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An evaluation of smart windows in a reference office building in Kayseri

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Abstract

As a building element, the facade which interacts with external factors between two different environmental conditions is an important interface in energy consumption and the building life cycle. In recent years, smart materials have become a research topic in the field of sustainable architecture and facade technologies. The traditional material understanding which expects materials to not be affected by external environmental conditions by preserving their qualities throughout their lifespan has begun to leave its place to the understanding of materials that change quality and energy by reacting to external stimuli. Developing facade technologies and the energy-efficient design approach also achieve the development of new technologies in window systems. The most promising of these new window technologies, called smart windows, are electrochromic, thermochromic, and photochromic windows. Within the scope of this study, the energy performance of smart window systems has been evaluated comparatively with a traditional window system in a reference office building in Kayseri, Turkey. This study aims to evaluate the energy performances of smart windows and reveal their advantages and disadvantages over the available window system in this climate condition. In this context, smart window systems have been classified and explained their properties. In the simulation part, a reference office building has been modeled with each smart window system to evaluate their energy performances comparatively. Nevertheless, a reference office building with a traditional window system has also been modeled to reveal differences in energy performances with an available window system. Finally, the results have been evaluated with graphs and recommendations on the best-performed window system have been explained.

Keywords: energy efficient buildings, facade materials, smart materials, smart windows, sustainability

1. Introduction

Today, facades have a large amount of energy consumption in high-rise office buildings. The facade is a building element that separates the interior and exterior environment in buildings and is an interface that interacts with physical, chemical, and biological factors throughout the building life cycle. Due to being in interaction with the exterior conditions, most of the energy loss of a building occurs in the facade, especially in the window systems. Factors such as daylight, visual, and thermal comfort in high-rise office buildings affect the quality of the work, user comfort conditions, and energy consumption. High heating and cooling energy use in buildings cause depletion of energy resources and significant problems in the scope of sustainability. Therefore, the window system used in a high-rise office building has a significant impact on the importance of sustainable architecture and energy-efficient building targets in the field of architecture.

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Technological developments in material science and architecture allow the development of new facade materials and systems. In this context, innovative window systems have been developed to prevent and minimize energy gains and losses. Smart materials, which are used and intended to be used in many fields of architecture, also have a wide extent for facade technologies. The main varieties of smart windows are film-coated window systems consisting of electrochromic, thermochromic, or photochromic materials. In these innovative window systems, the window aims to balance heat losses and gains by changing its opacity level according to the solar radiation intensity, and temperature or with an actuator to provide thermal insulation and lighting control. In brief, smart windows aim to provide user comfort and reduce energy loses by balancing heating, cooling, and lighting loads.

1.1. Purpose of The Study

This study focuses on the performance of smart windows in high-rise office building facades in Kayseri, Turkey. The primary aim of the research is to provide brief information on the definition and characteristics of smart facade materials and to compare smart window systems with a standard window system in Kayseri climate conditions. Also, the impacts of opacity changes in smart windows for comfort conditions and energy consumption in high-rise office buildings are aimed.

1.2. Methodology

In this study, the properties of electrochromic, thermochromic, and photochromic window systems, together with a preferred window technology today, are explained. Afterwards, a simulation study is carried out on a case high-rise office building placed in Kayseri.

First, electrochromic, thermochromic, and photochromic smart facade materials, which are the components of smart window systems have been revealed. This part contains a brief literature review with recent case studies and examples of buildings that are designed with smart windows.

For the optimization round, the material properties to investigate are the U-value of building components suitable for the climate conditions specified. Optical and physical properties of the smart windows such as U-value, SHGC, and VT values, application system of the window, and dimensions are compiled. These properties have been found on manufacturers' websites, articles, and other open channels. For the simulation study, energy simulation software's have been evaluated considering their ease of use, accessibility, and capacity to generate the desired data.

After the research review, a high-rise office building is modeled as a prototype with a defined geometry and window application in the simulation process. The first model consists of the electrochromic window as an active smart window that changes its opacity with voltage. The second smart window model contains the thermochromic material as a passive property-changing smart material that changes its opacity according to temperature changes. The third model represents the photochromic window as a passive smart window that changes its opacity with light. Also, Low-E coated window system has been chosen as the fourth model to compare with other smart windows since it is suitable for the required window properties according to the standards and widely has been used in Turkey. Thus, the advantages and disadvantages of the standard window can be compared to smart windows. These models are analyzed and optimized through computer simulations. As a result of extensive research, Design Builder software has been chosen as the building simulation tool. The performances are evaluated through four window systems via simulation run-time. Finally, an evaluation is done for energy performance through energy consumption for heating and cooling.

2. Smart Materials

Until the 20th century, materials were expected not to change their properties due to environmental impacts during their use. Because thereupon, the material changes in properties have been expressed as decay, corrosion, collapse, mold, etc. (Okay, 2003). After the industrial revolution at the end of the 19th century, the traditional material understanding, and facade systems have been changed through developments in technology and gained awareness for a better future (Orhon, 2012). With the new material understanding, the expected outcome from smart materials in the facade will help make quality changes against external influences besides the classic material understanding (Okay, 2003). The understanding of smart materials is based on responding to external stimuli, unlike the classical materials that struggle against external influences (Orhon, 2012).

2.1. Properties of Smart Materials

The principle of the definition and classification of the smart materials are according to the two approaches that are used as the main references, which are Addington & Schodek's and Ritter's approaches. Basically, there are five fundamental characteristics to distinguish between traditional and smart materials as follows: transiency, selectivity, immediacy, self-actuation, and directness. Also, the expected to be found in smart materials are (Addington and Schodek, 2005):

- Property change capability
- Energy exchange capability
- Discrete size/location
- Reversibility

The classification of smart materials is determined by the environmental factor affected, the way of responding to this effect, and the perceived change in the material by the human eye. All of these parameters are included in the classification system (Karakaya and Özgünler Acun, 2021). If the external input affects the internal energy of the material by altering either the material's molecular structure or microstructure and a property change occurs in the material, it is accepted that these types of materials are property-changing smart materials. If the external effect changes the energy state of the materials while material composition does not alter and only results in an exchange of energy from one form to another, these types of materials are energy-exchanging smart materials. In brief, in property-changing smart materials, the material absorbs the input energy and goes through a change, whereas in energy-exchanging smart materials, the material stays the same, but the energy undergoes a change. In addition, these changes are on the micro-scale (Addington and Schodek, 2005).

Today, many smart materials are still under research and have a wide area in the field of architecture, especially in facade technologies. Color and optically changing smart materials or in other words chromogenic smart materials are the most used smart materials in facades (Table 1). In this group, external input or inputs influence the material's molecular-atomic structure generally from its surface and a change occurs in the material's opacity. These inputs can be passive factors such as light, temperature, or active inputs via electric current, voltage, etc. The materials respond directly and reversibly by changing their opacity states due to these passive and active inputs (Addington and Schodek, 2005).

Table 1 Color and optically changing smart material types in relation to input and output stimuli (Addington and Schodek, 2005).

Type of Smart Material	Input	Output
Electrochromics	Electric potential difference	
Thermochromics	Temperature difference	Color/Opacity Change
Photochromics	Radiation (Light)	

Addington and Schodek have entitled this smart material group chromic or color-changing smart materials. However, the term color changing does not mean that the materials change their colors. The material changes its optical properties; hence this change is perceived as a color and/or opacity changing by the human eye. These color changes can be perceived in many colors depending on the optical features (crystalline or molecular structure) of materials and the light may be absorbed or converted to energy (Addington and Schodek, 2005).

2.2. Smart Window Systems

In order to meet the requirements, glazing materials and window systems have been developed by adding extra layers to the window in today's technology. Furthermore, new material types such as window layers have been applied to high-rise buildings with large facades to enhance building performance (Kızıltoprak, 2019). Result of extended surveys of color and optically changing smart materials in facade technologies, they are generally used in passive or active applications in facade systems, which are called smart windows. There are three main smart window systems that are manufactured with color and optically changing smart materials in the market, which are electrochromic, thermochromic, and photochromic smart windows (Orhon, 2012).

2.2.1. Electrochromic Smart Windows

Electrochromic smart windows reversibly change their optical properties by application of an electric current and/or potential via a small voltage through the user control. The reversible color change in the window is based on the movement of ions between the electrochromic layers by applying a small amount of voltage basically (Figure 1) (Lampert, 1998). Optical changing in the chemical structure of the material is perceived as color and/or opacity change (Figure 2) (Ritter, 2007).

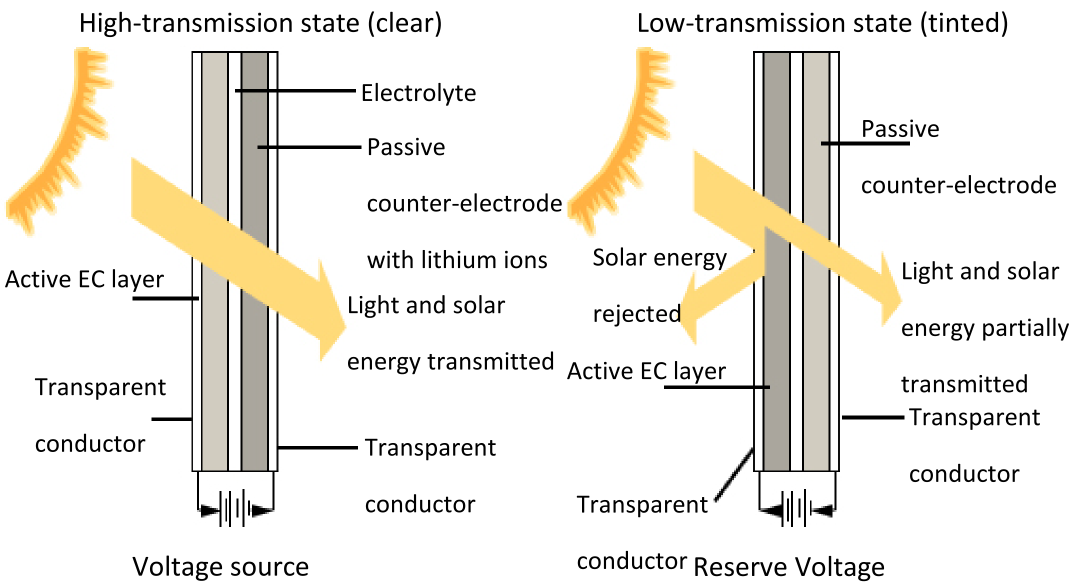

Figure 1 Diagram of the tungsten-okside covered electrochromic windows (URL-1).

Figure 2 Transparent and tinted states of electrochromic smart window in Dirty Habit DC facade (URL-2).

2.2.2.Thermochromic Smart Windows

Thermochromic smart windows reversibly change their visible optical properties in response to temperature changes in thermochromic thin films that are integrated into the window system through absorption of heat (Figure 3). This temperature change generates a chemical reaction or phase transformation in the structure of the material, hence the material opacity convert into the perception of color change (Ritter, 2007).

Figure 3 Trasparent and tinted states of thermochromic smart window in Masco Building facade (URL-3).

2.2.3.Photochromic Smart Windows

Photochromic smart windows reversibly change their optical properties due to the impact of light (visible light, UV light, IR light; electromagnetic radiation) with the perception of color change. This change can be achieved with a photochromic film applied to the window without needing any actuator (Ritter, 2007).

2.3. Advantageous and disadvantageous of smart windows

The smart behavior of the smart window system is advantageous to reduce heating and cooling loads (Lee and DiBartolomeo, 2002). However, the application of smart windows to high-rise office building facades can be disadvantageous depending on the climate conditions. In the study "An Evaluation of Chromic Glazing as Smart Material in High-Rise Office Building Facades Within The Scope of Sustainability" it has been observed that electrochromic windows increase the building energy efficiency compared to other smart window systems and Low-E coated windows in Istanbul for winter and summer periods, hence total energy use, and it has been determined that their use is advantageous in temperate climates. However, the Low-E coated window system shows the best performance in Antalya, which is in the hot climate, since smart windows increase lighting loads due to being in the tinted state cause of high solar radiation intensity in hot climate regions, therefore their use may be considered disadvantageous when considered the total energy uses for winter and summer periods (Karakaya, 2022). Other advantageous and disadvantageous of smart windows are as follows:

- Thermochromic and photochromic smart windows can change their opacity state to optimize energy losses and gains passively, yet, electrochromic smart windows work with an actuator to achieve the opacity change, hence called active systems. However, electrochromic smart windows need even less energy to maintain the desired color (Erdemli, 2018). Therefore, the application of a voltage can be a disadvantage in the scope of sustainability, however, the total energy uses should be considered (Addington and Schodek, 2005).
- The optical transmittance of smart window systems is continuous, and it has the ability to reflect and absorb between transparent and tinted surfaces (Yelkenci Sert and Güzel 2015). However, in opacity-changing smart window systems, generally, the switching time to darken takes a little longer than transparency (Erdemli, 2018).
- One of the most important advantages of smart windows is that they can be applied to various window systems with different numbers of layers and glass types, hence, the performance of the window system can have better quality (Lee and DiBartolomeo, 2002).
- They can operate between a wide range of glass surface temperatures (Yelkenci Sert and Güzel 2015).

- The switching time of the window has also a major impact on user comfort. In thermochromic smart windows, it takes 20-30 minutes to switch the color, thus electrochromic products have a remarkable difference within 3-5 minutes of switching time on visual comfort (Tällberg et al, 2019).
- Among passive smart windows, thermochromic smart windows have lower manufacturing costs despite photochromic materials (Yelkenci Sert and Güzel 2015).
- When taking into consideration users' requirements in office buildings, the smart window is a good solution to control brightness levels and glare in working zones. However, although they have advantages in energy balance and daylight control, which is significantly important for visual comfort, artificial light may be a necessity when the window got tinted (Lee and DiBartolomeo, 2002).

3. Case Study

Smart window systems can switch the state from clear to tinted without interrupting the visual connection due to solar radiation intensity. In recent years, simulation studies have been carried out to evaluate the energy performances of smart windows in different climate conditions. Smart windows have an important role in today's window technology with the optimization ability of heating and cooling loads. Recent studies show that smart windows contribute to the energy efficiency of the building and more positively affect the comfort conditions of the user in some climate conditions. In order to enlarge the knowledge of smart window performances in different climates, the energy performance evaluation of electrochromic, thermochromic, and photochromic windows is made comparatively with a reference window system in Kayseri. In this context, a case office building with 15 floors has been modeled in the DesignBuilder simulation tool (Figure 4).

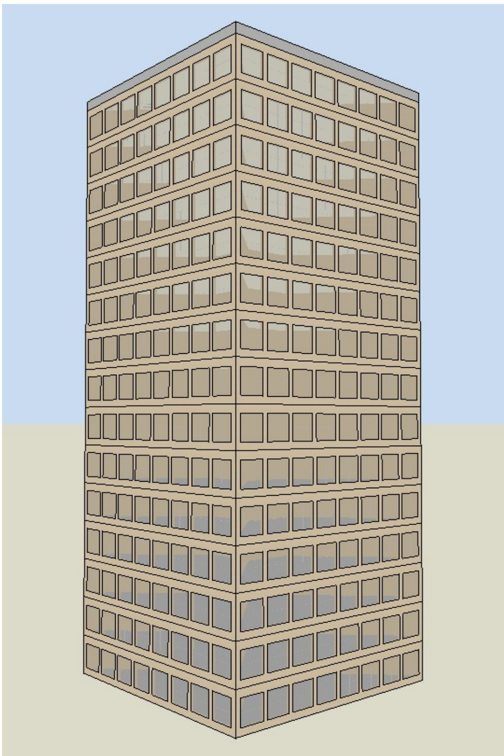

Figure 4 Rendered view of the case high-rise office building.

As the result of extended surveys of suitable building simulation tools, the EnergyPlus-based DesignBuilder Simulation Program has been found as the best software to simulate and comparative in high-rise office buildings facades designed with smart windows since the requirements of a higher-level work and expertise for other program tools are needed (Crawley et al, 2008, Loonen et al, 2013).

The case high-rise office building is designed with a square plan, four open facades, and 15 floors. The area of the building is 625 m² (25 m x 25 m), with a floor height of 4 m and a total building height of 80 m. The schematic plan of the model building is given in Figure 5. The working hours of the day are accepted between 08:00 and 18:00.

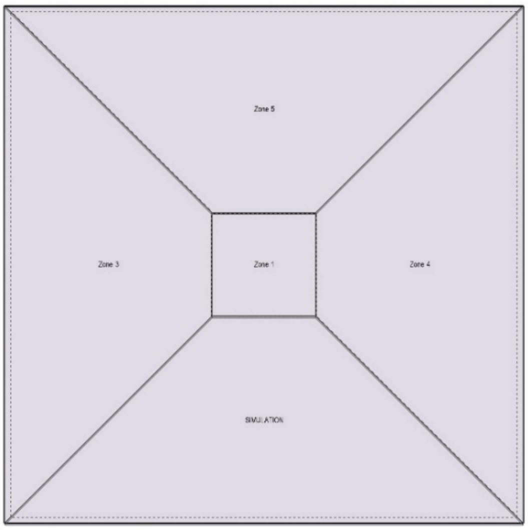

Figure 5 Schematic plan of the case building

3.1. 3.1 Location and Climate Characteristics

Information and assumptions about climate conditions, building structural features, spatial conditions, and user features are explained in detail below. In computer modeling, necessary parameters related to environment, building, and user are defined according to ASHRAE and TS-825 standards.

The building location has been selected as Kayseri which is a plot city of the 4th climate zone in Turkey. The climate and location characteristics of these region are given in Table 2. Each facade of the building consists of four facades of linear and equal dimensions. Modeling has been done by assuming that the surrounding buildings are far, hence shading factors from them have not been taken into account. In calculations, evaluations have been made on a module located. In evaluating the thermal performance of the building, climatic data accepted by ASHRAE is defined on the simulation program (ASHRAE, 2009, TS825, 2013).

Table 2 Location features of reference building for Kayseri.

Location:	Kayseri
Climate Type:	Continental Climate
Climate Zone (TS825):	4. Region

The reference U-Values determined for the climate zones in the TS 825 standard for the building materials used in the case buildings are given in Table 3. The required U-values of the external wall, floor, roof, and window components of each are highlighted (TS825, 2013).

Table 3 The required U-values (W/m²K) for the climate zones (TS825, 2013).

Climate Zone	Exterior Wall	Floor	Roof	Window
1.Region	0,66	0,43	0,66	1,80
2.Region	0,57	0,38	0,57	1,80
3.Region	0,48	0,28	0,43	1,80
4.Region	**0,38**	**0,23**	**0,38**	**1,80**
5.Region	0,36	0,21	0,36	1,80

According to the required U-values of building envelopes for TS 825, the case high-rise office building is modeled (Table 4).

Table 4 U-Values of reference building envelopes for Kayseri.

Exterior Wall	Floor	Roof
0,36 W/m²K	0,23 W/M²K	0,37 W/m²K

3.2. Heating system

The set temperature for heating period is considered to be 21°C. It is assumed that the heating system starts to operate when the indoor temperature is below 19°C.

3.3. Cooling system

During the cooling period, the indoor set point temperature is accepted as 26°C and it is assumed that the cooling system activates when the indoor temperature is above 28°C.

3.4. User heat gain and office equipment loads

The working hours of the day are accepted between 08:00 and 18:00. The office work area is designed as an open office with equal 4 zones, assuming that 15 people work in each zone. A value of 123 W/person has been chosen for light workers from the DesignBuilder activity list. It has been assumed that there are a total of 15 computers in a department, one for each employee. 230 W/computer value was selected for these computers in the DesignBuilder program. The heat loads of the other devices that continue to work on weekends and during office hours have not been taken into account in the calculation.

3.5. Properties of Window Systems

In the simulation process, electrochromic, thermochromic, photochromic, and Low-E coated windows are selected to operate.

- window height: 3 m
- window width: 2,5 m
- window parapet height: 0,2 m
- the total number of windows on the facade: 10.

Each window type is modeled as a double-glazing system with 6mm glass, 12 mm air gap, and 6 mm glass. Even though different gases have been used in different windows, the gas in the air gap is selected the same from the program library properly to ignore the effect of gas type. The frames for each window are fixed and the most suitable aluminum frame with a thermal barrier has been used in the systems since different types of frames would affect the evaluation. The U-value of the frame system has been considered while selecting. In all of the alternatives, the impermeability value (infiltration) is accepted as 0.5 ac/h according to ASHRAE standard 55 and BEP-TR data.

Optical properties such as SHGC, VT, and U-Values are significant properties that create the difference in the performance of each window. Moreover, these values differ for each tinted state of smart windows, for instance, VT and SHGC values reduce when the clear state turns tinted. The linear optical change can not be calculated with the simulation tool. In order to evaluate the performance of the smart windows, 4 opacity states during the day of the window with optical properties are selected from manufacturers' websites, case study data, and articles. In the calculation, smart window states are selected in accordance with the manufacturers' websites. Consequently, all graphs and tables for each state have been evaluated with daytime behavior outcomes.

In the daily evaluations, August 14 is chosen as the hottest day for the summer months and February 12 as the coldest day for winter months, representing the summer and winter months, and the changes in cooling and heating loads have been analyzed depending on the external climatic changes on these days. The evaluation has been represented for the south facade office zone on the 5th floor of the building. The optical properties of the windows are represented (Table 5, Table 6, Table 7, Table 8).

Table 5 Optical properties of electrochromic windows per state.

Window States	U-Value	SHGC	VT
Clear State	0,29 W/m²K	0,33	0,45
Intermediate State 1	0,29 W/m²K	0,20	0,19
Intermediate State 2	0,29 W/m²K	0,12	0,06
Tinted State	0,29 W/m²K	0,10	0,01

Table 6 Optical properties of thermochromic windows per state.

Window States	U-Value	SHGC	VT
Clear State	1,36 W/m²K	0,25	0,30
Intermediate State 1	1,36 W/m²K	0,21	0,20
Intermediate State 2	1,36 W/m²K	0,17	0,10
Tinted State	1,36 W/m²K	0,13	0,05

Table 7 Optical properties of photochromic windows per state.

Window States	U-Value	SHGC	VT
Clear State	1,58 W/m²K	0,33	0,28
Intermediate State 1	1,58 W/m²K	0,30	0,26
Intermediate State 2	1,58 W/m²K	0,28	0,24
Tinted State	1,58 W/m²K	0,25	0,23

Before evaluating and comparing the energy performance of windows for heating, cooling, and lighting, it is important to clarify how the smart window system works during the day and how it responds to external influences. In the evaluation, 4 different opacity states of smart windows are calculated. In the literature review and the data collected from the manufacturers, it has been seen that the smart windows are colorless at 10 °C and the direct solar radiation intensity on the glass surface is 100 W/m². Likewise, it was determined that at 65 °C, the direct solar radiation intensity on the glass surface was 450 W/m², in which the glass became tinted (Tällberg et al, 2019). It has been explained in the previous sections that different types of windows change with the intensity of solar radiation coming to the glass surface, with the temperature change, and with the user control. Considering that these control strategies differences can not be controlled in the simulation program, the threshold temperature and solar radiation intensity are accepted that the windows change their levels at these threshold values. Accordingly, smart windows can be found in clear, intermediate-1, intermediate-2, and tinted states. It is assumed that when the direct solar radiation intensity on the glass surface is 0 W/m², the smart window is clear and the smart window is tinted when the solar radiation intensity is 450 W/m². Intermediate states are changed between 0-450 W/m².

Table 8 Optical properties of Low-E coated windows.

U-Value	SHGC	VT
1,80 W/m²K	0,59	0,77

In the simulation study, the cooling system is modeled to fix the indoor temperature to 26ºC during the summer months. In the evaluation, it is assumed that the smart window changes the opacity level when the energy is consumed for the cooling load and the window level is fixed when the cooling energy is 0 W/m² again. It is also assumed that when the indoor temperature reduces below 26ºC, the opacity level of the window increases and gets into a clear state linearly. In this context, daily cooling loads have been compared in the south-facing zone of the high-rise office building.

3.6. Evaluation of Cooling Loads

For the calculation of the daily cooling loads, the hourly outdoor air temperature and direct solar radiation intensity graph of August 14 for Kayseri is given (Figure 6). The maximum value of outdoor temperature is 34,30°C at 14:00. The lowest value of solar radiation intensity is 323.71 W/m² at 08:00 and the highest value of solar radiation intensity is 842.64 W/m² at 16:00. Consequently, when the solar radiation intensity is in the range of 300-450 W/m² at 08:00, smart windows are at the intermediate-2 state in Kayseri. The solar radiation intensity is higher than 450 W/m² between hours 09:00 and 18:00. Therefore, the window is in the tinted state.

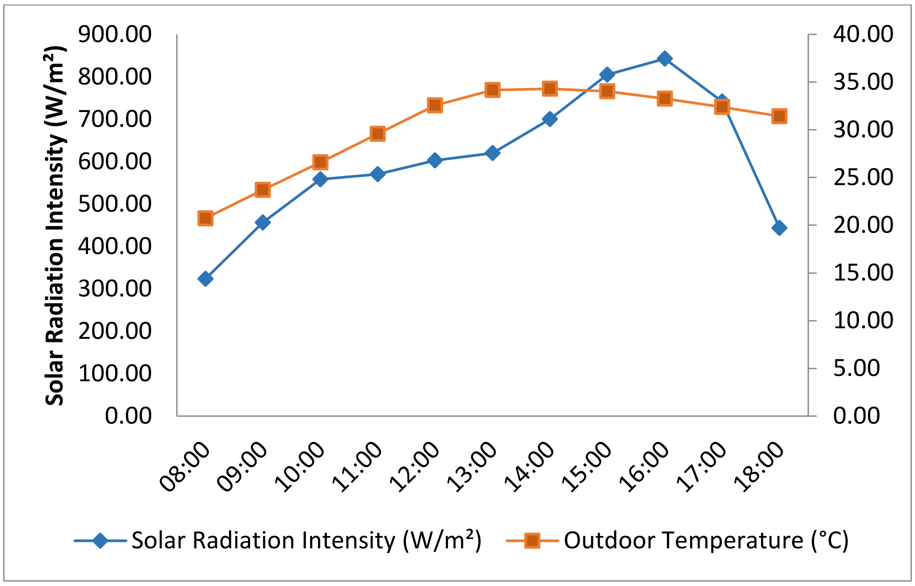

Figure 6 Solar radiation intensity and outdoor temperature for August 14 in Kayseri.

According to the solar radiation intensity levels, cooling loads of windows for August 14 graph is given in Figure 7.

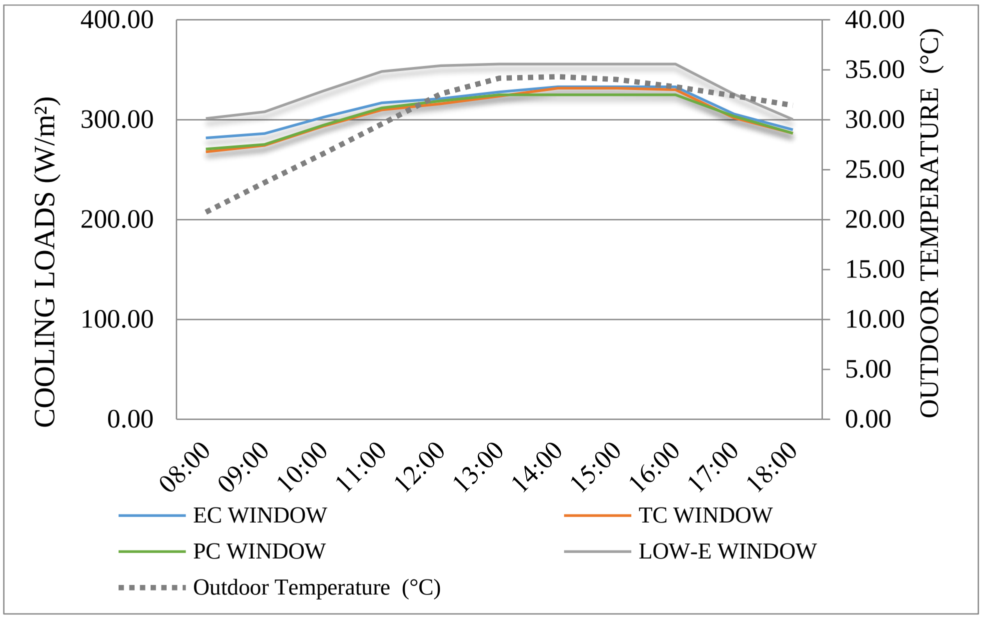

Figure 7 Cooling loads of windows for August 14 in Kayseri.

The smart windows are at the tinted state in this time interval, however, between 08:00 and 09:00 it has been in the intermediate-2 level when the solar radiation intensity on the window surface is down the threshold value. All window types have reached the maximum value of cooling loads at 14:00. After reaching the maximum value at 14:00, a decrease in cooling loads has been observed in smart windows for rest of the day.

Cooling loads for each window option are at minimum values at 08:00 when the outdoor temperature is 20.73ºC. An increase has been observed in the cooling loads on all windows until 14:00. Accordingly, the lowest and the highest cooling loads are 281.70 and 332.90 W/m² for the electrochromic window, 267.78 and 331.49 W/m² for the thermochromic window, 270.58 and 324.88 W/m² for the photochromic window, and 300.18 and 355.66 W/m² for the low-E coated window in this hour range.

In the Low-E coated window, the maximum cooling loads have been calculated among all windows during the working hours. Similar to the photochromic window, an increase in cooling loads has been observed until 14:00, reached the maximum level at this time, and decreased after all. The maximum cooling load reached during the day is 323,97 W/m² and the lowest is 280,29 W/m² at 18:00.

For the electrochromic window, the minimum cooling loads have been calculated among all windows during the working hours. In the electrochromic window, cooling loads increase during the day. The maximum cooling load reached 275,98 W/m² at 17:00. The electrochromic window switched to the intermediate-2 state between 17:00 and 18:00 with the solar radiation intensity on the window surface exceeding the threshold value.

In the thermochromic window, cooling loads reduce until 09:00 in the tinted state. The thermochromic window has also shown similar behavior to other smart windows as is in the intermediate-2 until 18:00 and in the tinted state for the rest of the day. The maximum cooling load reached 301,96 W/m² during the day. After 14:00, the cooling loads relatively reduce until 17:00, and during this period the cooling loads are approximately equal to 300,15 W/m². Although the outdoor temperature has continued to increase until 18:00, the cooling load has not increased due to the glazing being in the tinted state, preventing overheating.

In summary, the highest cooling load at 08:00 was measured as 295,76 W/m² for the PC window. The highest cooling loads for each window type are between 14:00 and 17:00. In this hour range, the energy consumed for cooling increased up to 275,98 W/m² for the EC window, 301,96 W/m² for the TC window, 307,26 W/m² for the PC window, and 323,97 W/m² for the Low-E window. This can be explained in direct proportion to the air temperature graph because the outdoor air temperature reached the highest levels in this hour. The best-performing window system is the electrochromic smart window when the total cooling loads are compared.

The window option with the highest total cooling load is the Low-E coated window. The SHGC value of the Low-E window is 0.56, and therefore, since the SHGC value is high, a high rate of solar radiation coming to the glass surface causes heating by passing into the interior environment, thus causing an increase in the cooling energy. The SHGC values (from the clear state to the tinted state) of the electrochromic, thermochromic, and photochromic windows are 0.33-0.10, 0.25-0.13, and 0.33-0.25 respectively. The lower values in tinted states of electrochromic and thermochromic windows are important factors in lower cooling loads compared to photochromic windows.

Cooling loads tend to increase when the solar radiation intensity is the highest. Since the illuminance values could not exceed the determined value for office buildings (500 lux), a sufficient illuminance level was not provided in the indoor environment and the comfort condition could not be met. It has been observed that artificial lighting is needed to provide the necessary comfort condition (500 lux), and therefore an increase in lighting loads needed to occur.

When the total cooling loads of the south-oriented office unit are compared during the day, the photochromic window shows the best performance with the lowest cooling energy use of 3360.02 W/m² on February 12 in Kayseri (Figure 8).

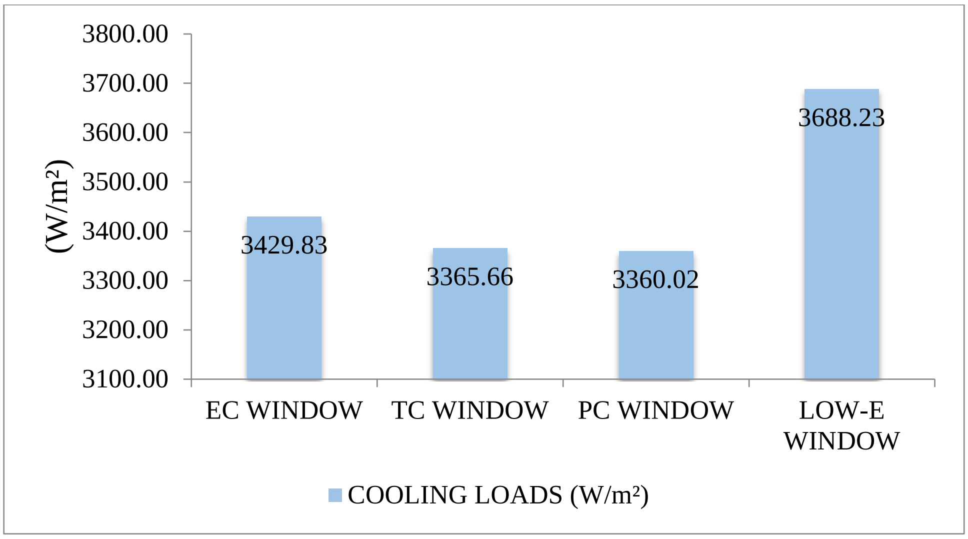

Figure 8 Total cooling loads of the windows for August 14 in Kayseri.

Total cooling loads on other smart windows are higher during the day to ensure indoor comfort conditions. The best performing window systems after the electrochromic window are the thermochromic window with a value of 3365.66 W/m² and the electrochromic window with a value of 3429.83 W/m², respectively. The worst-performing window system with the highest heating energy consumption is the Low-E coated window with a value of 3688.23 W/m².

3.7. Evaluation of Heating Loads

According to the graph, the outdoor temperature stays between -10°C and 4 °C without showing a sudden rise or fall during the day (Figure 9). The highest value of solar radiation intensity is 18.61 W/m² at 13:00. Therefore, smart windows remained in the clear state throughout the day due to the solar radiation intensity on the smart window surface being below the threshold value to reverse its level.

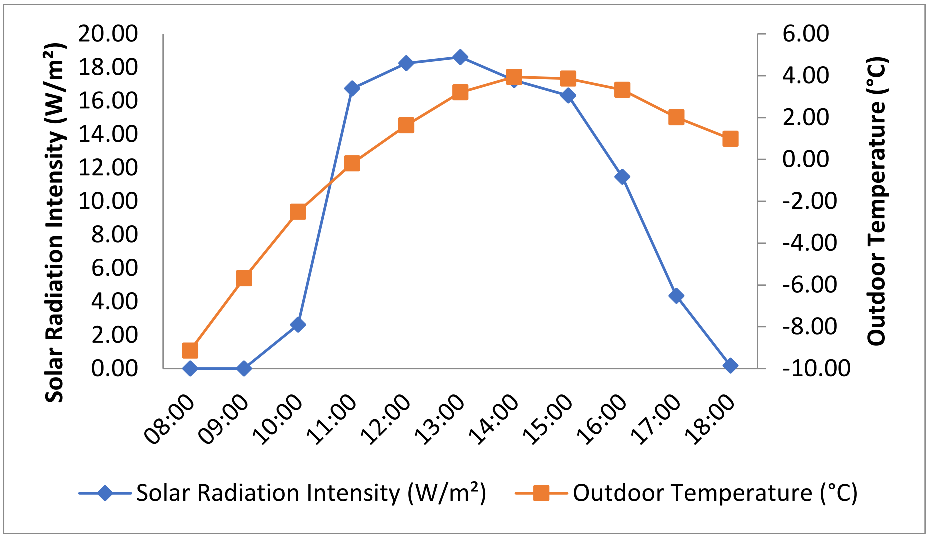

Figure 9 Solar radiation intensity and outdoor temperature for February 12 in Kayseri.

According to the solar radiation intensity levels on the window surfaces, heating loads have been evaluated for February 12. In the evaluation, the hours of 08:00-18:00, which are determined as the working hours of the day, have been taken into account (Figure 10).

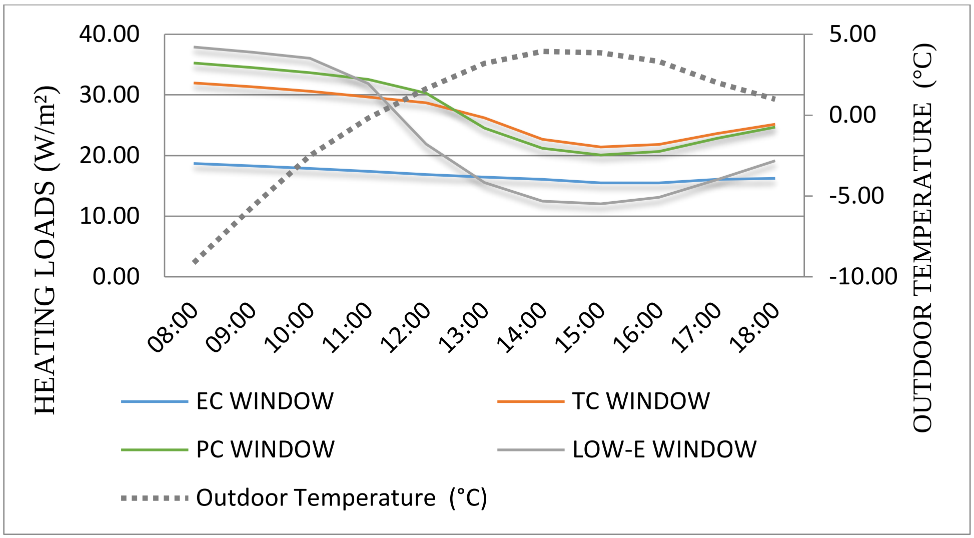

Figure 10 Heating loads of windows for February 12 in Kayseri.

Heating loads for each window option are at maximum values at 08:00 when the outdoor temperature is -9°C. A reduction has been observed in the heating loads on all windows until 15:00. Accordingly, the lowest and the highest heating loads are 15.49 and 18.69 W/m² for the electrochromic window, 21.41 and 31.97 W/m² for the thermochromic window, 20.09 and 35.26 W/m² for the photochromic window, and 12.03 and 37.90 W/m² for the low-E coated window in this hour range.

While there were no sudden fluctuations in the heating loads between hours 15:00-18:00, an increase has been observed in the heating loads on all windows. Accordingly, in this hour range, the heating loads reach the value of 16.24 W/m² for the electrochromic window, 25.16 W/m² for the thermochromic window, 24.69 W/m² for the photochromic window; and low-E coated window reached 19.15 W/m² at 18:00.

In the evaluation, the best-performing window type with the lowest heating load is the electrochromic window. The Low-E coated window has shown the best performance after the electrochromic window even though the beginning value of heating energy is the highest. Although the heating loads in thermochromic and photochromic windows are close by, the thermochromic window performed relatively superior to the photochromic window, hence photochromic window has shown the poorest performance.

When the total heating loads of the south-oriented office unit are compared during the day, the electrochromic window shows the best performance with the lowest heating energy use of 184.89 W/m² on February 12 in Kayseri (Figure 11).

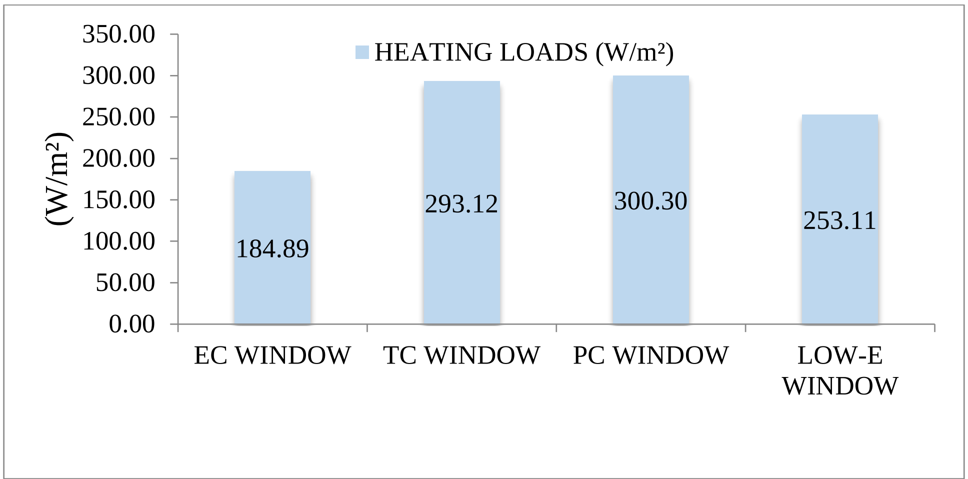

Figure 11 Total heating loads of the windows for February 12 in Kayseri.

Total heating loads on other smart windows are high during the day to ensure indoor comfort conditions. The best performing window systems after the electrochromic window are the Low-E coated window with a value of 253.11 W/m² and the thermochromic window with a value of 293.12 W/m², respectively. The worst-performing window system with the highest heating energy consumption is the photochromic window with a value of 300.30 W/m².

4. The Results of the study

Window systems in the high-rise office buildings are one of the most important components that make up the outer shell of the building, advanced in terms of functional and aesthetic aspects with the development of technology and offer better solutions to user needs. Windows are the facade elements with the highest heat loss and gain in the building envelope. Since they are transparent facade elements, they have a big role in terms of light and glare control in the interiors. Therefore, the windows used in the buildings are aimed at controlling the heat losses and gains while providing indoor comfort conditions for the user.

Within the scope of sustainability, it is expected that the building elements minimize energy loads such as heating, cooling, and lighting, that is for energy efficiency. Smart windows are innovative window systems developed and under research within the scope of this goal. The purpose of smart windows is to reduce heating and cooling loads and reduce energy expenditure by changing the opacity level of the window in response to solar radiation intensity. In recent studies, it is observed that smart windows can reduce heating and cooling loads in buildings. Within the scope of this study, the performances of smart windows and a traditional window system in Kayseri have been compared. In this comparison, the Low-E coated window system, which is a highly preferred window system, has also been added to the evaluation. The change in opacity of smart windows against solar radiation intensity in this climatic condition is given on an hourly basis for the dates of August 14 and February 12. The simulation study has been carried out with the Design Builder program. In this context, a case building has been modeled with four different window systems; daily performance of heating and cooling performances have been evaluated. Finally, total energy uses for electricity and primary energy in winter and summer time have been evaluated in Kayseri. Nevertheless, the differences in electricity are converted into primary energy with a conversion factor to prevent energy type differences in heating and cooling. According to the results, the total energy used for heating and cooling is given (Figure 12).

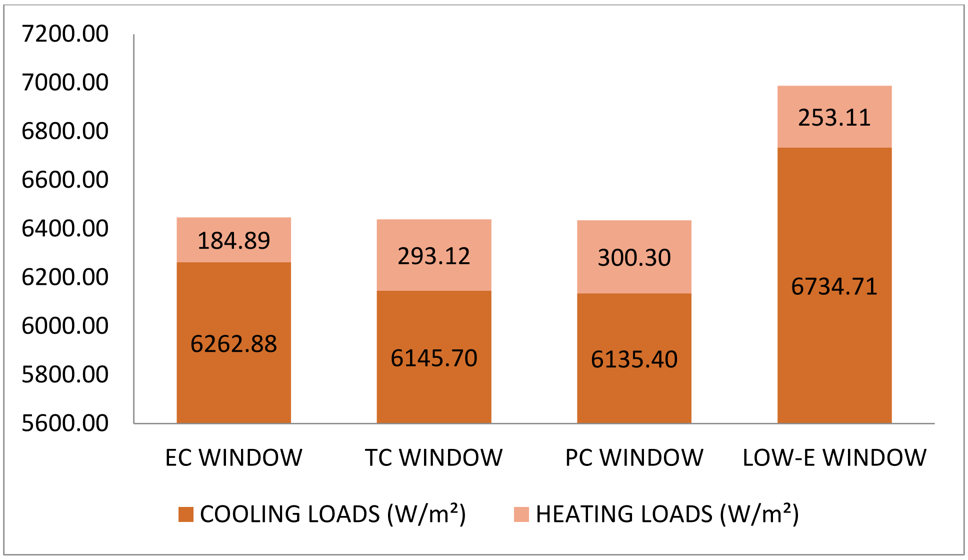

Figure 12 Total energy uses for heating and cooling for August 14 and February 12.

As the results of this study.

- Low-E window system has the least efficient cooling performance with the highest cooling loads of 6734,71 W/m².

- Although the cooling performances are close, the photochromic window system has a better performance than the thermochromic window system with the value of 6135,40 and 6145,70 W/m² respectively.
- In all smart window systems, the electrochromic window system shows the poorest performance on cooling loads with a value of 6262,88 W/m².
- Photochromic window system has the least efficient heating performance with the highest heating loads of 300,30 W/m².
- Although the heating performances are close, the thermochromic window system has a better performance than the photochromic window system in the winter period with a value of 293,12 W/m².
- In all window systems, the electrochromic window system shows the best performance on heating loads with a value of 184,89 W/m².
- Low-E coated window system shows the best performance on heating loads after electrochromic window systems with the value of 253,11 W/m².
- The photochromic window is the window system that showed the best performance with the lowest total energy use in Kayseri.
- In total energy uses, Low-E coated window system has the worst performance.

5. Conclusion

In conclusion, it has been observed that photochromic and thermochromic windows increase the building energy efficiency compared to other windows in Kayseri for winter and summer periods, hence total energy use, and it has been determined that their use is advantageous. In all smart window system types, electrochromic windows show the poorest performance, however, using electrochromic window have advantages in winter periods. When looking at the total values in Kayseri, the photochromic window shows the best performance. Therefore, photochromic windows are relatively preferable when compared to thermochromic and electrochromic windows in total energy use. Although Low-E coated window systems perform more positively in heating loads when compared to the photochromic and thermochromic window systems, Low-E coated window shows the poorest performance among all in total energy uses due to the higher cooling loads. This result can be explained by switching all smart windows to darker states due to the high solar radiation intensity, hence preventing overheating in the summer period in Kayseri. However, it has been observed that smart windows increase lighting loads due to being in the tinted state cause of high solar radiation intensity in recent studies, therefore their use may be considered disadvantageous for energy efficiency.

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Resume

Ayşenur Karakaya has completed the M.Sc in Environmental Control and Construction Technologies Programme from Istanbul Technical University, Turkey. She has a publication in smart materials named 'A Research About Smart Facade Materials Within the Context of Sustainable Architecture'. She is presently workings on more papers on smart materials and energy performances of smart windows and comparative studies on different cities. Her other areas of specialization include architectural design and construction drawings due to her career experiences.

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