-48	709	151	664
8	-318	1062	10	799	209	756
9	-229	1419	99	992	298	877
10	-123	1830	205	1268	404	1087
11	0	2203	329	1531	528	1304
12	120	2478	449	1717	648	1462
13	215	2610	543	1785	743	1521
14	283	2575	612	1726	811	1477
15	317	2381	645	1585	845	1383
16	308	2107	636	1475	836	1323
17	269	1906	597	1377	797	1243
18	200	1713	528	1241	727	1130
19	113	1584	441	1115	640	9922
20	23	1480	351	1041	550	927
21	-56	1383	272	973	472	866
22	-130	1292	198	909	398	809
23	-192	1207	137	849	336	756
Total	**-1999**	**36654**	**5878**	**25764**	**10664**	**31691**

Smart window with photovoltaic layer on the south orientation						
Time	**July**		**August**		**September**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	369	793	369	1105	181	1681
1	326	741	326	1032	139	1571
2	283	692	283	964	95	1467
3	246	646	246	901	58	1371
4	216	604	216	842	28	1281
5	200	564	200	786	12	1197
6	205	616	205	785	18	1124
7	233	700	233	863	46	1323
8	291	791	291	1028	104	1755
9	380	950	380	1361	193	2287
10	486	1207	486	1754	299	2820
11	610	1467	610	2119	422	3285
12	730	1661	730	2391	542	3632
13	825	1746	825	2527	637	3820
14	893	1708	893	2503	705	3817
15	927	1583	927	2326	739	3609
16	918	1476	918	2070	730	3227
17	879	1384	879	1878	691	2790
18	809	1255	809	1686	622	2528
19	722	1114	722	1552	535	2361
20	632	1040	632	1450	445	2206
21	554	972	554	1355	366	2061
22	480	908	480	1266	292	1926
23	418	848	418	1182	230	1799
Total	**12632**	**25466**	**12632**	**35726**	**8129**	**54938**

Smart window with photovoltaic layer on the south orientation						
Time	**October**		**November**		**December**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-100	2086	-569	2251	-967	2291
1	-143	1949	-612	2103	-1010	2140
2	-186	1821	-655	1965	-1053	2000
3	-223	17011	-692	1836	-1090	1868
4	-253	1589	-722	1715	-1120	1746
5	-269	1485	-738	1603	-1136	1631
6	-263	1387	-732	1497	-1347	350
7	-235	1732	-704	1557	-1103	1424
8	-177	2364	-646	2439	-1045	2203
9	-89	3012	-557	3196	-956	3050
10	17	3622	-451	3881	-850	3783
11	141	4146	-328	4469	-726	4417
12	261	4538	-208	4916	-606	4913
13	356	4754	-113	5177	-512	5228
14	424	4760	-45	5209	-443	5312
15	458	4529	-11	4955	-410	5097
16	449	4034	-20	4268	-419	4394
17	410	3358	-59	3623	-457	3687
18	340	3136	-129	3385	-527	3445
19	254	2930	-215	3163	-614	3218
20	164	2738	-305	2955	-704	3007
21	85	2558	-384	2761	-782	2809
22	11	2390	-458	2579	-857	2625
23	-51	2233	-520	2410	-918	2452
Total	**1381**	**84162**	**-9873**	**73913**	**-19652**	**73090**

Smart window with electrochromic layer on the west orientation						
Time	January		February		March	
	Transmission Load	Solar Load	Transmission Load	Solar Load	Transmission Load	Solar Load
0	-774	781	-660	437	-393	526
1	-803	730	-690	409	-423	492
2	-833	682	-720	972	-453	459
3	-859	932	-745	908	-478	429
4	-879	871	-766	848	-499	401
5	-890	814	-777	793	-510	375
6	-887	760	-773	740	-506	350
7	-867	710	-754	705	-487	353
8	-827	740	-714	734	-446	362
9	-766	791	-652	761	-385	372
10	-692	573	-579	789	-312	382
11	-607	601	-494	319	-226	391
12	-524	631	-411	330	-144	402
13	-459	367	-345	450	-78	549
14	-412	598	-298	703	-31	813
15	-388	799	-275	943	-8	1063
16	-394	853	-281	1090	-14	1239
17	-421	494	-308	945	-41	1223
18	-469	461	-356	658	-89	791
19	-529	431	-416	614	-149	739
20	-591	403	-478	574	-211	691
21	-646	376	-533	536	-265	645
22	-697	895	-584	501	-316	603
23	-740	836	-626	468	-359	563
Total	**-15954**	**16129**	**-13235**	**16227**	**-6823**	**14213**

Smart window with electrochromic layer on the west orientation						
Time	**April**		**May**		**June**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-166	597	60	642	198	648
1	-196	557	31	600	169	605
2	-226	521	1	560	139	565
3	-251	487	-25	523	113	528
4	-272	455	-45	489	92	494
5	-283	425	-56	457	81	462
6	-279	414	-52	460	85	467
7	-260	421	-33	466	105	474
8	-220	430	7	474	145	482
9	-158	439	68	484	206	492
10	-85	449	142	493	279	502
11	0	457	227	501	365	511
12	83	473	310	520	448	527
13	149	641	375	681	513	668
14	196	895	423	920	560	896
15	219	1132	446	1145	587	1117
16	213	1304	440	1314	577	1289
17	186	1334	413	1372	550	1365
18	138	999	365	1189	502	1252
19	78	838	305	902	442	910
20	16	783	243	842	380	850
21	-39	732	188	787	326	794
22	-90	683	137	735	275	742
23	-132	639	94	687	232	693
Total	**-1379**	**16105**	**4064**	**17243**	**7369**	**17333**

Smart window with electrochromic layer on the west orientation						
Time	**July**		**August**		**September**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	255	637	255	588	125	504
1	225	595	225	549	96	471
2	195	556	195	513	66	440
3	170	519	170	479	40	411
4	149	485	179	448	19	384
5	138	453	138	418	8	359
6	142	453	142	407	12	337
7	161	461	161	417	32	348
8	201	470	201	428	72	359
9	263	480	263	439	133	371
10	336	491	336	451	206	382
11	421	500	421	461	292	393
12	504	515	504	477	375	417
13	570	647	570	629	440	608
14	617	877	617	873	487	863
15	640	1101	640	1102	511	1085
16	634	1276	634	1268	504	1209
17	607	1352	607	1299	478	1071
18	559	1223	559	1007	429	757
19	449	895	499	826	370	708
20	437	836	437	771	307	661
21	383	781	383	721	253	618
22	331	730	331	673	202	577
23	289	682	289	629	159	539
Total	**8676**	**17015**	**8756**	**15873**	**5616**	**13872**

Smart window with electrochromic layer on the west orientation						
Time	**October**		**November**		**December**	
	Transmission Load	**Solar Load**	**Transmission Load**	**Solar Load**	**Transmission Load**	**Solar Load**
0	-69	391	-393	308	-668	692
1	-99	365	-423	733	-698	646
2	-129	341	-453	685	-728	604
3	-154	319	-478	640	-753	826
4	-175	298	-499	598	-774	772
5	-186	278	-510	559	-785	721
6	-182	260	-506	522	-781	674
7	-163	265	-487	498	-762	630
8	-123	278	-446	536	-722	661
9	-61	291	-385	570	-660	712
10	12	303	-312	236	-587	518
11	97	315	-226	247	-502	544
12	180	350	-144	276	-419	579
13	246	557	-78	460	-353	376
14	293	805	-31	687	-306	593
15	316	999	-8	842	-283	752
16	310	1032	-14	753	-289	678
17	283	631	-41	496	-316	437
18	235	588	-89	464	-364	409
19	175	549	-149	433	-424	382
20	113	513	-211	405	-486	357
21	59	479	-265	378	-541	333
22	7	448	-316	353	-593	793
23	-35	418	-359	330	-634	741
Total	**950**	**11073**	**-6823**	**12009**	**-13428**	**14430**

Appendix B: Software comparison table

Below is the comprehensive list of software comparison of prominent energy simulation software along with their salient features as seen (but not limited to) which can help user to choose type of energy simulation software that can meet its need.

Sr. No.	Name	Organization / Company	Salient features
1	Building Load Analysis and System Thermodynamics (BLAST)	University of Illinois Urbana Champaign	• Sequential loads, system, plant calculation without feedback. • Building material moisture absorption/desorption (combined heat and mass transfer). • Stratified thermal storage tank.
2	Building Simulation (BSim)	Danish Building Research Institute Aalborg University Copenhagen	• User defined control strategy for HVAC equipment. • Beam solar radiation reflection from outside and inside window. • Models made in BSim can be exported to Radiance for advanced light simulation and visualization.
3	Designer's Simulation Toolkit (DeST)	Department of Building Science, School of Architecture, Tsinghua University, Beijing, China	• Beam solar radiation reflection from outside and inside window. • Libraries of the building components can be extended easily. • All the data are contained in just two database which user can modify easily.
4	DOE - 2	Department of Energy (DOE)	• Input can contain C-like logic not just fixed values. • Parameter substitution for parametric analysis. • User can build libraries with the building components. • Source available for user reference.
5	ECOTECT	Autodesk	• User friendly and highly graphical 3D user interface for model and data visualization, editing and creation (with OpenGL). • Auto creation of optimum shading device. • Exports building geometry to CAD program. • Excellent on-line and interactive help.

Sr. No.	Name	Organization / Company	Salient features
6	Energy Plus	Department of Energy (DOE)	• 3-D building display and 2-D floor plan display. • Building Integrated photovoltaic system accounts for heat removed from surface layers which have defined electrical characteristics. • Import/export model to other simulation programs. • Automatic result generation for energy balance checks.
7	eQUEST	Department of Energy (DOE)	• Built-in capabilities of energy code compliance analysis. • Stratified thermal storage tank. • HVAC air-side system diagramming. • HVAC water-side system diagramming. • Complete input available at interface. • Wizard to assist in running parametric analysis. • User defined control strategy for HVAC equipment.
8	Revit	Autodesk	• Provides user with different options for building design; either importing the design, tracing the design from CAD file or making the whole building in simulation tool itself. • Accounts for sun path and solar radiation. • Provides a user-friendly environment. • Users can obtain a variety of reports on different types of analysis.
9	AECOsim	Bentley	• Allows user to create building from its construction phase to mechanical-electrical-plumbing (MEP) utilities. • Higher visual qualities through stronger graphics and 3D rendering features. • Exports files from other simulation software.
10	TRACE	Trane	• Export building geometry to CAD program. • Offers a tool for LEED calculation. • Wizard for creating building models. • Graphical results reporting multi-run comparisons.
11	HAP	Carrier	• Complete input available through graphical user interface. • Extensive, context-sensitive on-line help. • Global search and replace for building data. • Global rotate for building envelope surfaces. • Offers project sharing for collaboration. • Offers project archival features.
12	HEED	University of California, Los Angeles (UCLA)	• Provides thermal load calculations by simply entering zip code, floor space, and number of stories. • Parameter substitution for parametric analysis • Built-in capabilities of energy code compliance analysis.

Sr. No.	Name	Organization / Company	Salient features
13	IES Virtual Environment	Integrated Environmental Solutions	• Building material moisture absorption/desorption(combined heat and mass transfer) • Provides number of modules for geometry creation, loads analysis, thermal simulation, natural ventilation and component based HVAC, shading visualization and analysis, fluid dynamics, lighting design, model optimization, life cycle analysis, and building evacuation simulation. • Automatic result generation for energy balance checks.
14	TRNSYS	Transient System Simulation Tool Inc.	• Fully integrated interface for defining the system setup (the TRNSYS simulation studio) with optional plug-ins to enter component parameters. • User configured solar system and wind power. • User defined control strategy for HVAC equipment. • Automatic result generation for energy balance checks. • User can create stand-alone executables (TRNSED applications) that can run a predefined set of input files. • MATLAB/Simulink components or subsystems can be implemented using m-files or in a Simulink project. • EES (Engineering Equation Solvers) program allows user to enter equations "as they are written" instead of programming their solution.
15	SUNREAL	National Renewable Energy laboratory (NREL)	• User interface for creating text input files. • Source and executable available for other applications with a license agreement with NREL. • Integrated into TREAT home energy auditing software.

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