ENERGY AND VISUAL COMFORT PERFORMANCE OF SMART WINDOWS IN OFFICE BUILDINGS IN HOT HUMID CLIMATE

BY

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بسم الله الرحمن الرحيم

This Thesis is dedicated

to

My parents, brothers,

Sister & Brother-in-law for their dua, constant support and encouragement throughout my life

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"Allah Grants Wisdom To Whom He Pleases, And The One To Whom Wisdom Is Granted Has Received Benefit Overflowing, And None Will Grasp The Message But Men Of Understanding." (Surah 2: Ayah 269)

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ABSTRACT

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In hot climates, the building envelope plays a crucial role in determining the building thermal and energy performance. Windows in particular play an important role in determining space cooling loads and also for the integration of artificial lighting and daylighting that can result in a significant energy reduction. Conventional windows while providing daylighting do not have any control over solar heat gain and visual discomfort resulting from glare. On the other hand, smart windows can be automatically tuned to control the glare level and consequently the amount of daylight and heat passing through the window. The objective of the study is to investigate the impact of smart window design on energy and visual performance in office buildings under hot climatic conditions.

To achieve the objective, the energy simulation program DesignBuilder was used to model a theoretical office building with conventional glass windows like clear, tinted and low-e. Low-e windows with daylight integration were found to be the most effective conventional glazing for reducing the building energy consumption. While automated venetian blinds as interior shading with solar controller reduced the building energy consumption by 16%. Three control techniques namely daylight, glare and solar are assessed and were used for altering the properties of smart windows. The analysis shows that replacing low-e windows with Electrochromic (EC) smart windows with daylight control resulted in the reduction of building energy consumption by 23%, but without satisfying the visual comfort. EC windows with glare control reduced the overall building energy consumption by 17%, satisfying the visual comfort. EC window with solar controller reduced the building energy consumption by 20%, and satisfying the visual comfort.

ملخص الرسالة

الاسم	:	محمد عبد ول فا سى
عنوان الرسالة	:	أداء الطاقة والراحة البصرية للنوافذ الذكية في المباني الإدارية في ظل المناخ الحار والرطب
التخصص	:	الهندسة المعمارية
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في المناخات الحارة، غلاف المبنى يلعب دورا حاسما في تحديد أداء المبنى الحرارية والطاقة. خاصة النوافذ التى تلعب دورا هاما في تحديد أحمال التبريد للفضاءات وأيضا دمج الإضاءة الاصطناعية وضوء النهار الذي يمكن أن يؤدي إلى خفض إستهلاك الطاقة بشكل كبير. رغم أن النوافذ التقليدية لها القدرة على توفير ضوء النهار بشكل جيد إلا أنها لا توفرأي سيطرة على اكتساب الحرارة الشمسية والراحة البصرية الناتجة من الوهج. من ناحية أخرى، النوافذ الذكية يمكن ضبطها تلقائيا للسيطرة على مستوى الوهج وبالتالي السيطرة على كمية ضوء النهار والحرارة التى تمر خلالها. الهدف من هذه الدراسة هو دراسة تأثير تصميم النافذة الذكية على الطاقة والأداء البصري في المباني الإدارية في ظل الظروف المناخية الحارة.

ولتحقيق هذا الهدف، تم استخدام برنامج المحاكاة للطاقة في تجسيد نموذج نظري لمبنى إداري ذو نوافذ زجاجية تقليدية ملون، وذات أستهلاك طاقة منخفض. خلال تحليل الطاقة تبين أن الزجاج منخفضة الطاقة هو الزجاج التقليدي الأكثر فعالية للحد من استهلاك طاقة المبنى على مختلف التوجهات. بينما الستائر المعدنية الآلي والتظليل الداخلية مع وحدة تحكم للطاقة الشمسية خفض استهلاك طاقة المبنى بنسبة 16٪.ثلاثة تقنيات للسيطرة هي ضوء النهار،الوهج، والطاقة الشمسية، قد وضفت وقيمت بتغيير خصائص النوافذ الذكية. يبين التحليل أن إستبدال النوافذ المنخفضة الطاقة بالنوافذ الذكية مع السيطرة على ضوء النهار أدى إلى الحد من استهلاك الطاقة في المبنى بنسبة 23٪، ولكن دون تلبية الراحة البصرية. النوافذ الذكية مع التحكم بالوهج خفض من استهلاك طاقة المبنى بنسبة 17٪، ولبى الراحة البصرية.النوافذ الذكية مع وحدة التحكم بالطاقة الشمسية خفض من استهلاك طاقة المبنى بنسبة 20٪،ولبى الراحةالبصرية.

CHAPTER 1

INTRODUCTION

1.1 Background

The present civilization is based on the ability of human to render the usefulness of energy. The cost of energy and demand are rising in real terms and it's likely to continue for the foreseeable future. There has been a sharp increase in the demand for electricity in the world due to the economic growth. According to the key world energy statistics 2012 edition, the primary energy supply in the world has increased by 52% from 1973 to 2010. **Figure** 1.1 shows the fuel shares of total primary energy supply in the world for the year 2010 **[1]**.

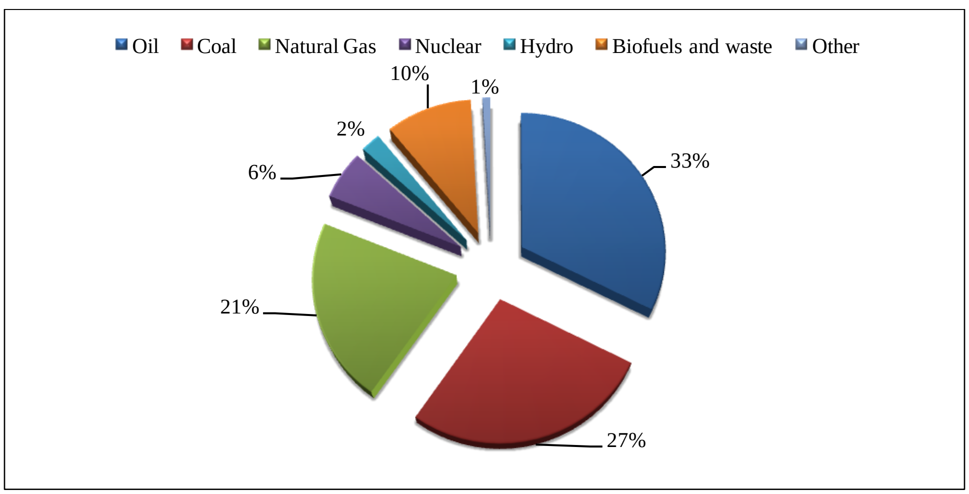


Figure 1.1: Total Primary Energy Supply in the World for 2010 **[1]**

Fossil fuels have been identified as the predominant source for low cost energy generation. They are formed by the anaerobic decomposition of buried dead organisms. **Figure** 1.2 shows the consumption of oil in the world, which has increased by 57% from

1985-2011. **[2]**. According to the International Energy Agency (IEA, 2011), the share of crude oil production is highest in Middle East, with 32% in 2011. Saudi Arabia produces most of the crude oil with 13% of total production in 2011 **[4]**. Nearly 85% of the world's energy consumption was based on fossil fuel. However if the ongoing rates of increasing energy consumption are allowed to continue, the world's total fossil fuel reserves would be completely exhausted within a few generation of a lifetime. Even if the annual rate of energy consumption were to remain constant, the diminishing availability of fuel would result in debilitating shortage, which would result in drastic changes in the sociological and economical behavior **[1]**.

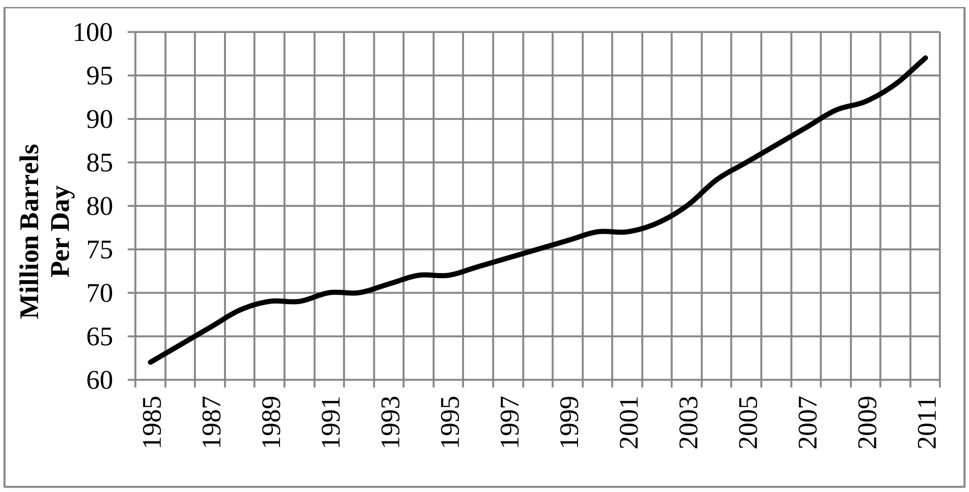


Figure 1.2: Oil consumption in the world based on EIA data 2012 **[2]**

The steady increase in the oil consumption has motivated many researchers to carry out their research in energy efficiency studies. Various energy conservation measures were developed as a result, aiming to provide cost-effective solutions for meeting instantaneous and short-term goals. With a growing concern regarding energy efficiency, developing countries started showing interest by doing investigation and developing their own energy standards for buildings. But the tasks are often delayed by the complexity of the building energy analysis and breadth of the subject. Efforts to investigate energy performance of buildings are usually impeded by insufficient recognition of the properties of energy analysis and simulation techniques and the lack of suitable local climatic data **[6]**. The building envelope is the interface between the interior of the building and the outdoor environment. By acting as a thermal barrier, it plays an important role in regulating interior temperatures and helps determine the amount of energy required to maintain thermal comfort. Minimizing heat transfer through the building envelope is crucial for reducing the need for space heating and cooling. Windows are generally considered as less energy efficient building components because they have the weakest thermal resistance in the envelope system. The transmission of solar radiation through windows is the primary energy flow through many commercial building envelopes. Solar heat loads often inflate building cooling loads. On the other hand, through the use of effective lighting control strategies, daylight admitted through windows can be used to offset electric requirements and lighting-induced cooling requirements, thus reducing building peak demand and energy use. These factors, in turn influence mechanical system sizing and cost **[4]**.

The total energy consumption in the world was about 505 quadrillion Btu in 2008 **[5]**. There were four major energy end-use sectors: commercial, industrial, residential, and transportation. The electric power sector produces the electricity which is consumed by the end-use sectors. During the process of electricity production the electric sector also consumes energy. Buildings worldwide account for a surprisingly high 40% of global energy consumption, and the resulting carbon footprint, significantly exceeding those of all transportation combined **[4]**.

Growth in population, enhancement of building services and comfort levels, together with the rise in time spent inside buildings have raised building energy consumption to the levels of transport and industry. Energy is consumed in buildings for various end use purposes: Space cooling/heating, water heating, ventilation, lighting, cooking, and other appliances. Office buildings and retail consumes the most energy and they account for 50% of the total energy consumption for non-domestic buildings **[5]**. Office buildings are required to provide better environmental quality to enhance occupant's productivity and performance. They consume large portion of energy to maintain the comfort level inside the building. In USA office buildings accounts for 17% of total non-domestic area and about 18% of the energy use, equivalent to 3.2% of the total consumption. **Table 1** shows the breakdown of energy consumption in office buildings in few developed countries

Table 1: Energy breakdown in office buildings

Energy End-Use	USA (%)	UK (%)	Spain (%)
HVAC	48	55	32
Lighting	22	17	53
Equipment	13	5	10
DHW	4	10	-
Food preparation	1	5	-
Refrigeration	3	5	-
Others	10	4	5

Figure 1.3 shows the energy flow in a typical office building based on studies conducted by researchers for the year 2010. From the survey it was found that lighting consumes bulk of the energy for maintaining the visual comfort in the building where as cooling and heating together accounts for 25% **[1]**. Lighting consumes the most because of the precision involve in the work and complex functional requirements,

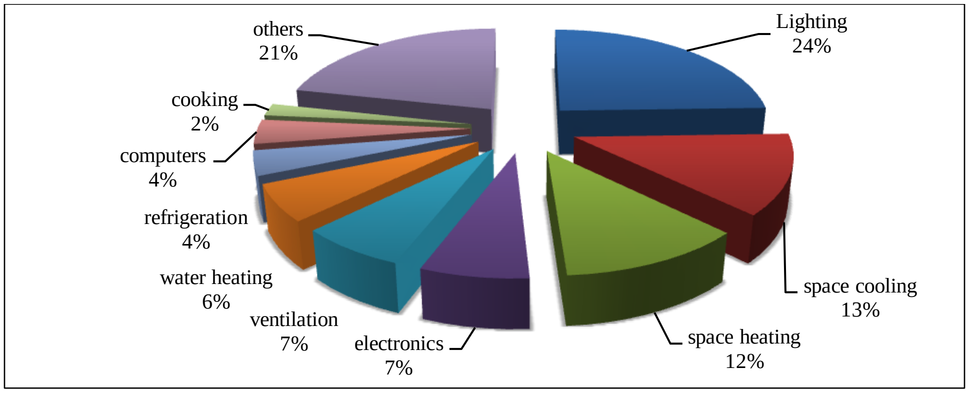


Figure 1.3: Typical Energy Flow in Office Buildings **[1]**

Figure 1.4 shows the energy signature for artificial lighting for different facilities in the world for the year 2010. **[1]**. Office and healthcare facilities rank the highest energy consumption per unit area because of the functionality and the impact of lighting on the productivity of the staff.

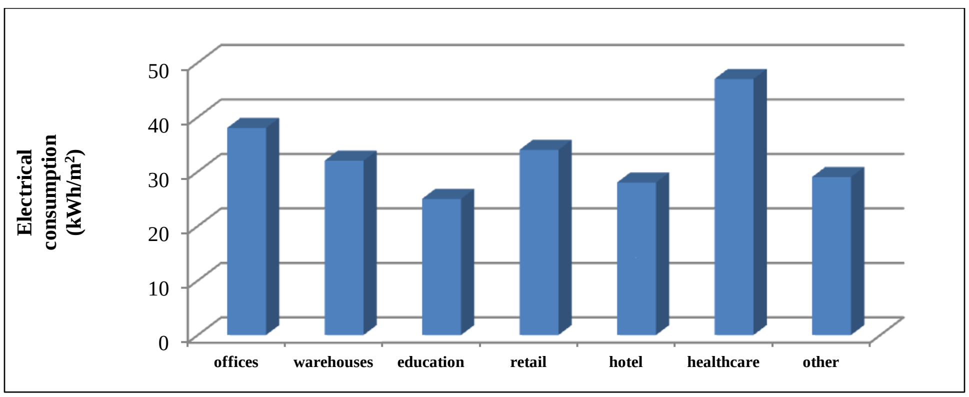


Figure 1.4: Lighting Energy Signature for Various Buildings for the Year 2010 **[1]**

In hot climates, cooling accounts the highest share of energy consumption in office buildings. Internal gains from occupants, equipment and lighting contribute a significant proportion of the heat gains. Solar heat gain through windows is a significant factor in determining the cooling load of many office buildings. Some radiation is directly transmitted through the glazing to the building interior, and some may be absorbed in the glazing and indirectly admitted to the inside. Some radiation absorbed by the frame will also contribute to overall window solar heat gain factor. Solar heat gain is influenced by the glazing type, the number of panes, and any glass coatings. Daylight is an important part of the desire for windows and has qualities that cannot be replicated by electric light. Daylight design is far more sophisticated than simply providing a window with a high enough visible transmittance. More daylight does not necessarily equate to better lighting conditions. It is a matter of balancing daylight admission with glare control, as well as providing uniform light distribution. Conventional glass windows do not have any control over solar heat gain while utilizing the daylight from outside. During the process of daylight admission, direct sunlight penetration in office spaces often produces an unpleasant glare on work surfaces, making it difficult to work or view a computer screen.

Daylighting also calls for controlling the amount of heat that enters a building through conventional windows, because the sun is such a powerful source to light buildings, it can also produce tremendous amounts of heat. If daylighting is not planned properly, undesirable heat may be transferred through the windows. It may seem that it would be difficult to increase the amount of light without bringing in extra heat. However, the use of Smart windows can minimize the heat gain and will reduce the cooling loads, eliminating the need for a larger cooling system, resulting in additional overall savings. A smart building is one which uses various advance process and latest technology to develop a building environment that is more productive and is safer for its occupants and more operationally efficient for its owners. Creating a smart building does require an endowment in advance processes, solutions and technology. An upfront investment is required to realize a significant return later on. It’s not practical expecting to make a project intelligent unless there is early buy in on investment. Early design decisions are needed to make the project feasible. One of the difficult tasks is to convey the benefits of an intelligent building design to the building owner. A smart building starts with an environmentally friendly design. Developing a project that is energy efficient and environmentally friendly ties in closely with many of the intelligent attributes **[6]**. These buildings are designed for minimal environmental impact and long-term sustainability through the construction maintenance and operation procedures and selection of materials. They are intended to be the preferred environment for occupants. This requires focused attention to environmental factors that affects occupant's comfort, productivity and perception. The design of the intelligent building finds the balance by optimizing the operations, providing the ability to integrate the controls in the building, and enterprise level management results in a significant enhancement in energy efficiency, lowering both cost and energy usage compared to non-intelligent projects **[7]**. In 2002, the US Department of Energy (DOE) worked with members of the window industry to create a roadmap that helped define the technologies and tools that will be needed to create and sell the next generation of windows. Window industry executives identified a new generation of dynamic, responsive "Smart Windows" as the number one top priority. Smart windows include chromogenic glazings that can be reversibly switched from a clear to a transparent, colored state by means of a small applied voltage, resulting in thermal and optical properties that can be dynamically controlled. "Smart windows" incorporating Electrochromic glazing's could reduce peak electric loads significantly in many commercial buildings and provide added daylighting benefits, as well as improve visual comfort and enhance productivity in homes and offices. These technologies can provide maximum flexibility in managing energy use in buildings in the emerging deregulated utility environment and could move the building community toward the goal of producing advanced buildings that will have minimal impact on the nation's energy resources. Customer choice will be further enhanced by the flexibility to dynamically control envelope-driven cooling and lighting loads **[8]**.

1.1.1 Energy Consumption in Countries with Hot Climate

Hot Desert climates are formed by high-pressure zones in which cold air descends. The descended air becomes warm but, instead of releasing rain, the heat from the ground evaporates the water before it can come down as rain. The ground becomes super hot because the sun's rays beat down on it directly overhead. Not a lot of atmosphere to protect it from radiant energy. The climate of Saudi Arabia can be a representative of hot desert climate with extremely high day-time temperatures and temperature drop at night in most parts of the kingdom. The kingdom is dependent on fossil fuels for generation of electric energy which happens to be the principle form of energy delivered to buildings. Summers can be extremely hot with temperatures rising to 50ºC in some areas. **Table** 2 reveals the electric production from 2004 to 2008 **[4, 6]**.

Table 2: Energy Production in Saudi Arabia **[6]**

Energy in Saudi Arabia						
	Capita	**Primary Energy**	**Production**	**Export**	**Electricity**	**CO_2-emission**
	Million	**TWh**	**TWh**	**TWh**	**TWh**	**Mt**
2004	24.0	1,633	6,469	4,811	148	324
2007	24.2	1,748	6,412	4,606	175	358
2008	24.7	1,879	6,734	4,796	187	389
Change 2004–2008	2.9 %	15.1 %	4.1 %	-0.3 %	26.1 %	20.1 %
Mtoe = 11.63 TWh, Prim. energy includes energy losses						

Electricity consumption in Saudi Arabia increased sharply between 1990–2010 due to rapid economic development. Peak loads reached nearly 24 GW in 2001—25 times their 1975 level-and are expected to approach 60 GW by 2023 **[6]**. The investment needed to meet this demand may exceed $90 billion. Consequently, there is an urgent need to develop energy conservation policies for sustainable development. Electricity generation was 65% from Oil, 27% from Natural Gas and 8% from steam. Generation capacity was approximately 30 GW **[5]**. A looming energy shortage requires Saudi Arabia to increase its capacity. Total energy consumption is growing steadily and very rapidly, at an average rate of 5.8 percent / year since 1990; and has tripled between 1990 and 2009 **[6]**. Energy consumption in building sector, reached about 76% with 11% allocated to commercial buildings including office buildings for the year 2007 in Saudi Arabia **[5]**. Office buildings, because of their functional and environmental requirements, have special characteristics compared to other buildings. They are required to provide better environmental quality to enhance occupants' productivity and performance, but at the same time they consume a large proportion of energy to maintain lighting requirements and visual comfort. As much as 20% of the total energy consumed by an office building goes to lighting **[10]**. Therefore, it is obvious that office buildings have great potential for energy savings and enhanced indoor environmental quality when daylight is integrated with artificial lighting. **Figure** 1.5 shows the distribution of energy in the various building sectors for the year 2007 **[5]**.

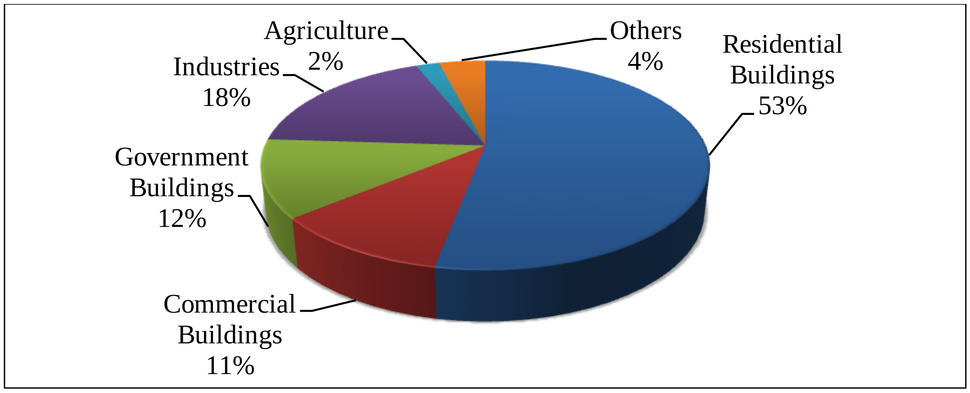


Figure 1.5: Electrical energy Usage in Different sectors, Saudi Arabia **[5]**

Kuwait is also considered to be an example of hot dry desert climate and is one of the smallest countries in the world in terms of land area. It's located in the North-East corner of the Arabian Peninsula. According to International Energy Agency, Ten countries produced over 60% of the world oil production in 2009. The countries were: Russia (13%), Saudi Arabia (12%), US (8%), Iran (5%), China (5%), Canada (4%), Mexico (4%), Venezuela (3%), Kuwait (3%) and United Arab Emirates (3%) [6]. Kuwait has a desert climate, hot and dry. In summer, average daily high temperatures range from 42 to 46 °C. The summers are relentlessly long, punctuated mainly by dramatic dust storms in June and July when northwesterly winds cover the cities in sand. In late summer, which is more humid, there are occasional sharp, brief thunderstorms. By November, all of the hot weather is over, and colder winter weather sets in, dropping temperatures to as low as0 °C (32 °F) at night; daytime temperature is in the 15–20 °C (59–68 °F) range. Table 3 reveals the electricity production from 2004 to 2008 in Kuwait **[39]**.

Table 3: Energy Production in Kuwait **[39]**

Energy in Kuwait						
	Capita	Prim. energy	Production	Export	Electricity	CO_2-emission
	Million	TWh	TWh	TWh	TWh	Mt
2004	2.46	292	1,544	1,246	36.8	64.9
2007	2.66	293	1,705	1,398	43.1	66.8
2008	2.73	306	1,777	1,452	45.7	69.5
2009	2.8	351	1,515	1,146	46.6	80.7
2010	2.74	388	1,558	1,159	50.1	87.4
Change 2004-2010	11.4%	33%	0.9%	-6.9%	36.3%	34.8%
Mtoe = 11.63 TWh, Prim. energy includes energy losses						

In relation to population the electricity use in Kuwait in 2008 was more than double compared to Saudi Arabia, Japan and Denmark. In Kuwait 45.7 TWh of electricity is used for 2.7 million capita, for Denmark 35 TWh is consumed for 5.49 million capita, for Japan 1031 TWh for 127.7 million capita and where as for Saudi Arabia 187 TWh is consumed for 24.7 million capita. The carbon dioxide emissions per capita of Kuwait were 1.6 times compared to Saudi Arabia and 2.8 times compared to Japan **[6]**. Buildings in Kuwait are estimated to consume 70% of the electrical power generated. The buildings are not only subjected to high ambient air temperatures, averaging 45.8 ^{o}C, but also to strong solar radiation, which strikes each part of the building in turn as the sun moves around a clear sky. The solar intensities on horizontal surfaces are the greatest at mid-July, reaching 940 W/m^2, affecting roof surfaces under high intensity solar radiation **[7]**.

1.2 Statement of the Research Problem

Among many other building types, office buildings have greater importance, because they house a lot of people who spend most of their time in offices. They are typically occupied during regular daytime hours while remain unoccupied or partially occupied at night and during weekends. An office building consumes a lot of electricity for maintaining the thermal and visual comfort in the building. The majority of this electricity is used for lighting and office equipment (such as computers, printers, faxes and photocopiers). Both lighting and office equipment produce heat, requiring more air conditioning, another predominantly electric end use to cool the buildings. The envelope of an office building contains high window-wall and it plays an important role in determining the thermal and energy performance of a building. Air-conditioning and artificial lighting consume significant amounts of the energy supplied to a building; therefore, it is essential that the performance of these systems be optimized in order to achieve energy savings. An important factor that can lead to savings is the amount of daylight entering a room, as this can reduce both the artificial lighting and air-conditioning load at the same time. Conventional windows do not have any control while utilizing the daylight, which results in high solar gain from outside and visual discomfort as result of which HVAC system and artificial lighting tend to consume higher energy.

1.3 Significance of the Research

Energy conservation in buildings can be achieved through many strategies. One of these strategies is the integration of daylight and lighting controls to reduce the energy consumption by Artificial lighting systems. Energy savings resulting from daylighting may not only lower electric lighting expenditure and reduce peak electrical demands, but also decrease cooling energy consumption by reducing the heat gain. The drive for energy conservation has fostered efforts to develop new types of window glass for everything from skylights and windows in houses to conference room walls in offices. Smart windows offer shading of solar light and heat to reduce building cooling loads in warm periods, yet allow greater amounts of light and heat in during warm periods, reducing heating and lighting loads as well. These improvements in energy efficiency are typically required to meet green certification requirements, and they are often preferable to mechanical louvers or other, more complex, alternatives.

Smart glass windows offers convenience features like controlled visibility, partial dimming, and privacy—in interior or exterior windows—provide important added value and are controllable at will. They can appropriately modulate heat transfer from the transmitted sunlight in a house and can moderately suppress unnecessary energy usage through air conditioning or heating.

This study will be directed towards the potential benefits of smart windows in reducing the cooling energy consumption and lighting consumption and maintaining the visual comfort in office buildings in hot climate. This study is significant for the designers as well as building owners of office buildings for exploring the benefits of smart windows.

1.4 Objectives

The main objectives of the research are as follows:

1. Investigate the impact of smart window design on cooling and lighting energy consumption in an office building considering daylight and artificial lighting integration.

2. Identify the most potential energy-efficient and visually comfortable smart window design with control mechanism for an office building in hot climate and also calculate the simple payback period for implementing various smart window designs and recommending various energy conservation opportunities.

1.5 Scope and Limitations

The scope of this research is to investigate the performance of smart window in minimizing the Lighting and cooling energy consumption while maintaining the visual comfort in the office building and also explore the benefits of smart window in hot climate. Controllers for smart window were selected based on electricity consumption and visual comfort. The research is focus on determination of smart window design to optimize daylighting and improve the visual comfort in office building. In the design of smart window, type of glazing and orientation was taken into consideration. Optimal WWR was determined for an office building with smart windows in hot humid climate. Energy performance is studied by rotating the building with smart window for different orientations. Three control techniques were used to alter the properties of smart window glazing. The research is limited to hot-humid climate as represented by the Dhahran city and the type of building which is considered is an office building with rectangular geometric shape, and the research focus only on two types of smart windows (Electrochromic smart window and Automated venetian blind smart window) due to the limitations of the software tool.

1.6 Research Methodology

Building energy simulation was carried out for investigating the impact of smart window on energy and visual performance in an office building for the daylight integration. It’s considered as a systematic way to measure, analyze and assess the performance of a smart window. In order to accomplish the objectives of the research, 4 phases were made which are as follows:

Phase-1: Literature Review

This phase includes a comprehensive literature review of

- Energy consumption and Energy End-use of office buildings in hot climate
- Visual comfort analysis of buildings
- Previous studies related to office building designs in hot-humid climate
- Influence of smart windows on lighting and cooling energy consumption and in office buildings
- The international standard requirements for lighting in office buildings

Phase-2: Formulation of Base model and Verification

- Selecting a software tool from group of available energy simulation programs for modeling the office building in hot climate
- Modeling the base case model of office building by inputting the Building characteristics obtained from literature review
- Simulating the base case model, and studying the energy performance and visual comfort for the zones in the office building
- Verification of the Base case model

Phase-3: Investigation and Analysis of Results

- Identifying the best controller for altering the properties of the EC smart window based on the energy and visual comfort performance
- Comparison of EC smart window with conventional windows
- Identifying the optimal WWR for office building with smart window based on the energy and visual comfort performance

Phase-4: Conclusion & Recommendations:

- Based on the analysis of the results, the conclusion and recommendations will be given and summarized to assist designers for making use of smart window system that possibly will improve the both energy and visual performance of office buildings.

Figure 1.6 shows the flow chart of the research methodology which was followed in order to accomplish the objectives of the research.

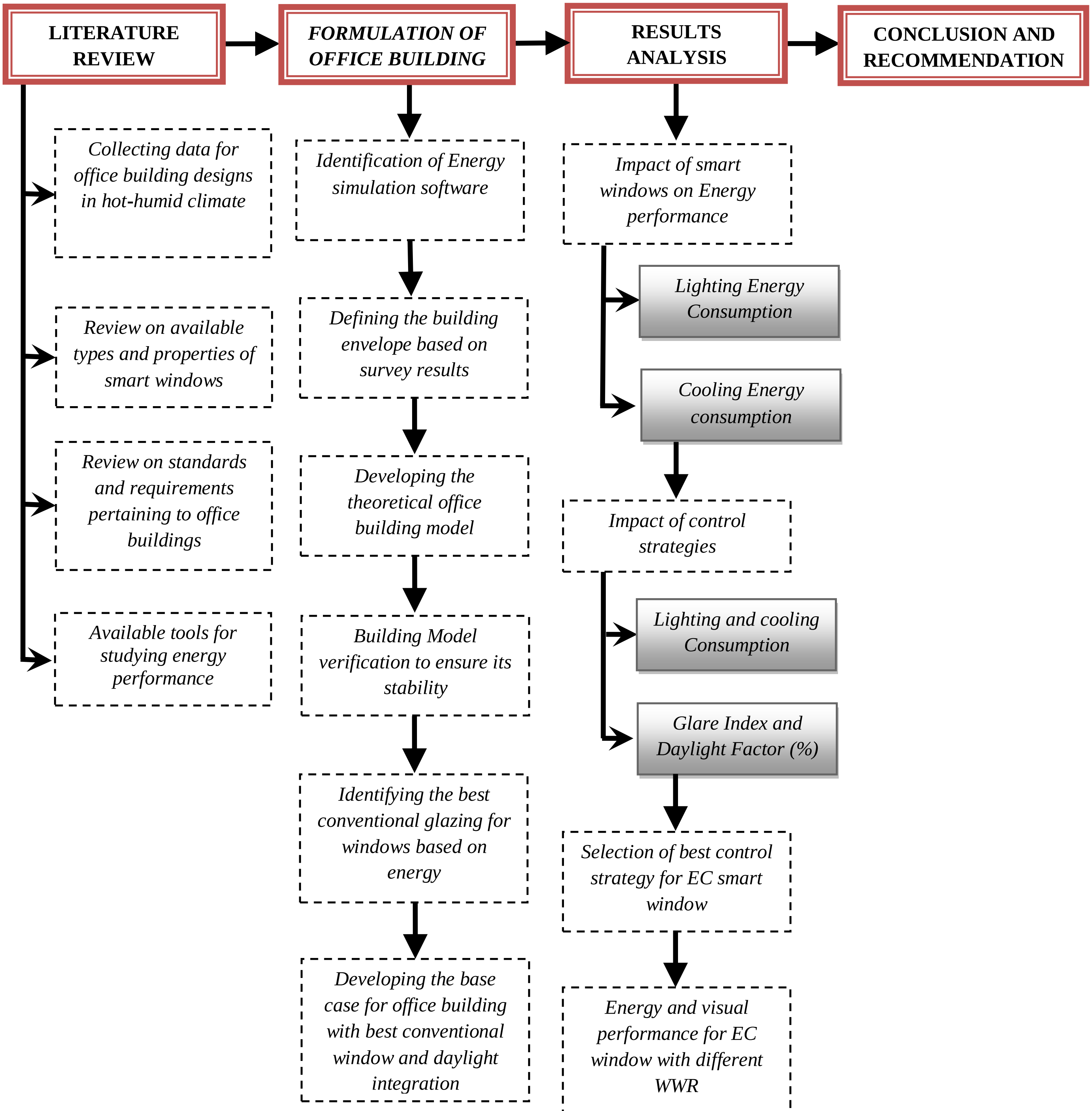


Figure 1.6: Flow Chart of Research Methodology

CHAPTER 2

LITERATURE REVIEW

The literature presented in this chapter is divided into three sections. The first section presents the energy consumption in buildings in hot climate. In the second section the research work done for smart windows in reducing the energy consumption and for maintaining the visual comfort is discussed. The last section of this chapter presents summary of the literature review.

2.1 Energy Consumption in Buildings

The rapidly growing world energy use has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). Growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside buildings, assure the upward trend in energy demand will continue in the future. For this reason, energy efficiency in buildings is today a prime objective for energy policy at regional, national and international levels **[9]**.

In the United Kingdom building energy consumption has increased at a rate of 0.5% per annum, which is slightly below the European figure of 1.5%. In contrast building energy consumption in Spain is increasing at a rate of 4.2% per annum, well above both the European and the North American (1.9%) rate **[10]**. Reasons can be found in the economic growth, expansion of the building sector and the spread of building services, especially lighting and heating, ventilation and air conditioning (HVAC) systems. Residential and commercial buildings consume more than one-third of Europe's primary energy budget **[12]**. Commercial buildings, and primarily office buildings, are classified among the buildings presenting the highest energy consumption. Typical primary energy values for offices in Northern Europe fall between 270 and 350 kWh/m^2/year **[1]**. Energy in office buildings is consumed mainly for heating, cooling, and lighting purposes, while a significant portion is devoted to the consumption of office equipment. Application of energy conservation techniques in offices, require knowledge of the specific energy characteristics of the buildings. The frequency distribution of the building's final energy consumption, the specific energy requirements for each type of use and the characteristics of the installed systems are amongst the necessary information **[11]**.

The exterior envelope of a building has a major effect on the heating and cooling loads required to maintain a satisfactory interior environment and, in consequence, on the energy consumption of the building. In addition to its influence on energy consumption, the building envelope also plays other roles. For instance, the amount of glazed area affects the level of satisfaction of occupants through the availability of daylight and view **[12]**. The overall aesthetic impact of a building is largely determined by its facade. In setting out to develop a systematic approach for the assessment of the exterior envelope, it is necessary to consider all of the functions of the envelope and not solely those that directly concern energy efficiency **[13]**.

According to the Department of Energy (Buildings Energy Data Book, 2010) Commercial buildings represent just over 18% of U.S. energy consumption of 96.3 Quads (1 Quad= 2.93*10^{11} kWh). Office, retail, and educational facilities represent about half of commercial sector energy consumption. Windows are responsible for 1.88 Quads of energy for heating and 3.86 Quads of energy for cooling **[13]**. Windows have a dominant influence on a building's appearance and interior environment, yet windows can be one of the most important components impacting its energy use, peak electricity demand, and environmental consequences. Heat gain and heat loss through windows can represent a significant portion of a building's heating and cooling loads. By providing natural light, windows can reduce electric lighting loads by using design strategies such as dimming controls, automated shading, and light redirection **[14]**.

2.2 Types of Conventional Windows

Windows are commonly characterized according to the type of tint or coating that is applied to the glass to alter its performance and the number of panes of glass. High performance windows include reflective, heat-absorbing and spectrally selective glazing’s **[13]**.

Glazing options – In order to satisfy different types of design conditions and performance requirements a wide variety of glazing options are available. It can be tinted, clear, spectrally selective coatings such as low-emissivity (low-E) coatings and reflective. They can be single, double or triple pane. The space between panes of glass can be filled with an inert gas (typically Argon) that doesn’t allow heat to pass readily. Common glazing options include **[13]**:

- **Clear glazing** – This is the standard without any type of coating or tint designed to alter the energy performance or visibility of the glass.
- **Tinted glazing –** They are often described as economical way to reduce solar heat gain though facades. Generally referred to as "heat-absorbing" glass. Tinted

glazing blocks solar heat and reduces the direct solar heat gain but it rises the temperature of the glass.

- **Spectrally selective glazing** – This type of glazing are designed specifically to transmit higher level of visible light while still controlling solar heat. This is done by giving different feedback to different wavelengths of solar energy allowing for much clearer glass with good solar control. They provide a high level of design flexibility as different coatings and performance characteristics can be selected for each orientation providing optimal solar control while maintaining a uniform appearance. Popular "low-e" or "low-emissivity" glazings are a type of spectrally selective glazing that is typically selected to provide good visible transmittance, and good solar control.
- **Reflective glazing** – Semitransparent metallic coatings are applied to clear or tinted glass to provide a high level of solar heat control. However, they reduce cooling loads at the expense of daylight transmittance. They can also cause glare problems in the surroundings and unintended heat gain in surrounding buildings.

2.2.1 Window Performance Ratings

Window systems are rated using several performance parameters that allow designers to select a glazing option that satisfies a project’s aesthetic, comfort, daylighting and energy efficiency criteria. Several important window performance ratings are discussed below, and **Table** 4 compares typical ratings for different types of windows **[13, 14]**.

- **U-Value** – The rate of heat flow through a window assembly due to the temperature difference between the two sides of the window. The lower the U-value, the greater is the thermal resistance offered by the window.

- **Shading Coefficient (SC) –** It's the ability of glazing to block the sun's radiant heat. Shading coefficient is the ratio of solar heat gain of a window compared to single-pane 1/8" clear glass. The lower the SC, the lower is the solar heat gain through the window.
- **Solar Heat Gain Coefficient (SHGC) –** It refers to the fraction of solar radiation passing through a window as heat compared to the amount of solar radiation striking the window. The SHGC is becoming a standard performance metric and is becoming more common in the performance ratings of manufacturers.
- **Visible Light Transmittance (VLT) --** The percentage of visible light that passes through the window assembly. A high VLT indicates a greater fraction of incident natural light passing through the window. Reducing cooling loads by specifying lower SC and SHGC ratings needs to be considered in conjunction with the visible light transmittance of the glazing choice to achieve a balance between cooling load reduction and the desired natural light environment.

Table 4: Typical Window Performance Values **[13]**

Glazing Type	U-Value Of Glazing ($W/m^2. K$)	Shading Coefficient	Solar Heat Gain Coefficient	Visible Light Transmittance
Single-pane, clear	0.88	1.00	0.86	90%
Double–pane, clear	0.48	0.87	0.75	81%
Double – pane, clear, low-e	0.32	0.70	0.60	73%
Double–pane, tinted (bronze)	0.48	0.59	0.50	48%
Double – pane, tinted (green), low-e	0.32	0.48	0.42	61%
Double–pane, reflective	0.48	0.26	0.22	18%

2.2.2 Windows Systems for High Performance Buildings

Smart widow design can be used in office buildings for reducing the lighting and cooling energy consumption and also satisfying the visual requirements in the office buildings. They allow the integration of daylighting with artificial lighting system **[14]**. Properly designed windows play an important role in achieving energy and environmental goals and contribute to the comfort, satisfaction, and productivity of building occupants. Smart windows that can change transparency to manage solar heat gain, glare, and daylighting are building buzz in the green building world. According to Environmental Protection Agency, in operating Buildings cooling, heating, lighting accounts for about 36% of overall energy consumption **[15]**. The 21st century has ushered in an era marked by the growing integration of technology and other scientific advances into commercial buildings and residential homes. Of particular interest to many architects, developers and builders are Smart glazing, a new category of technologically advanced glass and plastic building materials that can be used to control light, glare and heat entering an office or a home. Interest in Smart glazing technology is influenced by a variety of factors, including a growing movement to offer sustainable, energy-efficient building solutions, and the emerging desire by users to maintain greater control over their working and living environments. Windows are usually glazed or covered in some other transparent or translucent material like float glass. They are held in place by frames, which prevent them from collapsing in. Many glazed windows may be opened, to allow ventilation, or closed, to exclude inclement weather **[16]**.

A switching device integrated in or attached to a window glazing offers adjustable control of the energy that flows through the window aperture. Electrochromic optical shutter devices can eliminate internal and external shading devices and can provide daylighting for the workspace, reducing lighting energy loads. Also they assure privacy and glare control. An ideal optical shutter might be one that responds automatically to a changing ambient environment to provide comfort, visual needs, and energy savings. Such a device may be connected to a building's energy management system that adjusts heating, cooling, and even lighting to workplace needs **[17]**.

In 2002, the US Department of Energy (DOE) worked with members of the window industry to create a roadmap that helped define the technologies and tools that will be needed to create and sell the next generation of windows. Window industry executives identified a new generation of dynamic, responsive “Smart Windows” as the number one top priority. Smart windows include chromogenic glazings that can be switched from a clear transparent state to opaque colored state by means of a small applied voltage, resulting in thermal and optical properties that can be dynamically controlled. Smart windows incorporating Electrochromic glazings could reduce peak electric loads significantly in many commercial buildings and provide added daylighting benefits, as well as improve comfort and enhance productivity in homes and offices **[18]**. Customer choice will be further enhanced by the flexibility to dynamically control envelope-driven cooling and lighting loads **[17]**.

The ideal window would be one with optical properties that could readily adapt in response to changing climatic conditions or occupant preferences. There are two basic types of smart windows, Passive smart windows that respond directly to a single environmental variable such as light level or temperature, and Active smart windows devices that can be directly controlled in response to any variable such as occupant preferences or heating and cooling system requirements. The main Passive smart windows are photochromics and thermochromics; Active smart windows include suspended particle and Electrochromic **[19]**.

Photochromic Smart Window

The transparency of Photochromic materials changes in response to light intensity. These materials have been used in eyeglasses that change from clear in the dim indoor light to dark in the bright outdoors. They may be useful in conjunction with daylighting, allowing just enough light through for lighting purposes, while cutting out excess sunlight that creates glare and overloads the cooling system. Although small units have been produced in volume as a consumer product, cost-effective, large, durable glazings for windows are not yet commercially available **[13]**. **Table** 5 illustrates the thermal characteristics of photochromics glass for both bleached and colored state.

Table 5: Thermal Characteristics of Photochromics for Both States **[13]**

State of Glass	Visible Transmission (%)	Solar Transmission (%)	Solar Heat gain coefficient	Durability
Photochromic ON state	***10***	***23***	***0.12***	***10-15 years***
Photochromic OFF state	***60***	***53***	***0.46***	

Thermochromic Smart Window

Thermochromics change transparency in response to temperature. At specific temperature the material undergoes a semi-conductor to metal transition. At temperatures lower than critical temperature the window lets all of the solar energy that hits it through. At temperatures above critical temperature the window reflects the infra-red portion of solar energy. In such a way thermochromic windows may help reduce air conditioning and heating costs leading to more energy efficient buildings. **Figure** 2.1 shows the function of thermochromic in response to the outside temperature. The temperature of the glass, which is a function of solar intensity and outdoor and indoor temperature, would regulate the amount of sunlight reaching the thermal storage element. Prototype glazings have been tested but are not yet commercially available **[13]**. **Table** 6 shows the properties of a thermochromic glass for both clear and opaque state.

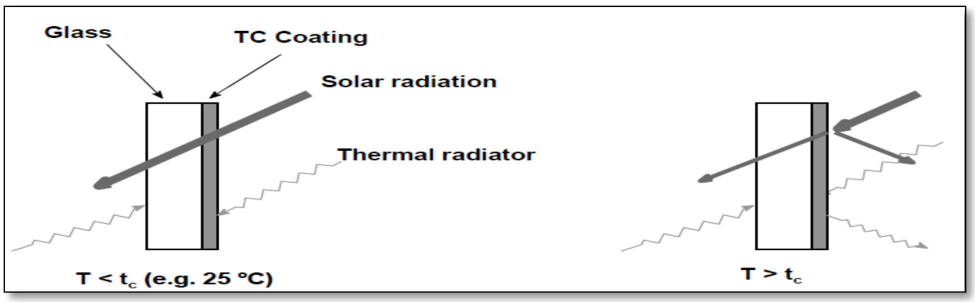


Figure 2.1: Schematic Demonstration of the Application of Thermochromic **[13]**

Table 6: Thermal Characteristics of Thermochromic Glass for Both States **[12]**

State of Glass	Visible Transmission (%)	Solar Transmission (%)	SHGC	Durability
ON State	***8***	***14***	***0.12***	***>12 years***
OFF State	***44***	***40***	***0.43***	

Suspended Particle Device (SPD) Windows

SPD-Smart Glass can be manually or automatically "tuned" to precisely control the amount of light, glare and heat passing through. Glass facades using SPD light-control technology reduce the need for air conditioning during the summer months and heating during winter. These windows give the ability to instantly switch a window to maximize daylight when it's really needed and to provide controllable solar shading during peak light conditions. This electrically controlled film utilizes a thin, liquid-like layer in which numerous microscopic particles are suspended. In its unpowered state the particles are randomly oriented and partially block sunlight transmission and view. Transparent electrical conductors allow an electric field to be applied to the dispersed particle film, aligning the particles and raising the transmittance. The device requires about 100 volts AC to operate from the off state (colored) to the on state (near transparent) and can be modulated to any intermediate state. Power requirements are 0.5 W/ft^2 for switching and 0.05 W/ft^2 to maintain a constant transmission state if not off. Long-term durability and solar-optical properties have not been independently verified. Products are now entering the market, but cost remains an issue **[12, 13]**. **Table** 7 illustrates the characteristics of SPD glass, which is actively controlled by means of electricity for changing the state from colored to transparent.

Table 7: Thermal Characteristics of SPD Glass for Both States **[12]**

State of Glass	Visible Transmission (%)	Solar Transmission (%)	SHGC	Durability
ON State	***44.5***	***34.4***	***0.8***	***>=30 Years***
OFF State	***4***	***11***	***0.47***	

Electrochromic Smart Windows

The most promising switchable window technology today is Electrochromic (EC) windows. An Electrochromic coating is typically five layers, about one micron thick, and is deposited on a glass substrate. The Electrochromic stack consists of thin metallic coatings of nickel or tungsten oxide sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film through the ion conductor (electrolyte) and into the Electrochromic film. The effect is that the glazing switches between a clear and transparent Prussian blue-tinted state with no degradation in view, similar in appearance to Photochromic sunglasses. The main advantages of EC windows is that they require low-voltage power (0–10 volts DC), remain transparent across its switching range, and can be modulated to any intermediate state between clear and fully colored **[13]**. Low emittance coatings and an insulating glass unit configuration can be used to reduce heat transfer from this absorptive glazing layer to the interior. A low transmission is desirable for privacy and for control of direct sun and glare, potentially eliminating the need for interior shading. A high transmission is desirable for admitting daylight during overcast periods. Therefore, the greater the range in transmission, the more able the window is to satisfy a wide range of environmental requirements **[16]**. This type of device has a long memory once switched (power is not required for three to five days to maintain a given switched state). A 3-by-6- foot window can take 10–15 minutes to switch across its full range if it is warm and up to 25 minutes when it is cold **[17]**. Electrochromic glazings are fabricated as insulated glass units using standard or laminated glazing. Wire leads extending from one edge are tied into the building's electrical system. The window can also be powered using photovoltaic cells to avoid the cost of wiring to the building. Once installed, the window or skylight can be operated by a manual switch or remote controller, a simple stand-alone automatic system, or a sophisticated central energy management system that integrates its operation with other building systems, such as the electric lighting and mechanical system **[18]**. Controlling and modulating incoming light and solar heat gains leads to lower energy bills and increased occupant comfort. Electrochromic windows give building owners the ability to modulate heat gain through the window, reducing cycling stress on HVAC motors and other equipment **[19]**. Electrochromic glazing provides functionality that other types of shading do not, for example, in darker states; it is still possible to provide view rather than blocking it completely with drawn shades or blinds **[18]**.

The energy and visual performance of EC smart window has been studied in this research and further benefits were highlighted after the daylight integration with artificial lighting in office building. **Table** 8 shows the thermal characteristic of the EC smart glass for ON and OFF states.

Table 8: Thermal Characteristics of EC Smart Glass for Both States **[13]**

State of Glass	**Visible Transmission (%)**	**Solar Transmission (%)**	**SHGC**	**Durability**
ON State	***4***	***9***	***0.09***	***>=30 Years***
OFF State	***62***	***35***	***0.48***	

2.3 Smart Window Systems for Reducing the Energy Consumption

Eleanor S. Lee et al. monitored the results from a full-scale demonstration of large-area Electrochromic windows **[28, 29]**. The test consisted of two side-by-side, 3.7x4.6- m office like rooms. In each room, five 62x173-cm lower Electrochromic windows and five 62x43-cm upper Electrochromic windows were installed. The window-to-exterior- wall ratio (WWR) was set at 0.40. The southeast-facing Electrochromic windows had an overall visible transmittance (Tv) range of Tv=0.11-0.38 and were integrated with a dimmable electric lighting system to provide constant work plane illuminance and to control direct sun. Artificial lighting load was decreased by 6 to 24% by using Electrochromic window compared to energy use with static, low-transmission (Tv=0.11), unshaded windows in overcast to clear sky winter conditions in Oakland, California.

Also, the visual environment produced by the Electrochromic windows was significantly improved for computer-type tasks throughout the day compared to the visual environment with unshaded 38%-glazing **[29]**.

Jeffrey L. Warner et al. explores the potential benefits of Electrochromic in comparison to other currently available and emerging glazing technologies. These effects are explored in office buildings in several climates as a function of window size, orientation and building operating characteristics **[31]**. The DOE- 2 building energy simulation program was used to model the performances of the smart coatings, accounting for both thermal and daylighting impacts. Very substantial savings are demonstrated compared to conventional glazings, but specific impacts on component and total energy consumption, peak demand, and HVAC system sizing vary widely among the options analyzed. In a hot, sunny climate probably the first niche market for Electrochromic, simple payback periods of three to ten years were calculated.

J. Karlsson evaluated the energy efficiency of switchable (variable transmittance) windows having a control system based on occupancy, temperature and impinging solar radiation. The heating and cooling performance of the smart windows are compared with the performance of several conventional glazings. He found that the energy efficiency of smart windows depends highly on several parameters, such as location, type of building, orientation, occupancy, etc **[34]**.

E.S. Lee et al. quantifies the potential impact of Electrochromic windows on US primary energy use in the commercial building sector and also provides a broader database of energy use and peak demand savings for perimeter zones. The DOE-2.1E building simulation program was used to predict the annual energy use of a three-storey prototypical commercial office building located in five US climates and 16 California climate zones. The energy performance of an Electrochromic window controlled to maintain daylight illuminance at a prescribed set point level is compared to conventional and the best available commercial windows as well as windows defined by the ASHRAE 90.1-1999 and California Title 24-2005 Prescriptive Standards. Perimeter zone energy use and peak demand savings data by orientation, window size, and climate are given for windows with interior shading, attached shading, and horizon obstructions (to simulate an urban environment) **[18, 41]**.

Manfredi et. al studied the energy consumption associated with the use of Electrochromic coatings in architectural glazing, using the Energy Plus and the optical spectra of Electrochromic films [22]. They suggested that the Electrochromic coatings could have an additional energy benefit above and beyond those approaches currently used in warmer climates; this arises from a combination of heat mirror and absorbing behavior. The best energy performance occurred in the warmer climates. Simulations based on idealized spectra indicated that the energy saving performance could be optimized by having a large change in optical properties in the near infra-red and by having a low transition temperature to maximize the amount of time the coating spends in its metallic state **[22, 38]**.

R. Lollini et. al developed a prototype of smart glazing system and tested at ITC-CNR; it was aimed at actively responding to the external environmental loads **[24]**. Both experimental and numerical analysis was carried out, aimed at evaluating the possible configurations depending on different weather conditions in several possible places. The analytical models of the building-plant system were defined by using dynamic energy simulation software (Energy Plus) **[24]**.

Engfeldt, Johnny Degerman et al., found that Electrochromic (EC) devices for use as smart windows have a large energy-saving potential when used in the construction and transport industries. They found that while up scaling EC devices to window size, a well-known challenge is to design the controller which can alter the state of EC smart glass. They design a well-defined current distribution model, validated with experimental data, which is a suitable tool for optimizing the electrical design for rapid and uniform switching. They prepared a methodology, based on camera vision, for experimentally validating EC current distribution models **[26]**.

A. Piccolo et al. did experimental investigation which aimed at assessing the performance of Electrochromic (EC) windows with respect to daylighting control in buildings **[35]**. They performed the research under real weather conditions by a small scale test cell equipped with a small area double glazing unit (DGU) where one pane consists of an EC device with visible transmittance (τ_v) ranging from 6.2 to 68.1% and the other of an ordinary clear float glass (τ_v =90%) [30]. Experimental tests were carried out as a function of time, weather conditions, test-cell orientation and switching strategies. Results show that the angle selectivity of the glazing combined with its active switching effect allows a wide range of selectable transmission states to suit the latitude and orientation of a building in relation to the local climatic conditions. For south facing windows and under the involved climatic conditions EC glazing driven by a dynamic control strategy can be very effective in reducing discomfort glare caused by high window brightness. Glare reduction can be realized contemporarily maintaining the work plane illuminance to adequate level for computer based office tasks so without compromising much of the available daylight. Furthermore, since EC glazing is never switched to heavily darkened states (τ_v >20%), color rendering of inside objects should be always acceptable, although internal illuminance level could be slightly lower than to what users prefer in relation to the correlated color temperature of the incoming light **[35]**. These results change when considering west orientation for which high-luminance direct sunlight patches are registered on the work-plane even for EC glazing switched to its lowest transmitting state letting suppose that EC windows cannot provide full control of uncomfortable direct sunlight effects without integration of additional shading devices **[35]**.

2.4 Visual Comfort Performance of Smart Windows

Eleanor S. Lee et al., conducted 20-month field study in order to measure the energy performance of south-facing large-area tungsten-oxide absorptive Electrochromic (EC) windows with a broad switching range in a private office setting **[27]**. The EC windows were controlled by a variety of means to bring in daylight while minimizing window glare. For some cases, a Venetian blind was coupled with the EC window to block direct sun. Some tests also involved dividing the EC window wall into zones where the upper EC zone was controlled to admit daylight while the lower zone was controlled to prevent glare yet permit view. If visual comfort requirements are addressed by EC control and Venetian blinds, a 2-zone EC window configuration provided average daily lighting energy savings of 15% compared to the reference case with fully lowered Venetian blinds. If the reference case assumes no daylighting controls, lighting energy savings would be 47%. Peak demand reductions due to window cooling load, given a critical demand-response mode, were 22% maximum on clear sunny days. Lighting energy use was found to be very sensitive to how glare and sun is controlled **[33]**.

E.S. Lee et al. conducted DOE-2 building energy simulations in order to determine if there were practical architectural and control strategy solutions that would enable Electrochromic (EC) windows to significantly improve visual comfort without eroding energy-efficiency benefits **[37]**. EC windows were combined with overhangs since opaque overhangs provide protection from direct sun which EC windows are unable to do alone. The window to wall was divided into an upper and lower aperture so that various combinations of overhang position and control strategies could be considered. The overhang with variable depth was positioned either at the top of the upper window aperture or between the upper and lower apertures. EC control strategies were fully bleached at all times, modulated based on incident vertical solar radiation limits, or modulated to meet the design work plane illuminance with daylight **[32]**. The EC performance was compared to a state-of-the-art spectrally selective low-e window with the same divided window wall, window size, and overhang as the EC configuration. The reference window was also combined with an interior shade which was manually deployed to control glare and direct sun. Both systems had the same daylighting control system to dim the electric lighting. Results were given for south-facing private offices in a typical commercial building. In hot and cold climates such as Houston and Chicago, EC windows with overhangs can significantly reduce the average annual daylight glare index (DGI) and deliver significant annual energy use savings if the window area is large. Total primary annual energy use was increased by 4% for moderate-area windows in either climate but decreased by 10% in Chicago and 5% in Houston for large-area windows.

Peak electric demand can be reduced by 7–8% for moderate-area windows and by 14–16% for large-area windows in either climate. Energy and peak demand reductions can be significantly greater if the reference case does not have exterior shading or state-of the-art static glass **[37]**.

Ruben Baetens et al., conducted survey on prototype and currently commercial dynamic tintable smart windows. The technologies of Electrochromic, gasochromic, liquid crystal and suspended- particle devices were examined and compared for dynamic daylight and solar energy control in buildings. It was found that state-of-the art commercial Electrochromic windows seem most promising to reduce cooling loads, heating loads and lighting energy in buildings, they have been found most reliable and able to modulate the transmittance up to 68% of the total solar spectrum **[38]**.

In 2002 a new test facility at LBNL with three side-by-side test rooms with unobstructed south views was constructed. The lighting power and the heating and cooling in each room are individually monitored and the rooms have a full array of illuminance and luminance sensors for monitoring. New Electrochromic samples were fitted over the complete facade as shown in **Figure** 2.2. Since the prototypes were of limited size the facade requires 15 glazing panels. The visible transmittance of these prototypes can be switched from 60% to 4% in several minutes **[20]**.

Figure 2.2: Three Sequential Views of One Test Room in the LBNL Facade Test Facility, Showing the Darkening Sequence **[20]**

2.5 Lighting Requirements in Buildings

Lighting or illumination is the deliberate use of light to achieve a practical or aesthetic effect. Lighting includes the use of both artificial lights like lamps and light fixtures, as well as natural illumination by capturing daylight. Daylighting (using windows, skylights, or light shelves) is sometimes used as the main source of light during daytime in buildings. This can save energy in place of using artificial lighting, which represents a major component of energy consumption in buildings. Proper lighting can enhance task performance, improve the appearance of an area, or have positive psychological effects on occupants. Lighting is classified by intended use as general, accent, or task lighting, depending largely on the distribution of the light produced by the fixture **[40]**.

Artificial lighting consumes a significant part of all electrical energy consumed worldwide. In homes and offices from 20 to 50 percent of total energy consumed is due to lighting. Most importantly, for some buildings over 90 percent of lighting energy consumed can be an unnecessary expense through over-illumination **[43]**. The cost of that lighting can be substantial. A single 100 W light bulb used just 6 hours a day can cost over $25 per year to use (.12/kWh) **[44]**. According to the UN Environment Programme, by simply replacing all incandescent lamps with energy efficient compact fluorescent lamps globally, 409 TWh per year would be saved, which is approximately 2.5% of global electricity consumption **[44]**. This is equivalent to the combined yearly electricity consumption of the United Kingdom and Denmark. Thus lighting represents a critical component of energy use today, especially in large office buildings where there are many alternatives for energy usage in lighting **[39]**. Specification of illumination requirements is the basic concept of deciding how much illumination is required for a given task. Clearly, much less light is required to illuminate a hallway or bathroom compared to that needed for a word processing work station. Generally speaking, the energy expended is proportional to the design illumination level. For example, a lighting level of 80 foot-candles might be chosen for a work environment involving meeting rooms and conferences, whereas a level of 40 foot-candles could be selected for building hallways **[44]**. Unfortunately, most of the lighting standards today have been specified by industrial groups who manufacture and sell lighting, so that a historical commercial bias exists in designing most building lighting, especially for office and industrial settings. Light Level or Illuminance, is the total luminous flux incident on a surface, per unit area. The work plane is where the most important tasks in the room or space are performed. Illuminance is measured in foot candles or Lux in the metric SI system). The outdoor light level is approximately 10,000 lux on a clear day. In the building, in the area closest to windows, the light level may be reduced to approximately 1,000 lux. In the middle area it may be as low as 25 - 50 lux. Additional lighting equipment is often necessary to compensate the low levels. Earlier it was common with light levels in the range 100 - 300 lux for normal activities. Today the light level is more common in the range 500 - 1000 lux - depending on activity. For precision and detailed works, the light level may even approach 1500 - 2000 lux **[39]**. **Table** 9 shows the recommended illuminance level for different work spaces:

Table 9: Recommended Light Level in Different Work Spaces **[46]**

Activity	**Illumination (lux, lumen/m^2)**
Public areas with dark surroundings	20 - 50
Simple orientation for short visits	50 - 100
Working areas where visual tasks are only occasionally performed	100 - 150
Warehouses, Homes, Theaters, Archives	150
Easy Office Work, Classes	250
Normal Office Work, PC Work, Study Library, Groceries, Show Rooms, Laboratories	500
Supermarkets, Mechanical Workshops, Office Landscapes	750
Normal Drawing Work, Detailed Mechanical Workshops, Operation Theatres	1,000
Detailed Drawing Work, Very Detailed Mechanical Works	1500 - 2000
Performance of visual tasks of low contrast and very small size for prolonged periods of time	2000 - 5000
Performance of very prolonged and exacting visual tasks	5000 - 10000
Performance of very special visual tasks of extremely low contrast and small size	10000 - 20000

2.6 Visual Comfort Requirements in Office Buildings

Appropriately balanced lighting is the most essential factor in designing for glare-free environments in office buildings. While existing lighting design codes and standards rely predominantly on illuminance-based recommendations and typically specify horizontal illumination levels, current qualitative thinking moves towards luminance-based lighting design as the eye responds to luminance differences, i.e. differences in brightness found in the visual field and in the space overall **[40]**. In theory, the analysis of luminance ratios and distributions in different lighting scenarios allows the designer to carefully assess visual comfort conditions. The earlier such assessments occur, the better. Lighting scenarios can be virtual or “real”. For the latter, both scale models and full-size mock-ups could be considered, depending on the complexity of the possible lighting solutions. Finding the right luminance balance for the different parts of the visual field observed when performing specific tasks is not a trivial undertaking. The designer needs to be aware of all the potential tasks to be performed in the space, where they are likely to be performed and who is performing them **[36]**. Daylighting conditions in a room and the associated view connections are key factors influencing an occupant’s choice of workspace layout. Sharing a workspace with others will result in different layouts than having an individual space due to privacy needs and relationships with co-workers. This will likely result in very different luminance distributions in the visual field. For daylighting design, the most critical luminance relationships are those between the daylight opening, its immediately adjacent surfaces and the surfaces surrounding the work tasks. Understanding the geometry between sun, sky, daylight opening and interior space at different times of the day and throughout the seasons is the key to setting the stage for visual comfort. But placing the opening just right to achieve a good balance between views of the outdoors, visual comfort, thermal control and architectural integrity can be tricky **[36]**. For visual and thermal comfort there might be some overlap, but this depends on the location and season. In winter, direct sunlight might contribute to warmth, but might at the same time create visual discomfort in the form of distracting patterns on the work plane or even glare. If visual comfort is the priority, then the next paragraph might come as a little bit of a surprise, as it is not the usual starting point. But it is certainly worth considering **[40]**.

Advanced computational methods allow designers to examine real spaces and digitally simulated spaces with emerging luminance based metrics to assess visual comfort and aspects of quality **[47]**. However, there is currently very little guidance for designers seeking to refine design solutions based upon these metrics because it is still an emerging research area. **Table** 10 shows the recommended glare index values for various facilities.

Table 10: Recommended Values of Maximum Allowable Discomfort Glare Index **[46]**

ACTIVITY OR ZONE TYPE	MAXIMUM ALLOWABLE DISCOMFORT GLARE INDEX
Art Galleries	16
Factories	
▪ Rough Work	28
▪ Engine assembly	26
▪ Fine assembly	24
▪ Instrument assembly	22
Hospital wards	18
Laboratories	22
Museums	20
Offices	22
School classrooms	20

2.7 Summary

From the literature it has been found that smart windows have a great potential for reducing energy consumption in different climates. They are used for controlling the solar heat gain and minimizing the energy consumption in buildings. An office building consumes bulk of energy for maintaining the required lighting level. Daylighting can be considered as best source to minimize the lighting energy consumption and also it creates a positive impact on the health of the occupants. Occupants in an office building prefer a well day-lit environment, which improves the productivity rate. The conventional windows such as Double clear glass, colored glass, Low-E glass windows can be used for the daylight integration. It has been found that by using the clear glass window with proper daylight integration, significant reduction can be made in the artificial lighting, but at the expense of visual comfort. Double Clear glass windows bring in all the available daylight from outside which creates unbalanced lighting level inside the office creating visual discomfort. Smart windows are made of glazings that can be switched from clear transparent state to colored opaque state by means of small applied voltage. The thermal and optical properties of these windows can be controlled automatically, which is very much necessary during the daylight integration. Control triggers are used to alter the properties of smart windows. Very limited research has been done to evaluate the energy and visual performance of smart windows in hot climate. Also there is a need to identify the best control technique which shall be used to control the state of smart glass, from view point of energy and visual comfort. This study will help the architects/designers in deciding which control strategy they should use for the smart window, based on the energy reduction and visual comfort.

Electrochromic smart window was selected in this study for carrying out the energy and visual analysis. They require very low voltage power (0-10 volts DC) to alter the state of glass when compare to other smart windows, also they offer maximum flexibility in managing energy use in buildings. Electrochromic smart window technology has been actively researched throughout the world, and is considered as best example of smart windows.

CHAPTER 3

FORMULATION OF BASECASE MODEL

This chapter focuses on the formulation of a base case model for an office building in hot-humid climate. As a first step towards formulating the theoretical base case model of an office building, a suitable software tool was selected from the available energy simulation tools for carrying out the energy analysis of office building. The thermal and physical characteristics of a representative building in hot-humid climate were determined. Information about geometric shape, building envelope properties, lighting system requirements, and window design parameters were collected based on previous survey results and energy standards. Verification of the model was carried out by comparing the energy performance of base case with an existing building.

3.1 Selection of Simulation Software for Energy Analysis

Building energy simulation is important for the study of energy flow in buildings. Computer simulation programs are effective analytical tools for building energy research and evaluation of architectural design **[47]**. Design Builder, DOE-2, Energy Plus, ENER-WIN, ECOTECT, PC-Blast, Energy Quest, BSim, Energy Express, TRACE, TRNSYS are the few simulation tools and programs which are used presently for carrying out the energy analysis in buildings. In this research, Design Builder software was used for carrying out the energy analysis, because of its features that will allow complex buildings to be modeled rapidly. It uses the latest Energy plus simulation engine to calculate the energy performance of the building and also for creating and assessing building designs. Energy Plus detailed daylighting module calculates interior daylighting illuminance, glare from windows, glare control and electric lighting controls and also calculates electric lighting reduction for the heat balance module. The capabilities of different energy simulation software's were studied and a table is developed which shows the comparison between the various energy tools based on their features. **Table** 11 shows the comparison between different building simulation programs.

Table 11: Capabilities of Building Energy Simulation Programs **[47]**

Features	BLAST	BSim	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy Plus	EQuest	TRACE	TRNSYS
Geometric description of Walls, Roofs, Floors	☑	☑	☑	☑	☑	☑	☑	☑	☑	☑
Geometric description of Windows, skylights, doors, and external shading	☑	☑	☑	☑	×	☑	☑	☑	☑	☑
Import/export model to other simulation programs	×	×	×	☑	×	×	☑	×	×	×
Heat balance calculation	☑	☑	☑	×	☑	×	☑	☑	☑	☑
Solar gain and daylighting calculations	×	×	×	☑	×	×	☑	×	×	×
Shading device scheduling	☑	☑	×	☑	×	×	☑	☑	☑	☑
Controllable window blinds	×	☑	☑	☑	×	☑	☑	☑	×	☑
Electrochromic Glazing	×	×	×	☑	×	×	☑	☑	×	×
User specified daylighting control	×	☑	×	☑	×	×	☑	×	☑	☑
Interior illumination from windows and skylights	×	☑	☑	☑	☑	×	☑	☑	☑	×
Stepped or dimming electric lighting controls	×	☑	☑	×	☑	×	☑	☑	☑	☑
Glare simulation and control	×	×	☑	×	×	×	☑	☑	×	×
Daylight illuminance maps	×	×	×	☑	☑	×	☑	☑	☑	×

Energy plus program includes the capabilities such as daylighting calculations, glare calculations, daylight integration, modeling of smart windows and defining control for smart windows. These capabilities are required for fulfilling the objectives of the research. So, Design Builder software was selected for carrying out the energy analysis of the theoretical base case model in this research.

3.2 Characteristics of the Selected Software Tool

Design Builder software creates an elegant and easy to use interface for Energy Plus, which is integrated tightly within Design Builder environment to allow the simulations without any fuss. Design Builder software is suitable for use by architects, building services engineers, energy consultants. The following are some features of Design builder **[46]**:

- Daylighting - models lighting control systems and calculates savings in electric lighting.
- Smart windows can be modeled easily, and there performance can be studied
- A comprehensive range of simulation data can be shown in annual, monthly, daily, hourly or sub-hourly intervals
- Energy consumption broken down by fuel and end-use.
- Internal temperatures ,Weather data
- Heat transmission through building fabric including walls, roofs, infiltration, ventilation etc.
- Heating and cooling loads, CO_2 generation.
- Heating and cooling equipment sizes can be calculated using design weather data.
- Parametric analysis screens allow the user to investigate the effect of variations in design parameters on a range of performance criteria.
- ASHRAE worldwide design weather data and locations (4429 data sets) are included with the software and more than 2100 Energy Plus hourly weather files are automatically downloaded as required.

3.2.1 Daylight Calculations

The daylighting simulations available in Design Builder allow the user to calculate daylight factors and illuminance data using the Radiance daylight simulation engine. It also provides the standard reports regarding the eligibility for LEED, Green Star Daylighting credits **[46]**. Calculations are made using the accurate physics-based Radiance simulation engine which is one of the most widely respected daylighting tools in use today. Building geometry, zone layouts, surface reflection and glazing visible transmission properties from the thermal model are used in the daylighting calculations.

The daylighting model of Design Builder software, in conjunction with the thermal analysis, determines the energy impact of daylighting strategies based on analysis of daylight availability, site conditions, window management in response to solar gain and glare, and various lighting control strategies. The daylighting calculations are carried out during the simulation in 3 main steps **[46]**:

1. Daylight factors, which are ratios of interior illuminance to exterior horizontal illuminance, are calculated and stored. The user specifies the coordinates of one or two reference points in each day lit zone. Energy Plus then integrates over the area of each exterior window in the zone to obtain the contribution of direct light from the window to the illuminance at the reference points, and the contribution of light that reflects from the walls, floor and ceiling before reaching the reference points. Window luminance and window background luminance, which are used to determine glare, are also calculated. Taken into account are such factors as sky luminance distribution, window size and orientation, glazing transmittance, sun control devices such as movable window shades, and external obstructions. Dividing daylight

illuminance or luminance by exterior illuminance yields daylight factors. These factors are calculated for the hourly sun positions on sun-paths for representative days of the run period.

2. A daylighting calculation is performed for each heat-balance time step when the sun is up. In this calculation the illuminance at the reference points in each zone is found by interpolating the stored daylight factors using the current time step's sun position and sky condition, then multiplying by the exterior horizontal illuminance. If glare control has been specified, the program will automatically deploy window shading, if available, to decrease glare below a specified comfort level. A similar option uses window shades to automatically control solar gain.
3. The electric lighting control system is simulated to determine the lighting energy needed to make up the difference between the daylighting illuminance level and the design illuminance. Finally, the zone lighting electric reduction factor is passed to the thermal calculation, which uses this factor to reduce the heat gain from lights.

3.2.2 Glare Index Calculations

Glare is defined as the particular condition that could cause discomfort or could reduce the visual performance, the visibility and the capability to define details and objects. It is caused by a high or non-uniform luminance distribution within the visual field or by high contrasts of luminance between the glare source (window) and its surroundings **[46]**. It arises when light coming from the side of the task is much brighter than the light coming from the task. The eyes attempt to focus on the light from the task, but so much extra light coming from side will confuse the visual processes and it will be difficult to concentrate for long periods. Prolong exposure to such conditions can result in headaches and eye fatigue. The program calculates the daylight discomfort glare at a reference point which occurs due to luminance contrast between a window and the interior surfaces surrounding the window and is given by the formula **[46]**:

$$G= \frac{L_w^{1.6}\ \Omega^{0.8}}{L_{b\ +\ 0.07\ \omega^{0.5}\ L_w}}$$

Where

G= Discomfort glare index

L_w=average luminance of the window as seen from the reference point

Ω= angle subtended by window

L_b=luminance of the background area surrounding the wall

ω= angle subtended by element in the window

The program considers a day lit zone which has windows, and it divides the window in small rectangular elements for the calculation of interior illuminance level. If the glare control has been specified in the program and the glare index at either reference points exceeds a user specified maximum value, then the windows in the zone are shaded one by one in attempt to bring the glare at both points below the maximum allowable glare index value **[46]**.

3.2.3 Lighting Integration and Control

Lighting control integrated with natural daylight is considered as an important and useful strategy in energy-efficient building designs and operations. It is believed that proper daylighting schemes can help reduce the electrical demand and contribute to achieving environmentally sustainable building development. Daylight is considered as the best source of light for good color rendering and its quality is the one light source that most closely matches human visual response **[46]**.

Electric lights in Design Builder are controlled according to the availability of natural daylight. By switching ON the Lighting control, illuminance levels are calculated at every time step during the simulation and then used to determine how much the electric lighting can be reduced. The daylight illuminance level in a zone depends on many factors, including sky condition, sun position, photocell sensor positions and location, size, and glass transmittance of windows, window shades and reflectance of interior surfaces. Reduction of electric lighting depends on daylight illuminance level, illuminance set point, fraction of zone controlled and type of lighting control **[46]**.

When lighting control is switched ON, all of the lights in the zone are controlled by the first (main) lighting sensor and % Zone Controlled by Lighting Area 1 has value 100%. Some larger spaces may have 2 Lighting Areas, each area having its own lighting sensor and covering its own area of the zone. The area is not defined geometrically in Design Builder - it simply reflects the fraction of the total General overhead electric lighting that can be dimmed by its lighting sensor. A large zone may need more than one sensor if the output from main sensor does not represent the daylight available in other parts of the zone. Here in this study 2 sensors were provided for each zone with first sensor controlling 70 % of the lighting area whereas the second sensor controlling 30% of the lighting area. Design builder program contains 3 lighting controls. They are as follows **[46]**:

i. Continuous lighting control: In this type of control, the overhead lights dim continuously and linearly from maximum electric power, maximum light output to minimum electric power, minimum light output as the daylight illuminance increases. The lights stay at the minimum point with further increase in the daylight illuminance.
ii. Continuous/ OFF control: It's the same as continuous control except that the light switches OFF completely when the minimum dimming point is reached.
iii. Stepped control: It allows the user to switch lighting ON/OFF according to the availability of natural daylight in discrete steps.

Stepped lighting control is used in this study for integrating the daylight with artificial lighting. The electric power input and light output vary in discreet, equally spaced steps. This control provides an idealized lighting control mechanism which can be useful for calculating upper limits on the potential for savings using natural daylight. Providing automatic daylighting control in rooms wired for stepped dimming (also called Inboard/Outboard) is possible using "Duo" operational mode. In this mode the sensor determines the necessary ON/OFF combination of lights in order to maintain adequate lighting. **Figure** 3.1 shows the mechanism of stepped lighting control **[46]**.

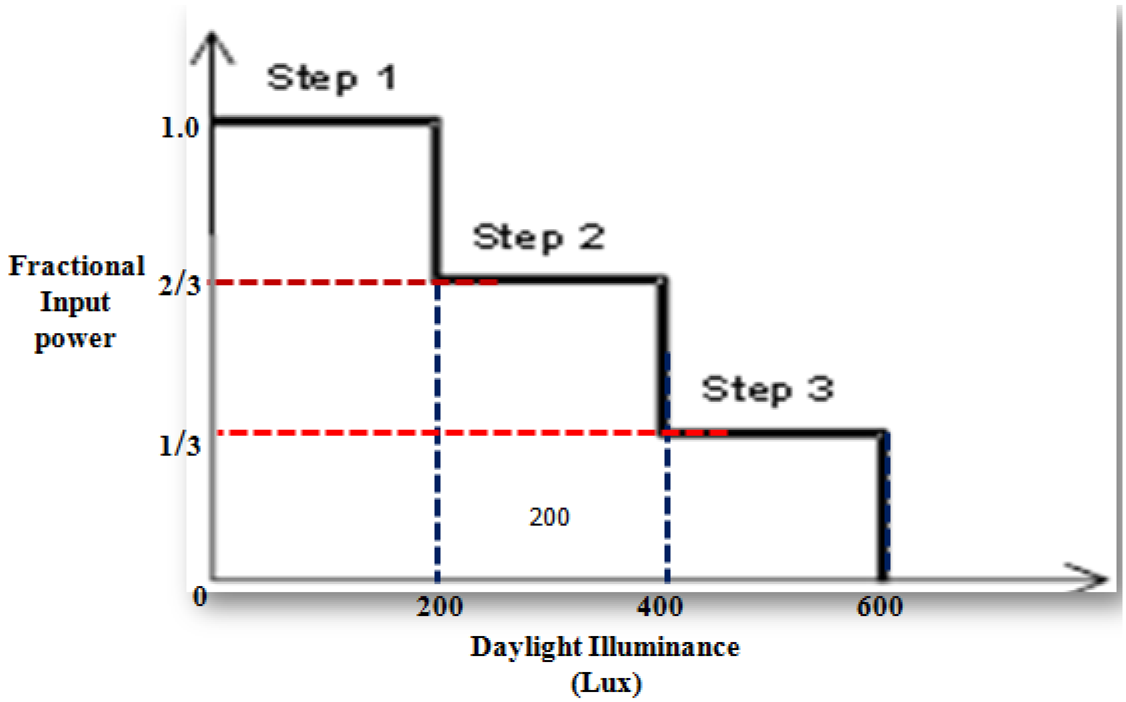


Figure 3.1: Stepped Lighting Control Mechanism **[46]**

Stepped lighting control has the ability to control any light, group of lights or all lights in a building from a single user interface device. Any light or device can be controlled from any location.

3.3 Building Characteristics

The area of the base case is considered based on the previous survey results conducted by researchers in the hot-humid region. Based on the review of design drawings, it is found that the average floor area that is commonly used for an office building in Dhahran ranges from 300 m^2 to 800 m^2 **[39]**, and common geometry of the office building plan is rectangular. For the base case model the total floor area is considered to be 800 m^2, and by applying the golden ratio rule the dimensions of the building were found to be 36 m in length, 22 m in width, and the larger dimension is assumed to be facing the North orientation. The building is assumed to have eleven floors including the ground floor and roof floor, with same office function throughout the floors. Each floor in the model is divided into 9 zones, because from the review it is found that the detection range for each daylight sensor is around 7m. Two daylight sensors were placed for each zone and were mounted in the ceiling. The first sensor is located at 3m away from the perimeter wall, whereas the second sensor is placed at 5m away from the wall, and the first sensor controls 70% of the total lighting area for that zone and the remaining 30% is controlled by the second sensor. No sensor is located for the core zone, because the availability of daylight is very low for that zone. The floor plan of the building base case model is illustrated in **Figure 3.2.**

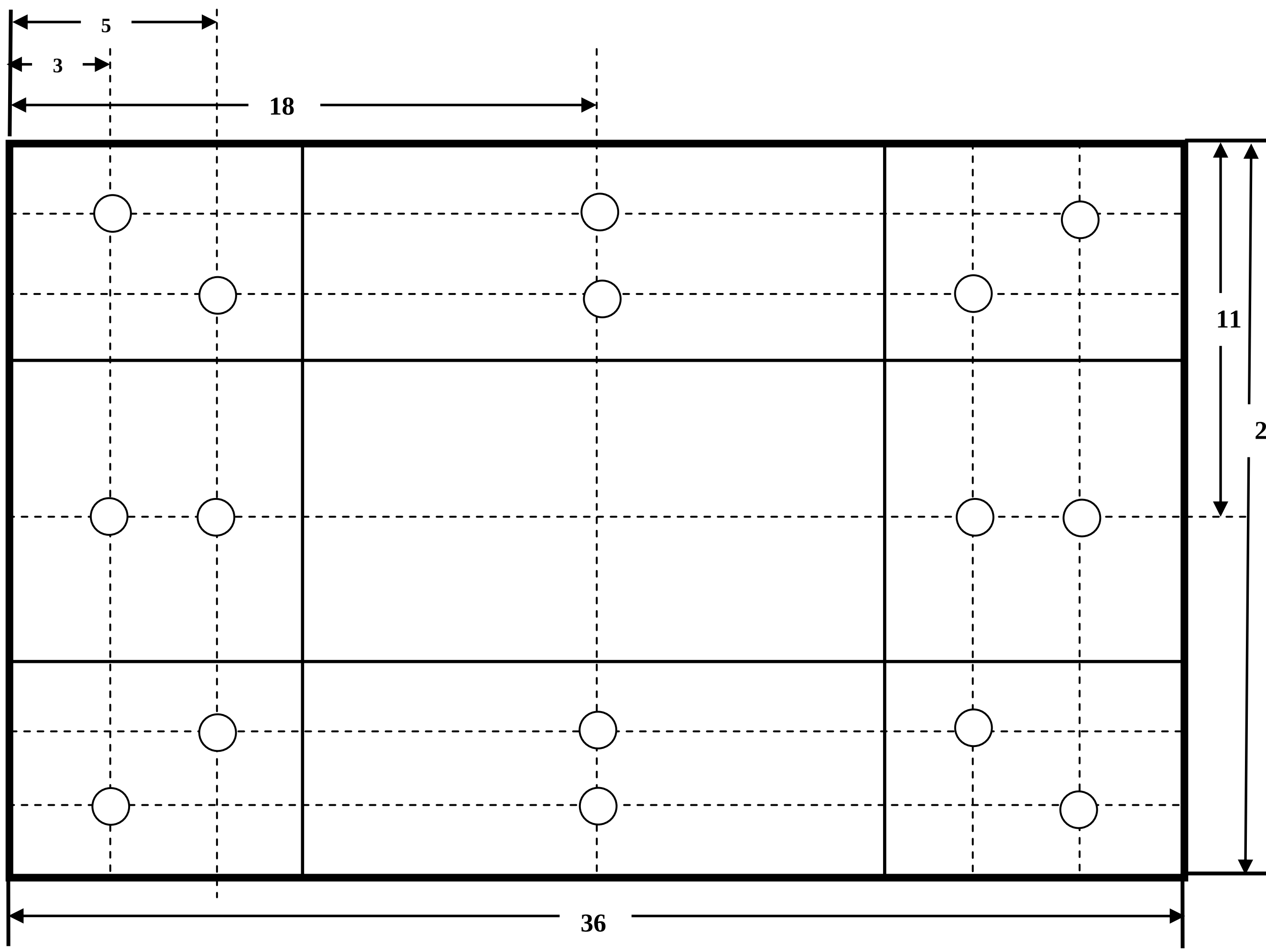


Figure 3.2: Office Building Base case plan with location of daylight sensors for different zones

Figure 3.3 shows the axonometric view of the base case office building with different paths of sun

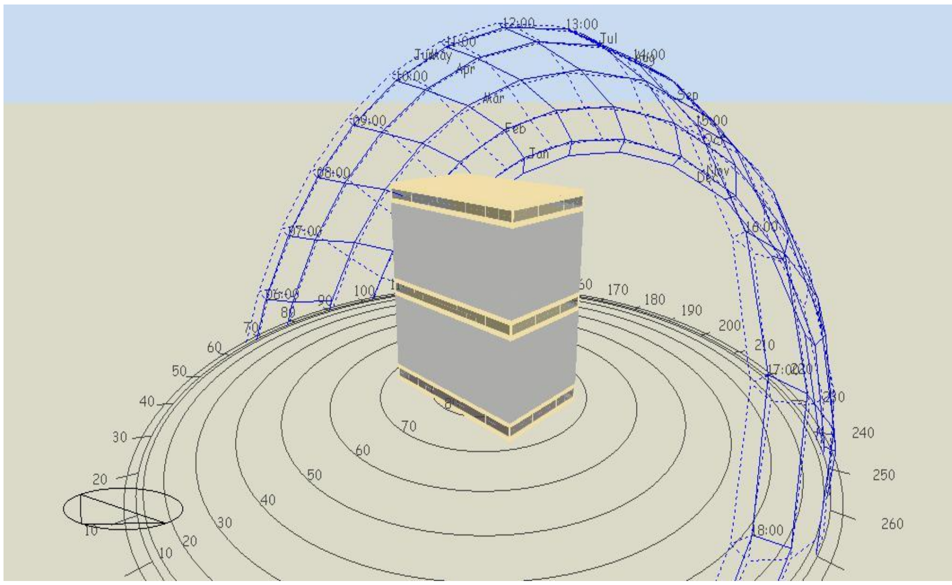


Figure 3.3: 3-D view of the base case plan

3.3.1 Building Envelope Details

A building envelope constitutes the barrier between the interior and the exterior environment of a building. The main components of building envelope are walls, roof, and windows. The envelope details of the building under study were obtained from the most common practice in Hot-Humid region **[39]**. **Table** 12 shows the physical and thermal properties of the exterior wall, roof and ground floor modeled for the base case. The roof of the building is based on ASHRAE Handbook-Roof 16. The floor of the building is a slab on grade floor.

Table 12: Cross Section and Physical Properties of the Exterior Wall, Roof and Ground floor of Base Case

Construction Assembly	Elements from outside to inside	Thickness (m)	Thermal conductivity (W/m-K)	Thermal Resistance (m^2-K/W)	U-value (W/m^2-K)
Wall Cross section	Stone cladding	0.02	2.9	0.007	0.740
	Air gap	0.025	0.3	0.083	
	Expanded polystyrene	0.025	0.04	0.625	
	Lightweight concrete	0.1	0.17	0.588	
	Plaster board	0.013	0.25	0.052	
Roof Cross section	Built-up roofing	0.0095	0.16	0.060	0.303
	Fiberboard sheathing	0.012	0.06	0.2	
	R-15, Insulation board	0.075	0.035	1.85	
	Lightweight concrete	0.203	0.17	1.19	
Floor Cross section	Flooring	0.03	0.14	0.214	0.509
	Floor screed	0.07	0.41	0.17	
	Cast concrete	0.1	1.13	0.09	
	Foam	0.06	0.04	1.5	

In this study, three different types of most potentially used glazings are investigated for the development of the base case model. Energy and visual analysis will be carried out for each glazing, and based on the results the best will be selected as a representative of an office building in hot-humid climate. Office building models were developed with Tinted, Low E and clear glass windows based on commonly used window system in hot-humid region **[39]**. The window-to-wall ratio (WWR) is assumed to be 50% in all the orientations respectively. Based on the common practice, the window sill is defined as 0.9 m **[39]**. These glazings are potentially used in the construction of office buildings. They are usually considered as an economical way to reduce the heat gain at the expense of daylight. They minimize the heat gain, by acting as a barrier between the outdoor and indoor environment and reduces the cooling load inside the building. Due to the colored tint on the exterior side of the glazing, the window blocks the solar rays from entering the building thereby reducing the cooling load. The building envelope details are summarized in **Table** 13.

Table 13: Building Envelope Details for the Base Case Model

Characteristics	Description
Plan shape	Rectangle
Clear floor height (m)	3.7
Number of floors	11
Gross floor area (m^2)	8712
Gross wall area (m^2)	4464
Glazing area (m^2)	2232
Overall WWR (%)	50
Type of glazing (mm)	Double Glazed-Clear 6/13/6

Table 14 shows the physical and thermal characteristics of colored and Low-E glazings which were selected for the simulation.

Table 14: Physical and Thermal Characteristics of Colored and Low E Glazings

Type of Glazing	SHGC	Light Transmission (%)	U-Value (W/m^2-K)
Double Clear (6mm/13mm Air/6mm)	0.7	0.74	2.8
Double Bronze (6mm/13mm Air/6mm)	0.5	0.47	2.6
Dbl Low-E Tint (6mm/13mm Air/6mm)	0.4	0.44	1.7

3.3.2 HVAC System Characteristics

The main purposes of a heating, ventilation, and air-conditioning (HVAC) system is to provide thermal comfort and to help maintain good indoor air quality. It is also needed to control the temperature, humidity, air movement, and air cleanliness. It is an essential system and has a major role in the building energy performance.

HVAC systems can be generally divided into three categories:

- All-air systems
- All-water systems
- Air-water systems

All-air systems transfer cooled or heated air from a central plant via ducting, distributing air to the room being served. In all water systems, water from a chiller or a boiler, is transferred by means of pipes, to a fan-coil unit in the room being served. An Air-Water system is a combination of all-air and all-water system, where both air and water are distributed to room terminals to perform cooling or heating function. In this study, an All-Air system is selected because of the following reasons:

- All-water systems are not capable of providing ventilation air to the zone being served, and hence, they will not be able to provide the required thermal comfort conditions in the zone.
- Operation and control are complicated for all air-water system, due to the need for handling and controlling both primary air and secondary water. Also the initial cost is the highest for this type of system.

Variable Air volume HVAC has been selected for cooling the zones in the perimeter area, where as constant air volume is used for the core zone, as they are found to be effective in hot climate **[48]**. The reason for the selection of VAV system is because it has been found that VAV system in office buildings can save substantial amount of electricity in Hot-humid region **[48]**. VAV systems can lead to significantly lower power consumption, especially in perimeter zones where variations in solar load and outside temperature allows for reduced air flow rates. A variable air volume (VAV) system changes the quantity of air supplied to a space in response to changes in loads. A central air-handling unit supplies air through a common duct pathway to all spaces conditioned by the unit. Each zone is provided with a VAV box (terminal control box) that adjusts air supply volume in response to the zone thermostat. The temperature of supply air to each zone remains constant, whereas its flow rate varies depending upon the load on that particular zone. The temperature of air supplied by the air-handling unit may be varied occasionally to adapt to building-wide changes in loads, but instant control of each zone is achieved through modulation of supply airflow rate. The variable airflow volume is achieved by VAV boxes. The boxes have a modulating damper that throttles in response to the thermostat setting. When the indoor temperature conditions vary from the set point, the VAV box damper responds by restricting or increasing the supply air volume to the space. The supply temperature at the diffuser is set based on ASHRAE standard, which is 14^{o}C. Also it's considered that electricity from grid is used to generate the cooling energy. Mechanical ventilation is set based on the energy standards, which depends on the number of persons and area to be ventilated for each zone. **Figure** 3.4 shows the layout of a typical variable air volume unit.

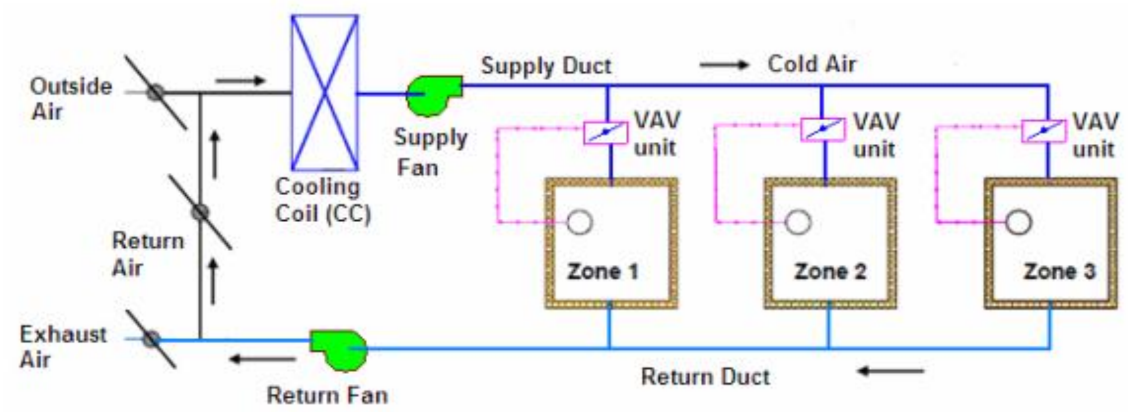


Figure 3.4: Layout of VAV Model in the Software Tool

Table 15 shows the characteristics and parameters of HVAC selected for cooling the space in the base case model.

Table 15: HVAC System Characteristics of the Base Case Model

Characteristics	Description
System Type	VAV system for the perimeter zones, CAV system for the core zone
Indoor Cooling Design Temperature (^{o}C)	24
Indoor Heating Design Temperature (^{o}C)	21
Ventilation (m^3/sec/person)	0.008 (ASHRAE 90.1-2010)

3.3.3 Lighting System Characteristics

Generally, the focus of lighting is to provide and maintain good, high-quality lighting for areas and tasks. Areas such as staircase and mechanical rooms require lower light levels. Finding ways to provide occupants with comfortable light levels, instead of providing the same light level throughout the building, is the key to improving energy efficiency and maintaining comfort and safety. This practice not only can help to reduce a building's lighting loads, but also reduce its cooling load substantially by reducing lighting heat build-up. It increases occupant comfort and reduces overall complaints regarding lighting levels **[40]**.

In the base case model the illumination level for the office area (perimeter zones) is set to 500 Lux based on IESNA (10^{th} Edition Handbook, 2011) where as for the core zone the illumination level is set to 300 lux because that zone contains staircase and mechanical room which requires lower light level as per the lighting standards **[40]**. Triphosphor Fluorescent lamps were selected for fulfilling the required illumination level in the base case model, because they produce more light for a given amount of electricity and also they are long-lasting and have up to 10 times the lamp life of standard incandescent lamps. The display lighting power density for the fluorescent lamp is set to 2.4 W/m^2-100 Lux based on ASHRAE 90.1-2010. Also it's assumed that the Luminaire is recessed into the ceiling.

3.3.4 Operational Characteristics

Building operation and occupancy follow the same pattern during both summer and winter seasons. Building occupancy schedule is set based on logical judgment and common practice. Building occupancy was assumed to start at 6:00 AM in the morning until 6:00 PM in the evening, with a break of one hour for lunch, from 12:00 noon to 13.00. The occupancy profiles for the building users and schedules for different building systems are shown in **Table** 16. It is assumed that the lighting system and HVAC system in the building will be turn-off during the holidays and Friday's.

Table 16: Office Building Base Case Operation Schedules

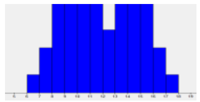
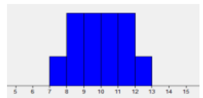
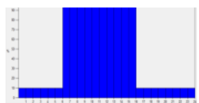
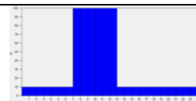
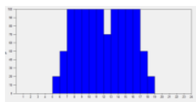
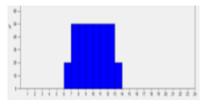
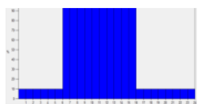
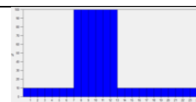
SCHEDULE TYPE	SATURDAY TO WEDNESDAY	THURSDAY	SCHEDULE DESCRIPTION
Occupancy Schedule			100% during occupied periods, 20% one hour before and after work, 70% during the lunch break
Lighting Schedule			100% during occupied periods, 10% during unoccupied periods
Cooling Schedule			100% during occupied periods, 50% one hour before and after work, 70% during the lunch break
Equipment Schedule			100% during occupied periods, 10% during unoccupied periods

Figure 3.5 shows the profiles of occupancy, cooling and lighting set in the base case model of the office building.

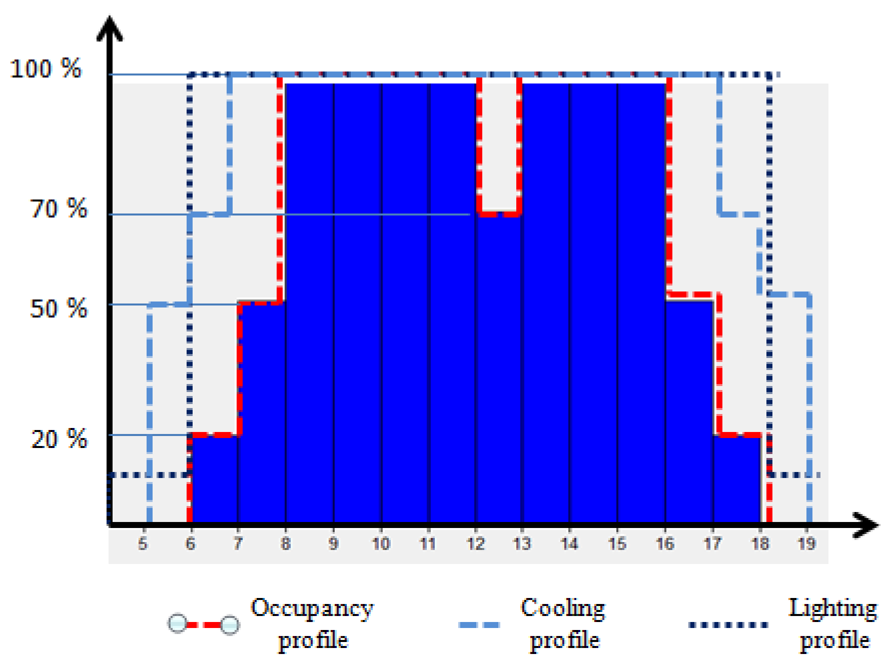


Figure 3.5: Lighting, Cooling and Occupancy Profiles of the Base case Model

Table 17 shows the holiday schedule set for the base case model, which is obtained from the Gregorian calendar for the year 2012.

Table 17: Holiday Schedule in Saudi Arabia

Name	Start Date	Number of Days
EID-Al-FITR	15 August	12
Saudi National Day	23 September	1
EID-AL-ADHA	21 October	14

Table 18 illustrates the physical characteristics of the building based on the literature **[39]**. The table also provides the details of HVAC and lighting which was set based on energy standards.

Table 18: Office Building Base Case Main Characteristics **[39]**

OFFICE BUILDING	DESCRIPTION
Type of building	Office
Weather Data file	Kuwait coastal weather station
Plan Shape	Rectangle
Number of floors	11
Clear Floor Height (m)	3.7
Floor Dimension (m)	22 x 36
Gross Floor Area (m^2)	8338
Gross wall area (m^2)	4500
Window area (m^2)	2250
Overall WWR (%)	50
Type of glazing (mm)	Double clear/Tinted/Low E
Building orientation	NORTH
Occupancy Density	9 m^2/person (ASHRAE 90.1-2010)
Perimeter Depth (m)	7
Solar Absorbance	0.5 for external walls and 0.5 for the roof
Lighting (LPD)	11 W/m^2 (ASHRAE 2010)
Equipment (EPD)	5 W/m^2 (ASHRAE 2010)
Computers	7 W/m^2 (ASHRAE 2010)
Infiltration	0.5 ACH (Average tightness constructed building)
Target Illuminance	Perimeter Zone: 500 Lux, Core Zone: 200 Lux
HVAC Type	Perimeter Zone: VAV, Core Zone: CAV
Lamps	T8 (25mm diameter) Fluorescent –triphosphor- with stepped dimming daylighting control
Luminaire type	Recessed
Outside air definition	Minimum fresh air (sum per person + per area)
Fuel for cooling	Electricity from grid
Supply air temperature	14 ^{o}C

3.4 Climatic Conditions

The base case model is simulated by using the typical weather data file of Kuwait coastal which is a representative of hot-humid climate. The weather of Kuwait is similar to that of Dhahran (Saudi Arabia). **Table** 19 and 20 shows the similarities between the weather conditions for both Kuwait and Dhahran region.

Table 19: Similarities in the Climatic Conditions for Kuwait Coastal Region and Dhahran

	0.4% DBT(^{o}C)	1%DBT(^{o}C)	2%DBT(^{o}C)	0.4% WBT(^{o}C)	1% WBT(^{o}C)	2%WBT(^{o}C)
DBT for Kuwait	44.1	43	42	35.4	35	34.4
DBT for Dhahran	44	42.9	41.8	34.4	34.3	33.5
WBT for Kuwait	22.9	22.7	22.8	30.5	29.7	28.8
WBT for Dhahran	21.8	21.7	22.1	29.9	29	28.1

Table 20: Heating and Wind Design Conditions for both Kuwait and Dhahran

Outdoor design Temperature for Kuwait (^{o}C)	7.6	7
Outdoor design Temperature for Dhahran(^{o}C)	7	8.3
Wind speed in Kuwait(m/s)	10.9	11.6
Wind speed(m/s)	11.6	10.1

3.5 Verification and Analysis of Base Case Results

Following the formulation of the base case model, the model is run through the design builder program. Simulation results, including energy performance, building lighting energy consumption, and End-use cooling energy consumption, were analyzed for comparison with available data for similar buildings from the literature. The breakdown of the annual electrical energy use for the base case revealed that about 67% (2,018,610 kWh) of the total energy was used for cooling (including fans), followed by 14% (403,722 kWh) for lighting and 18% (363,350 kWh) for equipments. The overall energy consumption for the building was found to be 2,883,729 kWh. Figure 3.6 shows the breakdown of the electrical energy usage in the base case. Bulk of the energy is being consumed for cooling which is around 52%. Artificial lighting accounts for 14% of the overall energy consumption.

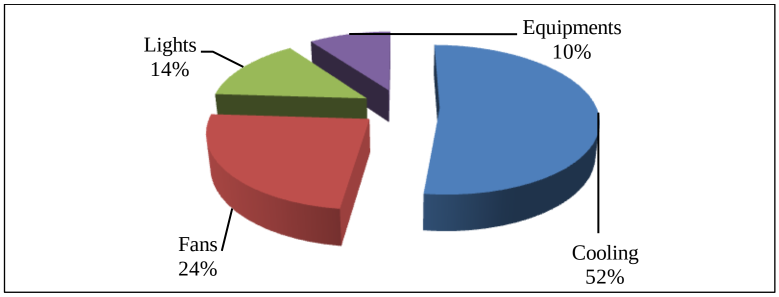


Figure 3.6: Electrical Energy Use Breakdown of the Base Case

3.5.1 Verification of Simulated Results

The annual electric energy use obtained for the base case model after performing the simulation is 2,883,729 kWh (346 kWh/m^2/year). These results are considered reasonable if comparable to the actual energy consumption of an existing office building **[48]**. The building which is chosen for the comparison is an office building located in the hot-humid climate of Al-Khobar, Saudi Arabia. The building is square shaped with its entrance facade facing east direction. The dimensions of the building are 30m length x 30m width x 41m height. The building consists of nine floors, among which the first to third floors are similar, the fourth to seventh floors also have similar characteristics, while remaining floors (ground, mezzanine and eighth floor) are unique. The total floor area of the building, as obtained from building plans, is 8400 m^2. Each floor occupies an area of 862 m^2, except the mezzanine floor, which occupies an area of 642 m^2. **Table** 21 illustrates all the characteristics of the existing office building **[48]**.

Table 21: Characteristics of Existing Building Located In Al-Khobar **[48]**

OFFICE BUILDING	DESCRIPTION
Location	Al-Khobar, Saudi Arabia
Type of building	Office
Plan Shape	Square
Total height (m)	40,730
Gross Floor Area (m^2)	8400
Gross wall area (m^2)	4690
Window area (m^2)	2040
Overall WWR (%)	43.5
Type of glazing (mm)	Double Glazed-clear 6/6/6
Building orientation	NORTH
Occupancy Density	9 m2/person (ASHRAE 90.1-2001)
External walls	Granite cladding cut to size 20mm thick, Concrete hollow block 150mm thick, 12.5mm thick Gypsum Board, , Paint on gypsum board
Roof	15mm Cement Plaster, 200mm Thick Reinforced Concrete Slab, Asphalt Tiles
Floor	100 mm Heavyweight Concrete, 25 mm Mortar Cement, 25 mm Terrazzo
Lighting (LPD)	16.65 W/m^2
Equipment (EPD)	9 W/m^2
HVAC Type	Packaged Single Zone
Supply air temperature	13 ^oC

Utility bills of existing office building were obtained from the building management, in order to obtain the data of monthly energy consumption for the year 2008 **[6, 48]**. **Table** 22 and **Figure** 3.7 shows the comparison of energy performance for the base case building and the existing office building. A deviation of 2.7% was seen between the electricity consumption of existing building and base case which concludes that the model is reliable for evaluating the effects of energy conservation measures for the building under study.

Table 22: Energy Consumption End-Use Comparison for simulated and existing building

Type of Building	Energy End-use				Energy Signature ($kWh/m^2/yr$)
	Cooling (%)	Lighting (%)	Fans (%)	Others (%)	
Existing	45	15	22	18	355
Base Case (Simulated)	52	14	24	10	346

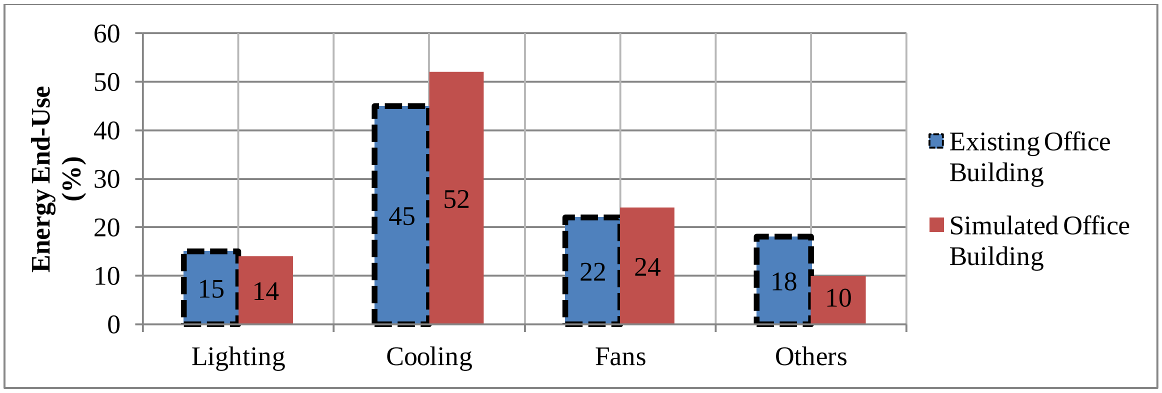


Figure 3.7: End-Use energy comparison between the existing and simulated office building

3.6 Impact of Different Glazing Windows on Building energy consumption

Different glazings were used for the development of Base case model. The results of the monthly energy consumption with different glazings, is illustrated in Figure 3.7. From the **Figure** 3.8, it can be inferred that the energy consumption increases during the summer months because of higher cooling load requirements. On the other hand, the consumption decreases during the winter months, as the demand for cooling is reduced by the change in outside weather conditions. The colored film on tinted and low E blocks a significant amount of the sun's heat, easing the load on the air conditioner. The film is also likely to protect the furnishings from fading, and it can reduce glare, which may make some rooms much more pleasant. The graph for cooling and total energy consumption reaches its peak during the month of August, because of the high solar radiation infiltrating through the roof and walls of the office building.

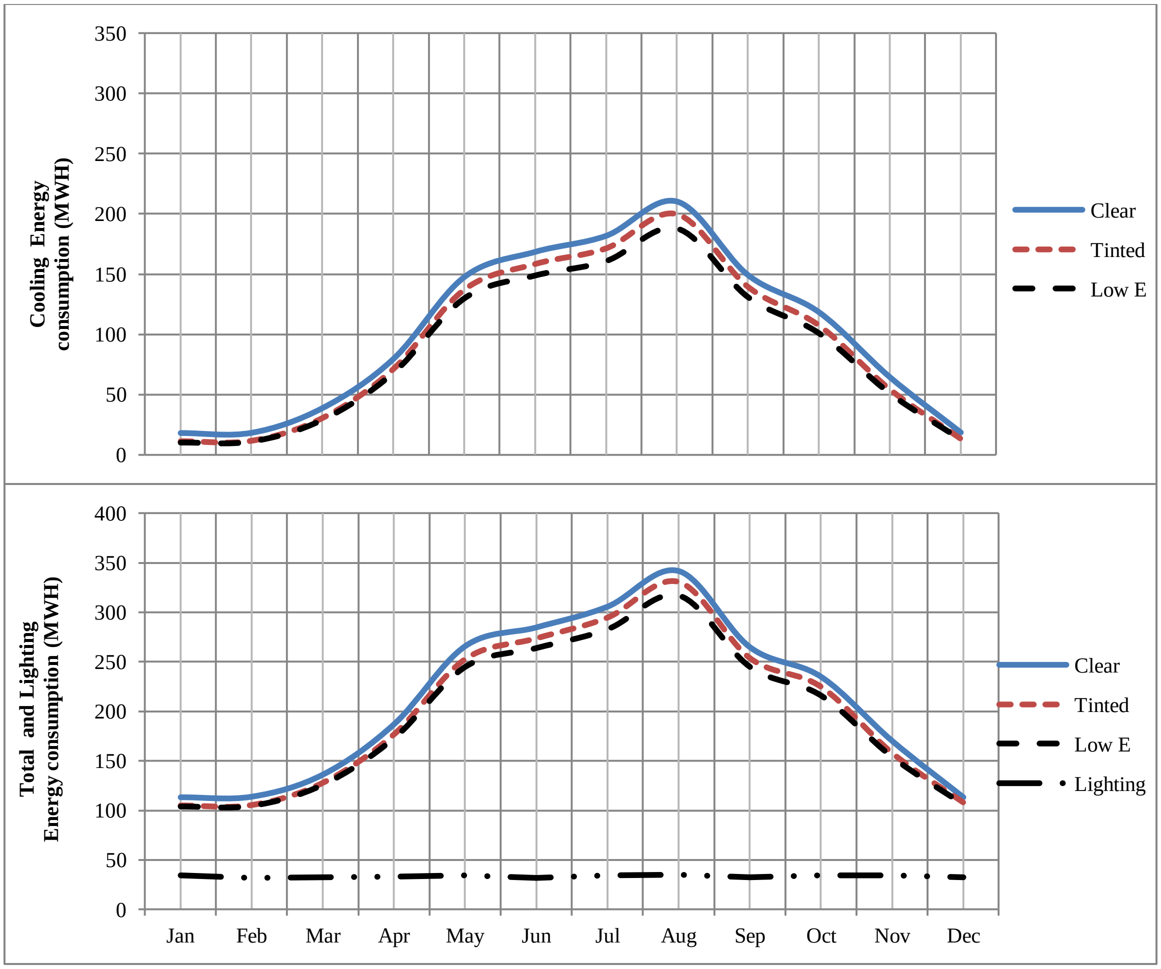


Figure 3.8: Total Monthly Electric Energy Consumption for the Different glazing windows

Table 23 shows the breakdown of energy flow for different glazing windows. The colored film on the colored and Low E windows keeps the solar radiation out in hot regions which is why we can see the reduction in the cooling energy.

Table 23: Energy breakdown for Colored and Low E glass windows

Energy Consumption	Base case		
	Dbl Clear glass	Dbl Colored Glass Windows (% Reduction)	Dbl Low-E windows (% Reduction)
Lighting (kWh)	403,722	403,722	403,722
Cooling (kWh)	2,018,610	1,838,007 (-9)	1,740,600 (-14)
Total (kWh)	2,883,729	2,684,186 (-7)	2,572,450 (-11)

The coating absorbs the heat from outside, thereby reducing the solar gain and cooling energy consumption.

3.7 Energy Analysis of Different Glazings with Daylight Integration

Stepped lighting control mechanism was used to control the artificial lighting in the perimeter zones of the office building. Two sensors were located for every zone in the ceiling to control the lighting levels inside the office. First sensor was placed at 3m away from the perimeter wall, and it was assigned to control 70% of lighting area for each zone respectively. Similarly the second sensor was placed at 5m away from the perimeter wall, and it controls 30% of lighting area for every zone. Simulations were carried out by allowing the Natural light or daylight to flow through the different glazing windows inside the office space. Due to very high level of daylight flow from outside, stepped lighting control minimizes the power input to the luminaries to balance the illumination level inside the office space, thereby reducing the artificial lighting energy consumption. The heat emitted by the lighting sources inside will be decreased due to the dimming effect provided by the stepped control, which will reduce the internal heat gain and thereby decreasing the cooling load of the building. **Table** 24 and **Figure** 3.9 shows the percentage reduction of lighting energy and cooling energy consumption by allowing the daylight to integrate with artificial lighting in an office with different glazing windows in all the orientations. The admission of sunlight from outside into the building reduces the lighting energy consumption. The lighting control integrated with daylight, dim the artificial lighting inside the office space there by reducing the energy consumption.

Table 24: Energy consumption for the office building with and without Daylight Integration

Energy consumption (kWh)	Without Daylight Integration			With Daylight Integration		
	Clear glass	Tinted glass	Low E glass	Clear glass	Tinted glass	Low E glass
Lighting	403,722	403,722	403,722	115,883 (-70%)	132,613 (-65%)	136,857 (-63%)
Cooling	2,018,610	1,838,007	1,740,600	1,857,818 (-8%)	1,688,714 (-9%)	1,587,191 (-11%)
Total	2,883,729	2,684,186	2,572,450	2,469,002 (-14%)	2,288,746 (-15%)	2,174,093 (-16%)

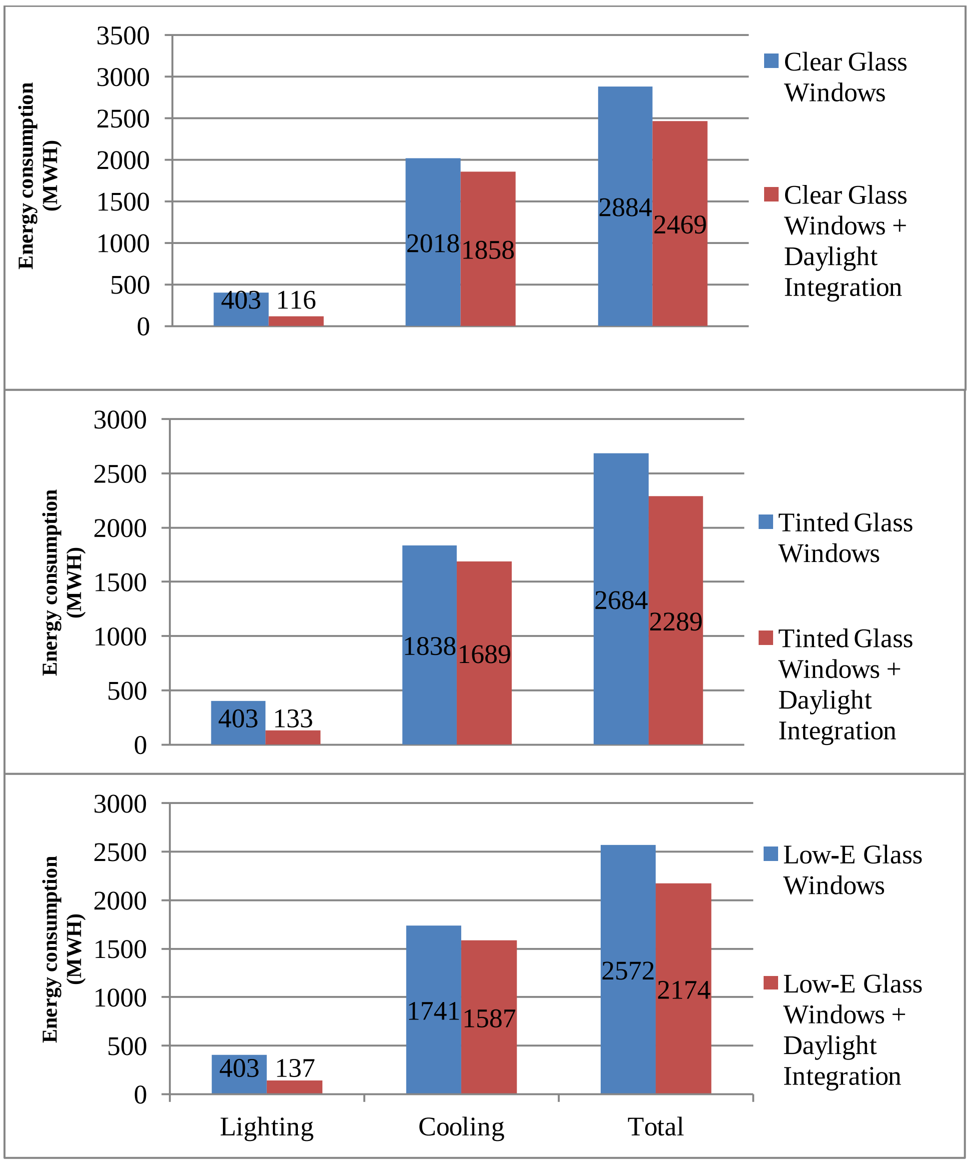


Figure 3.9: Variation in the End-use energy consumption for different glazing windows with and without Daylight integration

Daylight-responsive electric lighting controls are absolutely essential to any daylighting system. No daylighting design will save any energy unless the electric lights are dimmed or turned off when there is sufficient illumination from daylight. **Figure** 3.10 illustrates the monthly energy consumption with different glazings after the integration of daylight with artificial lighting system by using stepped control mechanism. Windows with Low – E coating have an emittance as low as 0.04. Such glazing would emit only 4% of the energy possible at its temperature, and thus reflect 96% of the incident long-wave, infrared radiation. By reducing the emittance of the glass, the solar gain from outside will be lowered which will reduce the cooling load in the building. This phenomenon can be inferred from the **Figure** 3.10.

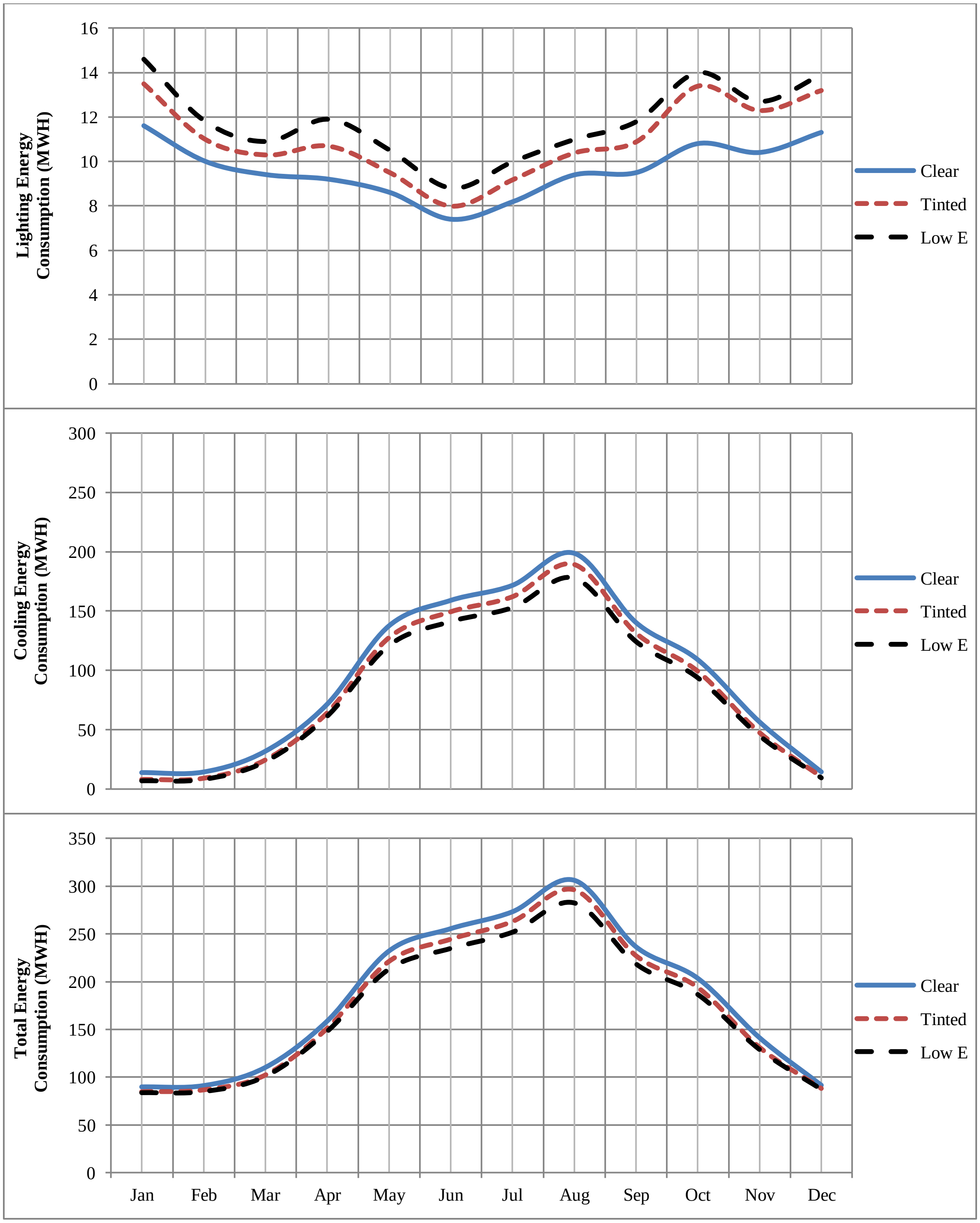


Figure 3.10: Total Monthly Electric Energy Consumption for the Different glazing windows after daylight integration

3.8 Visual Analysis of the Base Case

Visual comfort analysis was carried out for an office building with clear, colored and Low-E glass windows respectively. Daylight factor (%) and Glare index was studied to assess the visual performance of the windows. **Figure** 3.11 shows the Visual comfort analysis for every orientation when clear, colored and Low E glazings were used. Maximum Glare index is calculated in various orientations of the base case model based on the assumption that the occupant look directly at the windows. Glare index depends on the amount of daylight received through the window. The illumination level in the office was set to value of 500 Lux and the comfort level for the glare index was considered to be around 22.

During the analysis it was found that the glare index value for different glazings in various orientations was beyond the comfort level which was considered to be around 22 **[47]**. Due to the high diffuse solar radiation in the North orientation a peak in glare index value was observed during the summer months (April-July). Glare index value for windows in the East and West orientation follow the same pattern in reverse direction. Due to bright incoming light from sun which creates unbalance lighting level between the interior and exterior of the building, the average glare index value in the East and west orientation was found to be around 24.5. South orientation receives the highest amount of daylight during the winter season, because the sun stays for longer duration in the South. Because of the high amount of daylighting, the glare index value gets increased.

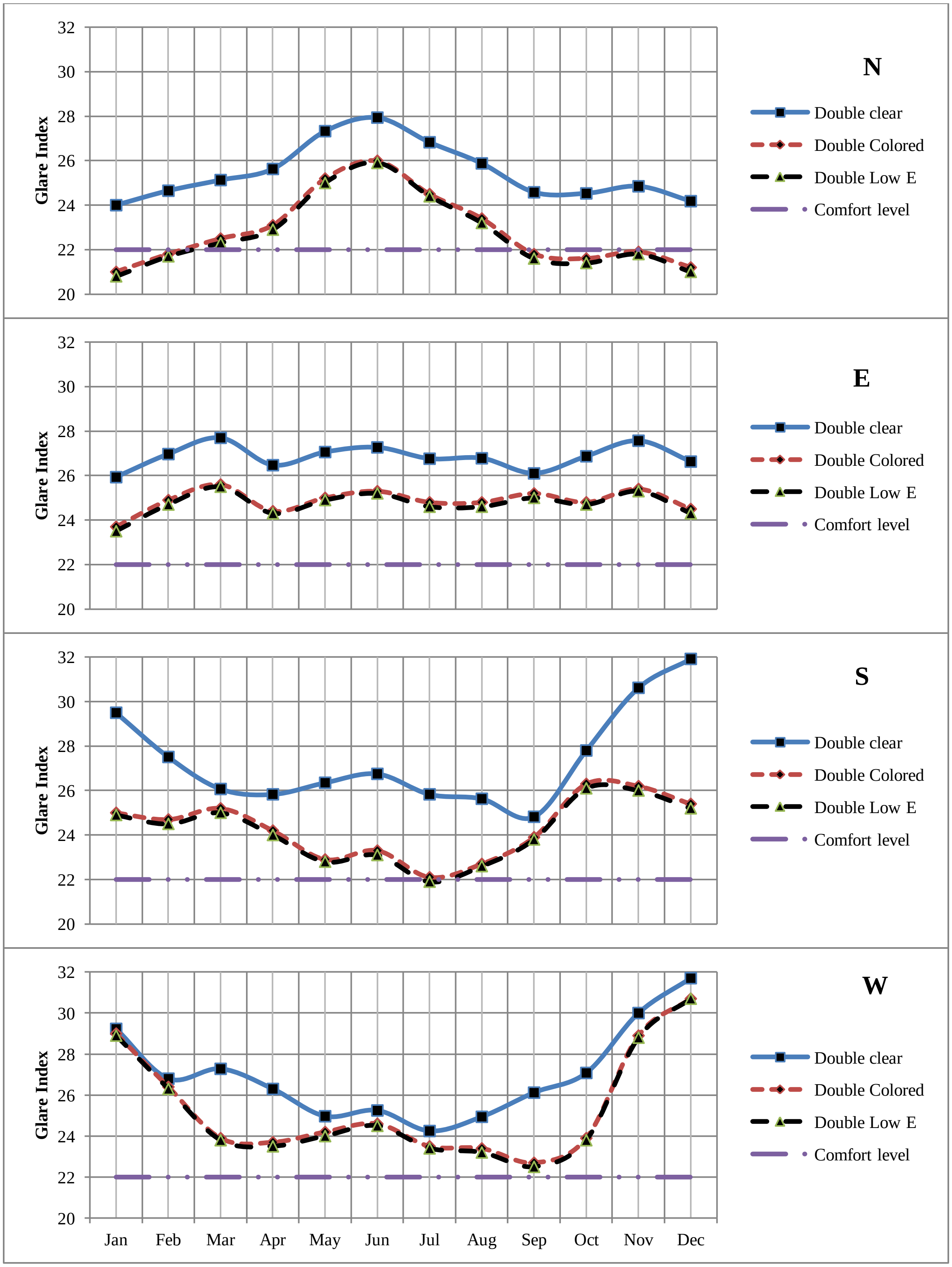


Figure 3.11: Monthly variation of Maximum Glare Index over a year for Various Orientations (Clear, Colored and Low E windows)

The illumination level for the perimeter zones in various orientations is determined to investigate the possibility of integrating the use of daylighting with the artificial lighting. For the purpose of illustration, on 21st of each month the illumination level was calculated for all the orientations at 9AM, 12 and 3PM. Two parameters were studied for assessing the visual comfort in the office building (Daylight Factor percentage, Glare Index). Daylight factors are used in architecture and building design to assess the internal natural lighting levels as perceived on the working plane, in order to determine if they will be sufficient for the occupants of the space to carry out their normal duties. This factor is defined as ratio of internal lighting level to external light level. The design day used for daylight factor calculations is based upon the Standard CIE overcast Sky for 21 September at 12:00pm. **Table** 25 shows the Daylight factors calculated for the office building with clear glass window in all the orientations on design day. In order to assess the effect of a poor or good daylight factor, one might choose to compare the results for a given calculation against published design guidance. In the UK CIBSE Lighting Guide 10 (LG10-1999) is used for the assessment, which broadly bands average daylight factors into the following categories **[49]**:

1. Daylight Factor (%) < 2: Not adequately lit – artificial lighting will be required.

2. Daylight Factor (%) between 2 and 5: Adequately lit but artificial lighting may be in use for part of the time.

3. Daylight Factor (%) > 2: Well lit – artificial lighting generally not required except at dawn and dusk – but glare and solar gain may cause problems.

Table 25: Daylight Factors for the Base case on the Design Day

Orientation	Daylight Factor at Different Time Intervals (Hrs)		
	9	12	15
North	3.78	3.76	3.77
East	3.93	3.94	3.93
West	4.25	4.25	4.2
South	4.08	4.07	4

Figure 3.12 shows the average Illumination level available for different duration of time on every 21st day of each month in various orientations of the base case model. For most of the months, the illumination level in the North orientation was beyond the required 500 Lux. North oriented facades receive good ambient and indirect daylight. The brightness of the sky gives the illuminance level measured on an unobstructed horizontal plane. When analyzing daylight, we often use illuminance values based on a "design sky" that represents a worst-case scenario. For East orientation, the daylight was found to be highest during the morning hours and as the day progresses, the daylight level got reduced. The illumination level for various orientations is to make sure that the occupants of building have the right level of light for their activity. These levels are usually measured on a working surface in the building. For West orientation it's totally the reverse action of East orientation. As the day progresses the daylight level increases and reaches the maximum during evening where the sun remains for longer duration. In the South orientation, the daylight level will be highest during the winter season and is considered to be the best orientation for harvesting the daylight and for reducing artificial lighting consumption. Also proper shading is a must on South to minimize the heat gain and for reducing the cooling load in the building.

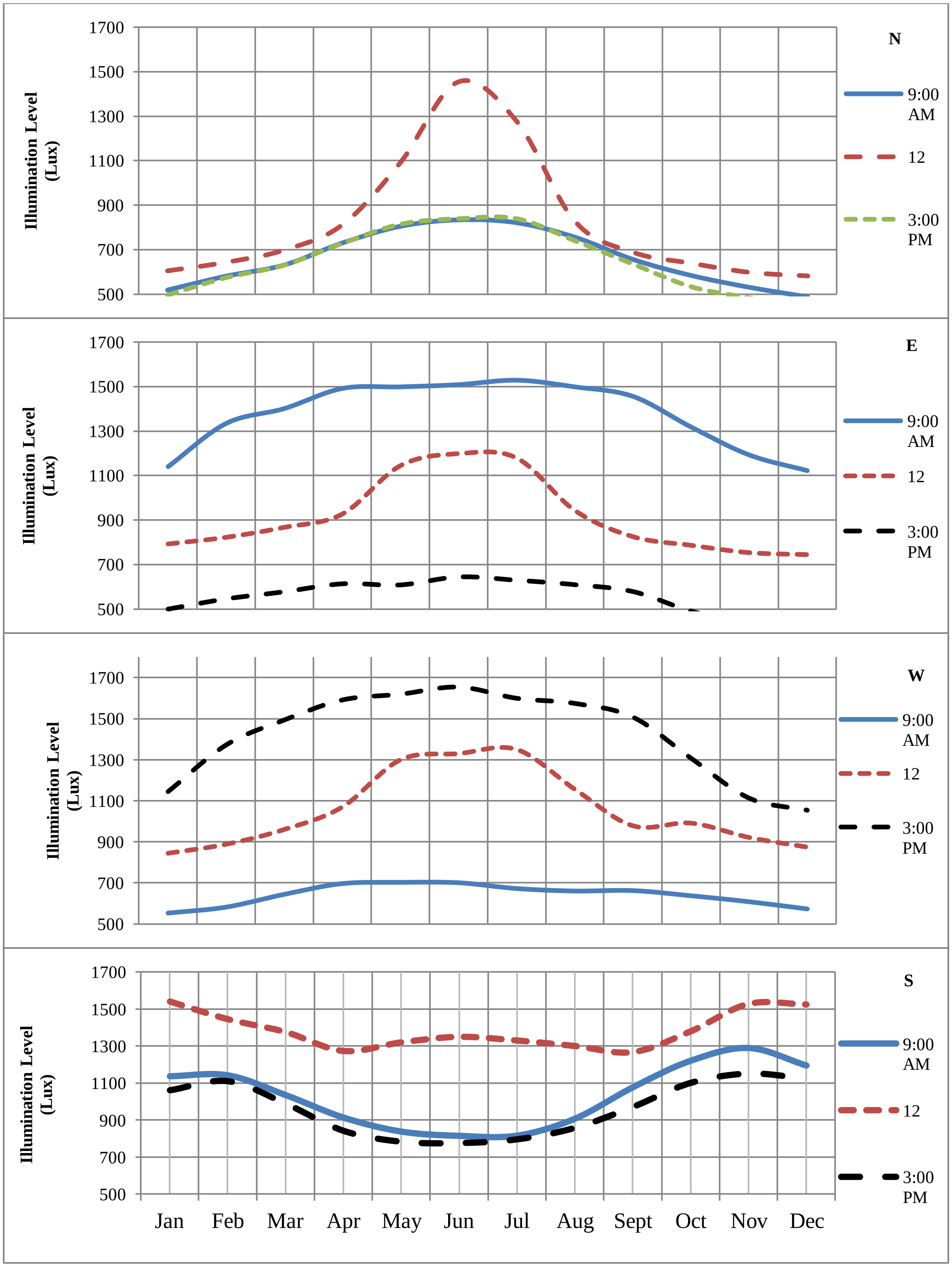


Figure 3.12: Illumination level on 21st of each month in different orientations of the office building

Simulations of daylight distribution in an office building with different glazings show that there can be significant visual discomfort associated with specific sky conditions. Figure 3.13 illustrates interior daylight distribution on 21st of June, during the Noon time. These calculations are used in assessing the visual comfort of a building. The clear glass windows transmit the most natural light due to its high visual transmittance characteristics.

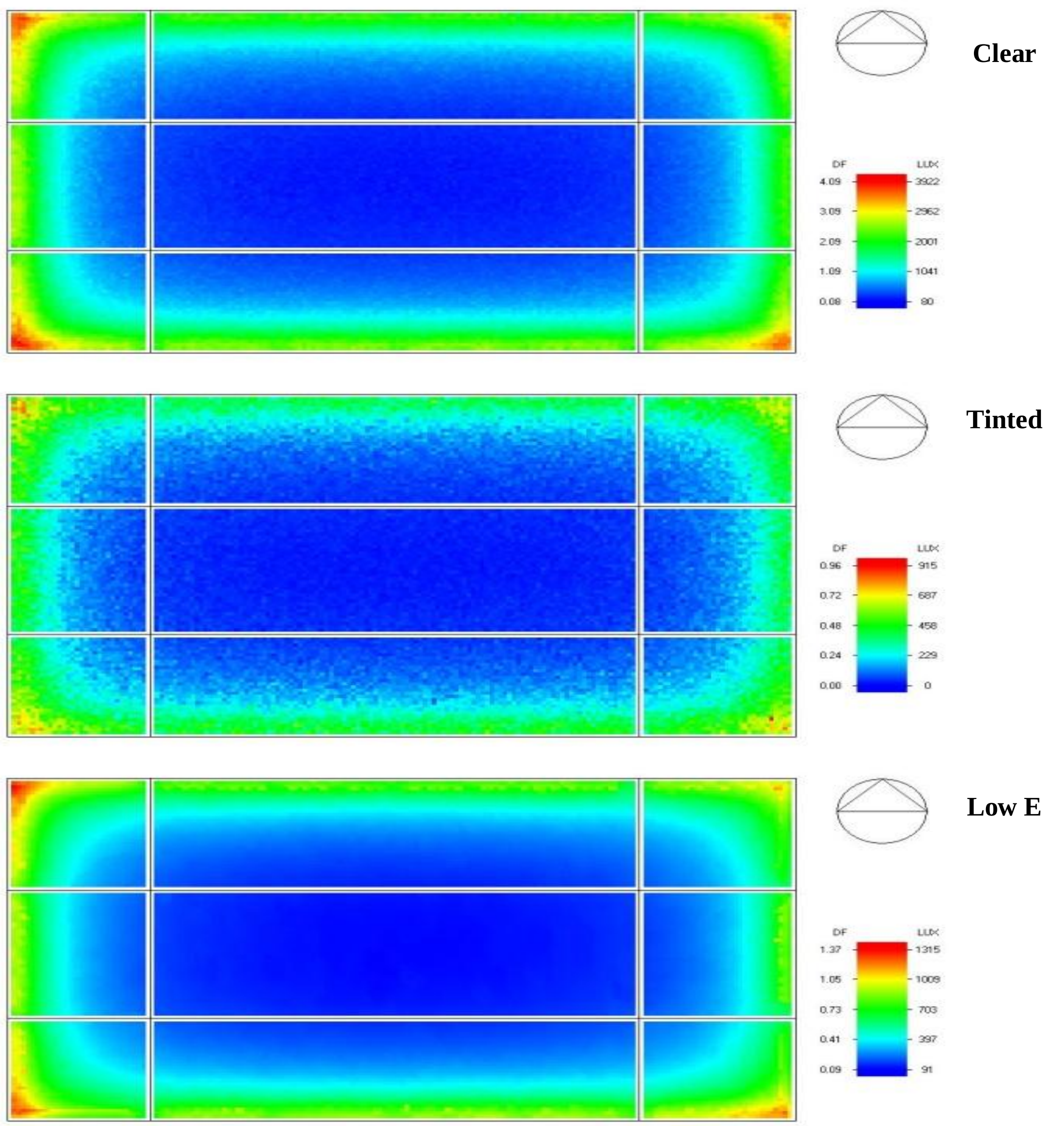


Figure 3.13: Daylight distribution for an office building with and without daylight integration

The daylight factor (DF) is a metric used to quantify the amount of diffuse daylight in a space. (Diffuse daylight is light that has been scattered in the atmosphere before reaching the Earth's surface). It is usually measured at the height of the work plane (i.e. a desktop), under a standardized CIE overcast sky. It is defined as the ratio of the illuminance of a point in a building and the illuminance at an unshaded outside point of a point in a building and the illuminance at an unshaded outside point facing upwards:

$DF = (E_{in} / E_{ext}) \times 100$

E_{in}: Interior illuminance at a fixed point on the work plane.

E_{ext}: Exterior illuminance under an overcast sky.

The mean daylight factor of a room is the average daylight factor value of a grid of sensors at work plane height that extends across the room. Figure 3.11 shows the pictorial representation of parameters needed for the calculation of Daylight Factor.

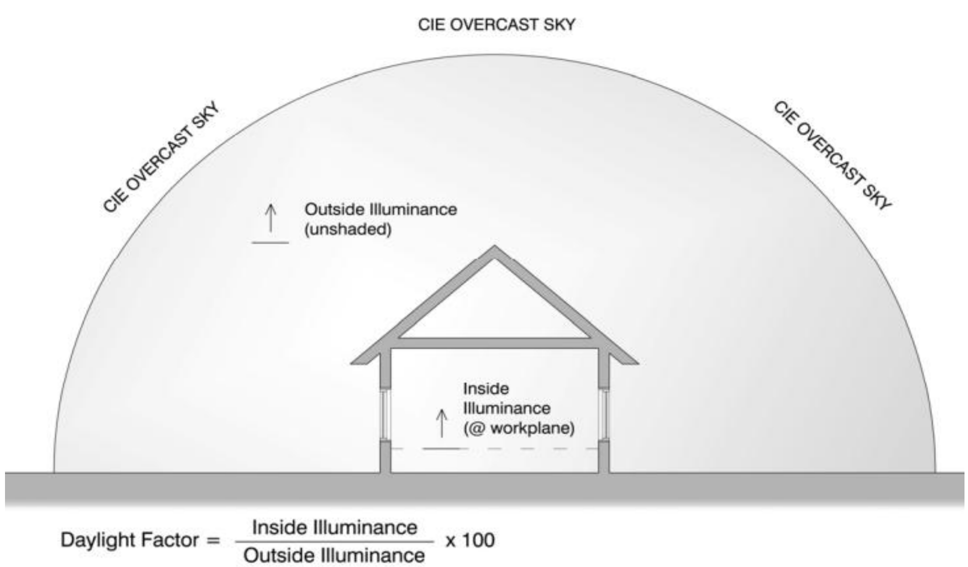


Figure 3.14: Schematic of Daylight Factor calculation

Figure 3.15, 3.16 and 3.17 shows the average DF (%) for an office building with clear, tinted and low- E glass windows, in different orientations on 21st of every month.

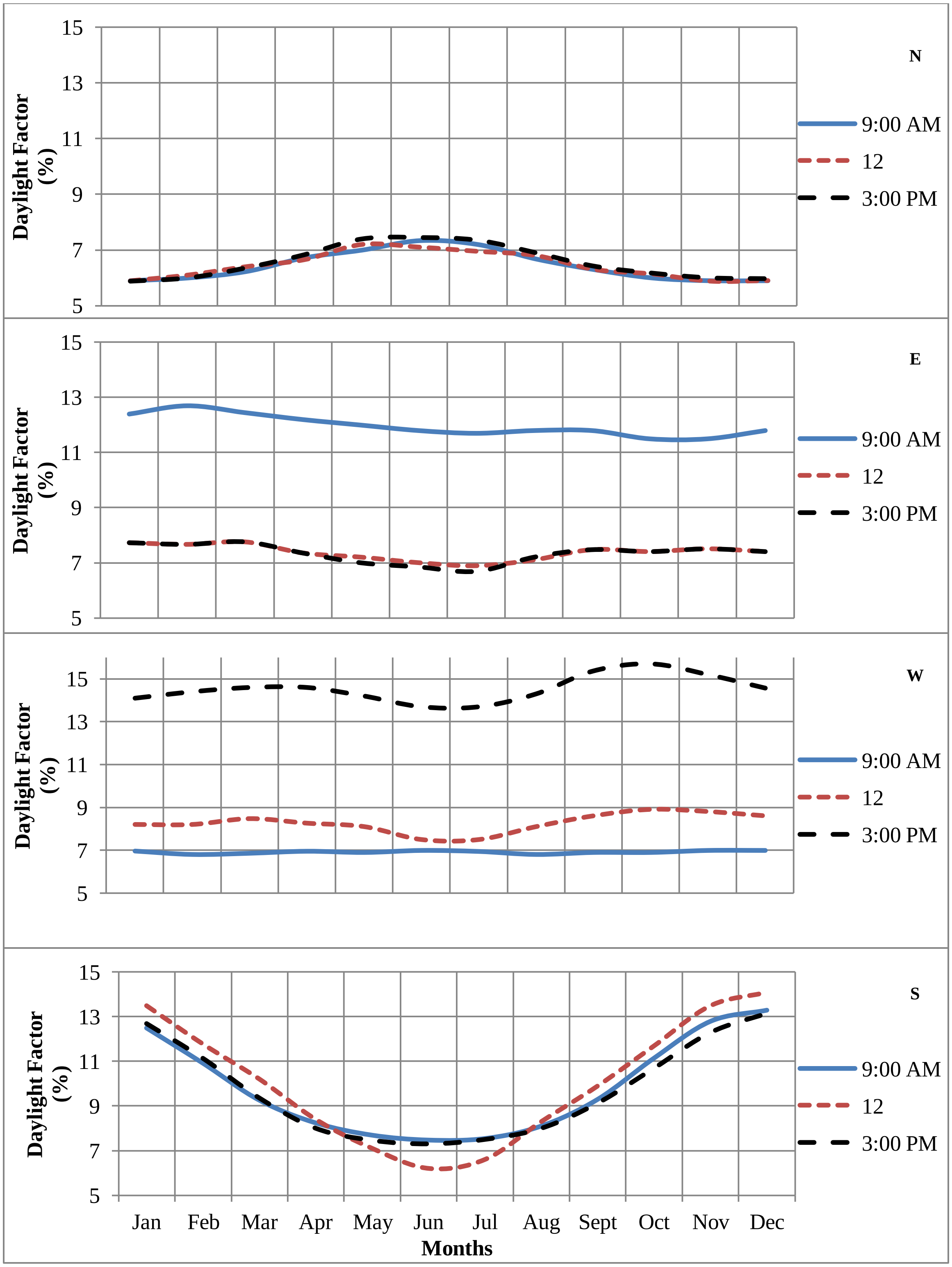


Figure 3.15: Average Daylight Factors on 21st of every month in different orientations (Clear glass)

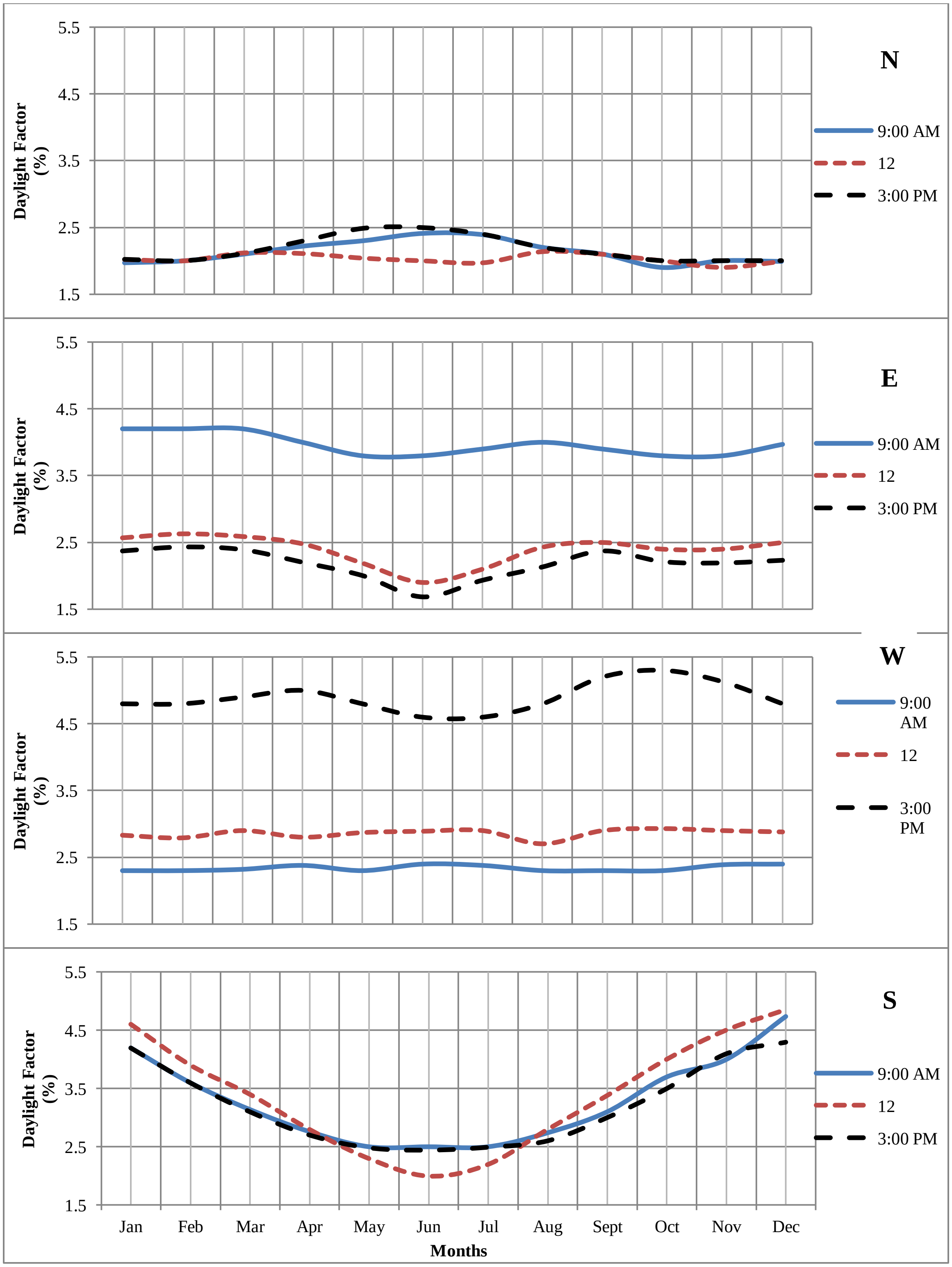


Figure 3.16: Average Daylight Factors on 21st of every month in different orientations (Tinted glass)

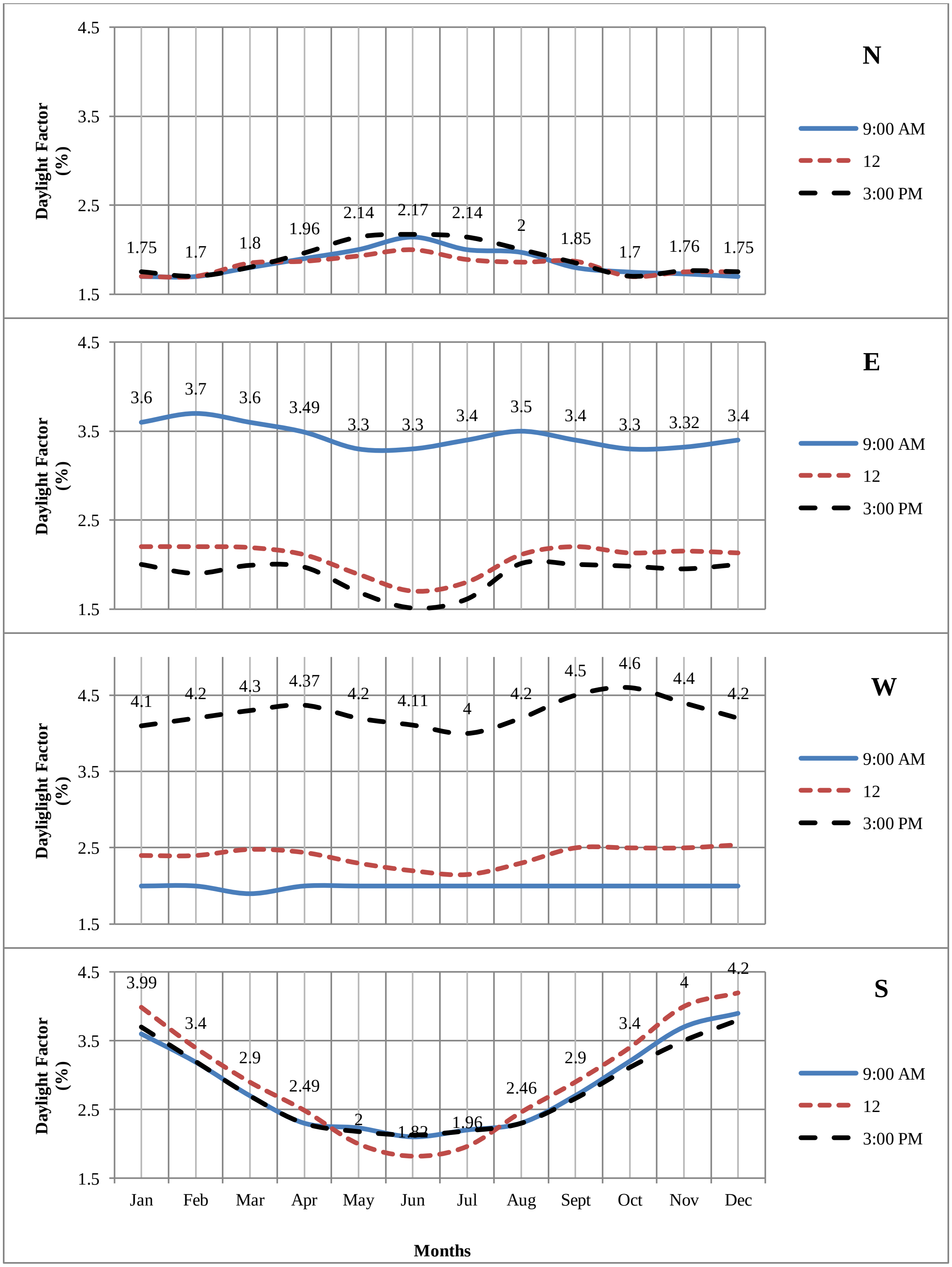


Figure 3.17: Average Daylight Factors on 21st of every month in different orientations (Low E glass)

CHAPTER 4

INVESTIGATION OF SMART WINDOWS ENERGY AND VISUAL PERFORMANCE

In this chapter the energy and visual performance of smart windows with various control techniques is investigated with the aim of improving the energy savings and also removing the visual discomfort from zones in the building. Artificial Lighting can be controlled according to the availability of natural daylight. When lighting control is switched on, illuminance levels are calculated at every time step during the simulation and then used to determine how much the electric lighting can be reduced. The daylight illuminance level in a zone depends on many factors, including sky condition, sun position, photocell sensor positions, size, glass transmittance and location of windows, window shades and reflectance of interior surfaces. Reduction of electric lighting depends on daylight illuminance level, illuminance set point, fraction of zone controlled and type of lighting control.

4.1 Types of smart windows

Smart windows are made of materials that can be easily switched between a transparent state and a state that is opaque, translucent, and reflective. The switching is done by applying an electric voltage to the material, or by performing some other simple, often mechanical, operation. They can be used to regulate the flow of light and radiant heat into or out of a building or other space. Two types of smart windows have been investigated in this research. They are as follows:

i. Electrochromic smart window

ii. Automated venetian blind smart window

4.1.1 ELECTROCHROMIC SMART WINDOW

Electrochromic smart window consist of a coating which has five layers, about 1 micron thick and is deposited on the glass substrate. The electrochromic stack consists of thin metallic coatings of nickel or tungsten oxide sandwiched between two transparent electrical conductors. When voltage is applied between the transparent electrical conductors, a distributed electrical field is setup. This field moves various coloration ions reversibly between the ion storage film through the ion conductor and into the Electrochromic film. The effect is that the glazing switches between a clear and transparent to tinted state. They require low voltage power (0-10 volts DC) and remain transparent across its switching range. They have a unique feature of changing the optical and thermal properties of a glass due to its chemical composition. Based upon a given set of control triggers, Electrochromic glass which features a wider range of thermal (SHGC) and optical (V_t) properties can result in more optimal operation of glass and thus results into more overall energy savings. **Table** 26 shows the characteristics of Electrochromic smart window for both ON and OFF state:

Table 26: Thermal and Visual characteristics of Electrochromic smart window

State of Glass	**Visible Transmission (%)**	**Solar Transmission (%)**	**SHGC**	**U-value (W/m^2. K)**
ON State (Bleached)	***75***	***64***	***0.73***	***2.4***
OFF State (Colored)	***13***	***11***	***0.11***	

To achieve ideal reduction in building energy consumption, innovative controlling strategies can be developed. Control strategies are directly related to the physical and visual comfort for a given space. For an office building, were occupant productivity is important, the selection of control strategies is critical.

4.1.2 Control Techniques for Electrochromic Smart Windows

Electrochromic smart window is composed of electro powered glasses, which alters transparency as electricity is passed through them. This can be managed manually or automatically. The manual mode only allows the electrical power to be switched on/off, corresponding to a tinted/clear state of glass. To automate the operation of Electrochromic window, control mechanism must be programmed to monitor and respond to specified triggers. Control trigger can be defined by variables, which describe exterior or interior condition of the given space. Exterior triggers include solar incidence on glazing while the interior triggers can include daylighting level, glare index at daylight sensor. These triggers function as explained below:

1. Daylighting Level: Daylighting illumination can be considered as a valid control trigger for Electrochromic glass. Daylighting sensors take care of the lighting parameter inside the building. Transmittance of the glazing is adjusted to just meet the daylight illuminance set point at the first daylighting reference point.
2. Solar control: Shading is on if beam plus diffuse solar radiation incident on the window exceeds Set Point radiation level. The designer can specify different radiation set point level for different orientations for the proper integration of daylight.
3. Glare control: Shading is on if the total daylight glare index at the zone's first daylighting sensor from all of the exterior windows in the zone exceeds the maximum glare index specified in the daylighting input for zone.

In this study the above triggers will be assessed in their effectiveness for maintaining the visual comfort and reducing the energy consumption. **Figure** 4.1 shows the mechanism of how EC smart window work. The properties of the window glass get adjusted based on the controller of the smart glass. The artificial lighting sensor placed on the ceiling measures the daylight coming from the EC window and it sends a signal to reduce the fractional input power of artificial lighting in discrete steps.

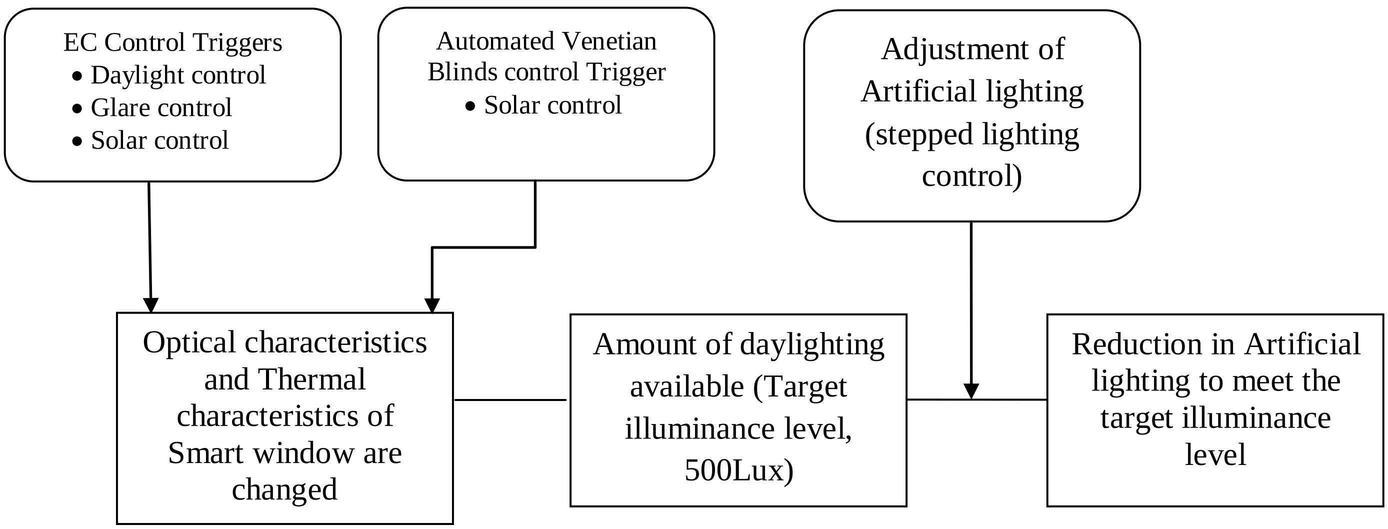


Figure 4.1: Control Mechanism of EC smart window

4.2 Automated Venetian Blind Smart Window

Automated Venetian blind systems are used to control solar gain and glare in the buildings. The control strategies adjust blinds on the basis of climatic criteria. Depending on the season, solar radiation that causes heat is either blocked or let in. Thermo sensors are placed near the windows to measure the amount of radiation falling on the windows, theses sensors are linked to the controller of automated venetian blinds. **Table** 27 shows the characteristics of automated venetian blinds for both fully closed and open position.

Table 27: Thermal and Visual characteristics of Automated Venetian Blinds

State of blinds	Visible Transmission (%)	Solar Transmission (%)	Solar Heat gain coefficient
Closed	***8***	***9***	***0.15***
Open	***80***	***76***	***0.78***

Figure 4.1 also shows the mechanism of how automated Venetian blinds work. The properties of the window glass get adjusted based on the solar set point. The artificial lighting sensor placed on the ceiling measures the daylight coming from the EC window and it sends a signal to reduce the fractional input power of artificial lighting in discrete steps.

4.3 Assessment of Different Control Strategies

The target illuminance in the building is set at 500 Lux which refers to the desired lighting level (in Lux) that needs to be maintained. Simulations were run with various control strategies as shown below for investigating the energy consumption and visual comfort in the office space.

4.3.1 Daylight Control Strategy

Daylight control strategy is employed to alter the property of Electrochromic (EC) smart window from opaque state to transparent state. Double low E glass is replaced with EC smart window in all orientations. Simulations were run to investigate the reduction in the lighting energy consumption and cooling energy consumption. The lighting energy consumption was reduced by 25% and cooling energy consumption was reduced by 14%. There was a substantial reduction in the building energy consumption by 23%. **Table** 28 shows the comparison between the energy performance of the base case and EC smart window with daylight controller.

Table 28: Energy Performance of the Base Case and EC Smart Window with Daylight Controller

Energy Flow	Base(kWh)	EC with Daylight Controller (kWh)	Energy Reduction (kWh)	% Reduction
Lighting Energy consumption	136,857	102,372	34,485	**-25**
Cooling Energy Consumption	1,587,191	1,462,242	124,949	**-8**
Total Energy consumption	2,174,093	1684371	489,722	**-23**

Maximum glare index values are plotted for identifying whether the visual comfort criteria was achieved or not. Figure 4.2 shows the variation in the maximum glare index value for both base case and EC smart window with daylight controller over a period of time. It is observed that for all the orientations the glare index value is beyond the acceptable level, because the transmittance through the glazing is adjusted to meet the daylight illuminance set point at the first daylighting sensor. It reduces the artificial lighting consumption, but along with the daylight it brings in the extra brightness that creates the visual discomfort to the occupants in the building. **Figure** 4.3 shows the variation in the Daylight Factor (%) when EC is used with daylight control. So, if daylight control strategy is selected for EC smart window, the savings will be substantial in lighting energy and considerable in cooling energy, but the visual comfort won't be attained.

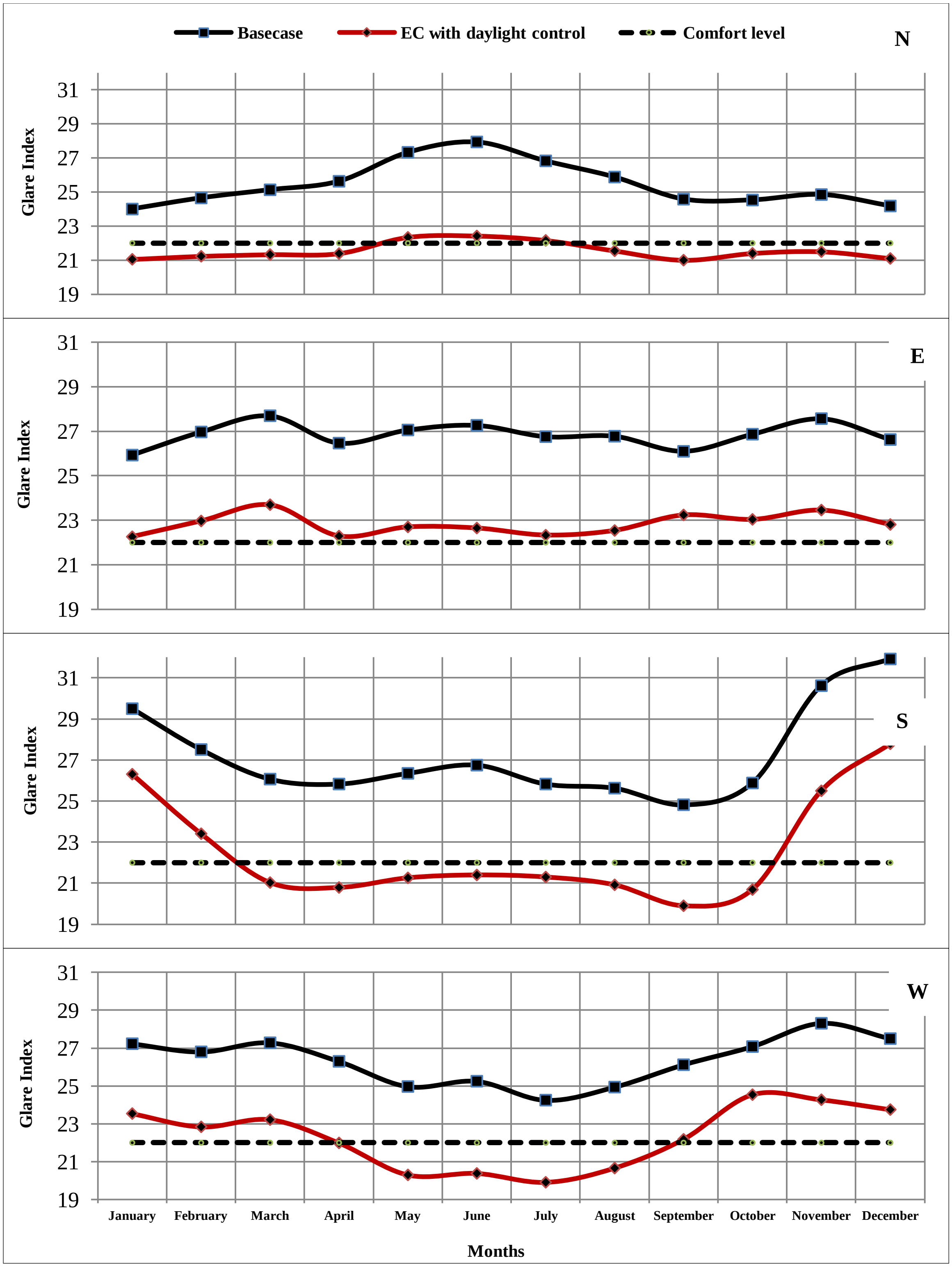


Figure 4.2: Monthly Variation of Maximum Glare Index with Daylight Control for Various Orientations

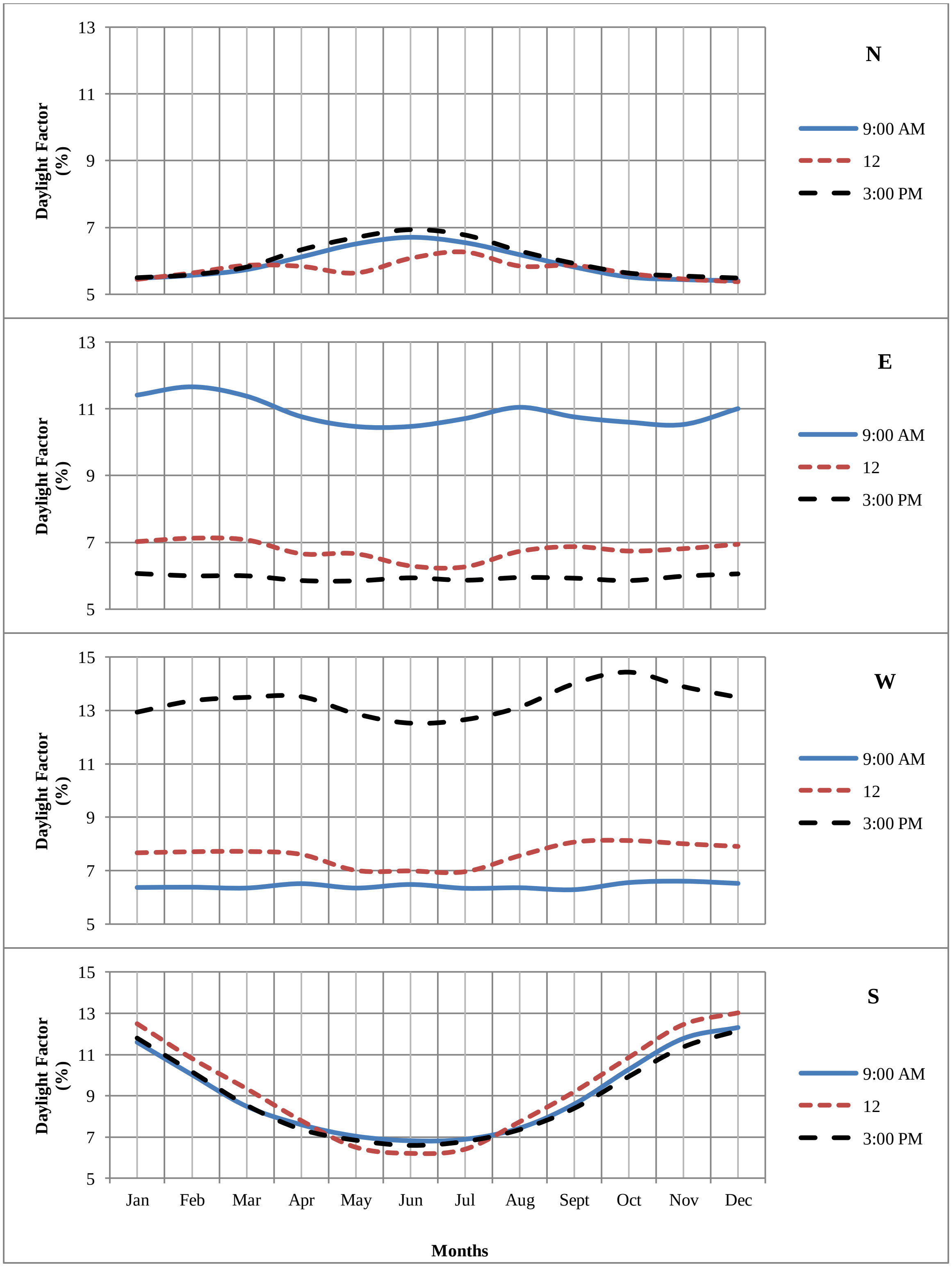


Figure 4.3: Average Daylight Factors on 21st of every month in different orientations (Daylight control)

4.3.2 Glare Control Strategy

EC smart window with Glare control strategy is used to change the transmission of smart window in order to control the daylight, so as no glare problem occurs. Simulations were carried out to investigate the energy savings along with the visual comfort criteria for every zone. Results showed that the lighting energy consumption is reduced by 12% and cooling energy consumption is reduced by 14%. Furthermore, a substantial reduction of about 17% is seen in the Building energy consumption. **Table** 29 shows the comparison between the energy performance of the base case and EC smart window with glare control strategy.

Table 29: Energy Performance of the Base Case and EC Smart Window with Glare Control

Energy Flow	Base case(kWh)	EC with Glare Control (kWh)	Energy Reduction (kWh)	% Reduction
Lighting Energy consumption	136,857	120,300	16,557	**-12**
Cooling Energy Consumption	1,587,191	1,372,784	214,407	**-14**
Total Energy consumption	2,174,093	1,808,756	365,337	**-17**

Figure 4.4 shows the variation in glare index values for every month in various orientations. The glare index setpoint value will be fed in the sensor of EC smart window, which will be used as trigger to alter the state of the window from colored to transition. Figure 4.5 shows the average Daylight Factor (%) for various orientations when EC is used with glare control strategy.

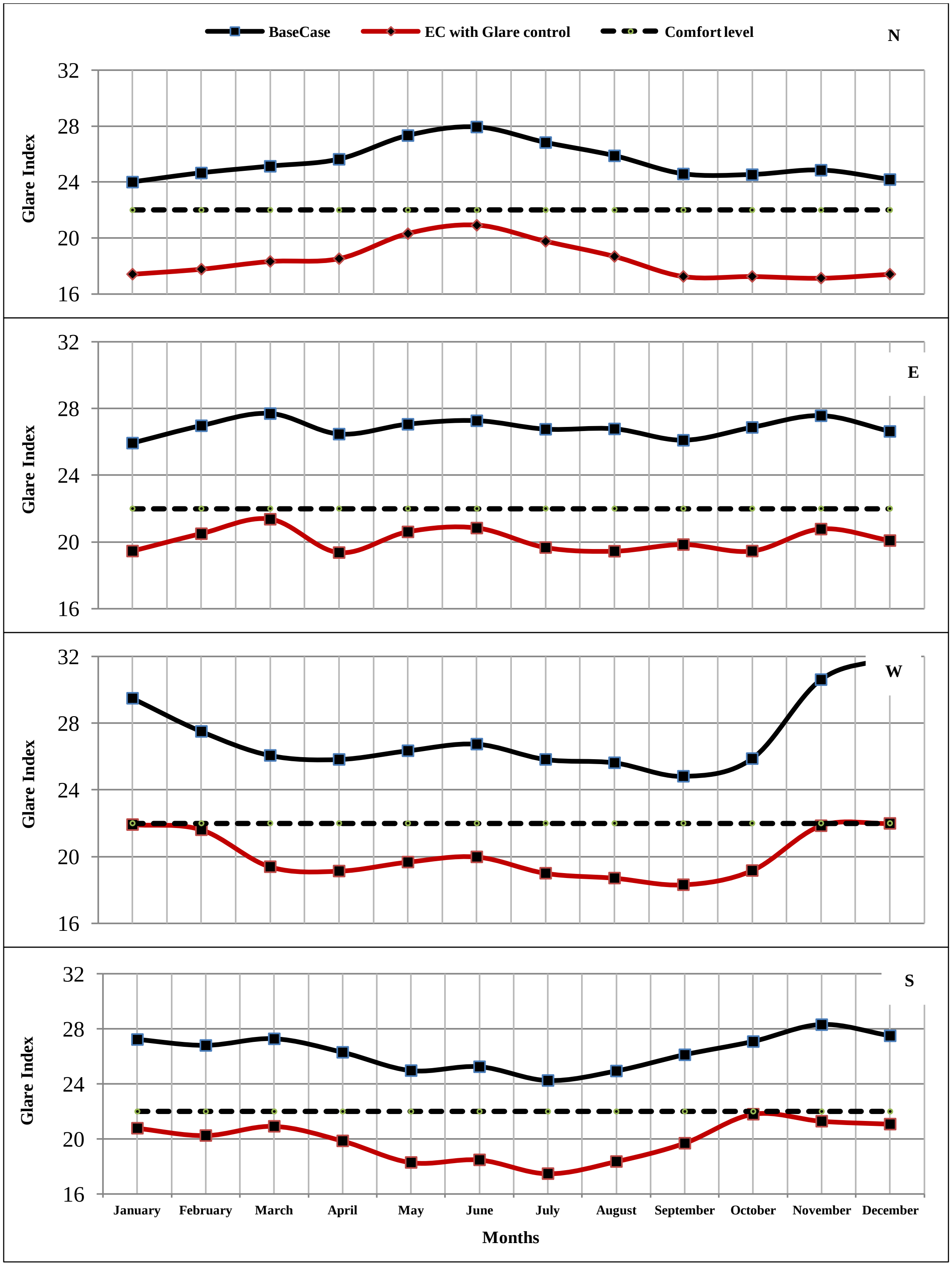


Figure 4.4: Monthly Variation in the Glare Index with Glare Control for different orientations

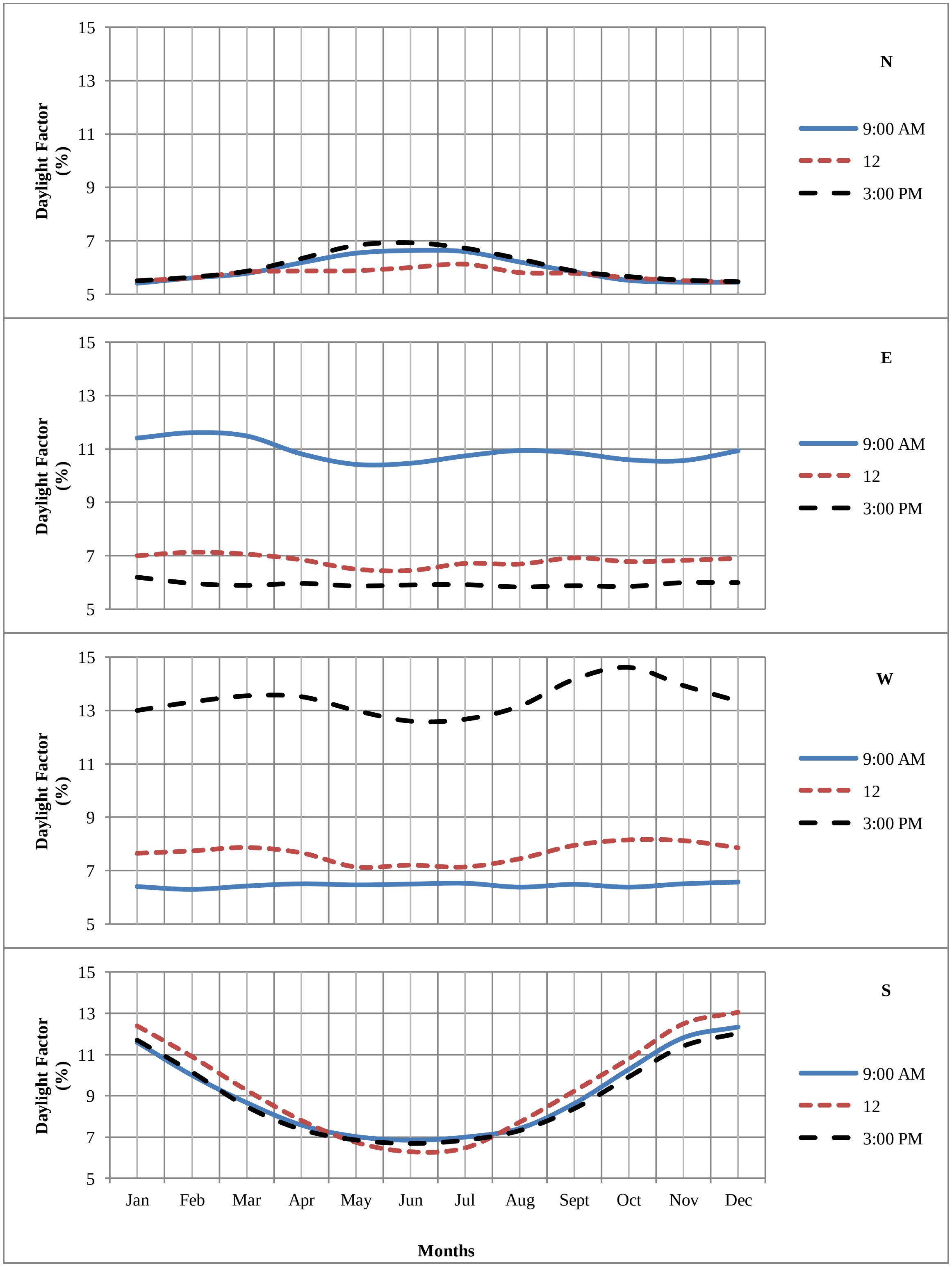


Figure 4.5: Average Daylight Factors on 21st of every month in different orientations (Glare control)

It is observed that for all orientations the glare index value is within the acceptable level, because the transmittance through the glazing is adjusted to meet the required glare index which is set at the first daylight sensor. In doing so, it lets in only certain amount of daylight as long as the glare index is within the acceptable limits, thereby reducing the lighting energy consumption and also satisfying the visual comfort criteria for the occupants. So, if glare control strategy is selected for EC smart window, the savings will be high in lighting energy and considerable in cooling energy, along with visual comfort being achieved in all the zones. So this strategy has a strong potential and should be considered for EC smart window.

4.3.3 Solar Control Strategy

EC window with solar control strategy is used to change the property of smart glass from clear state to darkened state. Transmission of daylight from smart glazing will be a function of radiation transmitted through the smart glass. Shading is on if beam plus diffuse solar radiation incident on the window exceeds Set Point radiation level. The set point value varies with the orientation of the windows, because the amount of radiation received will not be the same for all the orientations. Simulations were carried out to identify the set point radiation level for various orientations.

4.4 Determination of Set points for various orientations

A Building model is developed by replacing the conventional clear glass window with EC smart window for each orientation respectively. Solar controller is used to alter the thermal and optical properties of smart window. Series of simulations were carried out to identify the set point radiation at which the energy savings were high, along with visual comfort being achieved.

4.4.1 North Orientation Set Point Radiation Level

EC smart glass with solar controller is installed in the North orientation of the office building. Simulations were carried out by increasing the radiation level values in steps of 25W/m^2. Visual comfort and energy savings were predicted for every radiation level. During the series of simulations it is found that at solar set point value of 105 W/m^2, the energy savings were high with all the zones satisfying the visual comfort condition. Maximum glare index values are plotted at the solar set point of 105W/m^2 in order to show the visual comfort criteria is being achieved. **Figure** 4.6 shows the glare index values for every month for North orientation. It can be seen that for the whole year the glare index value is within the acceptable level.

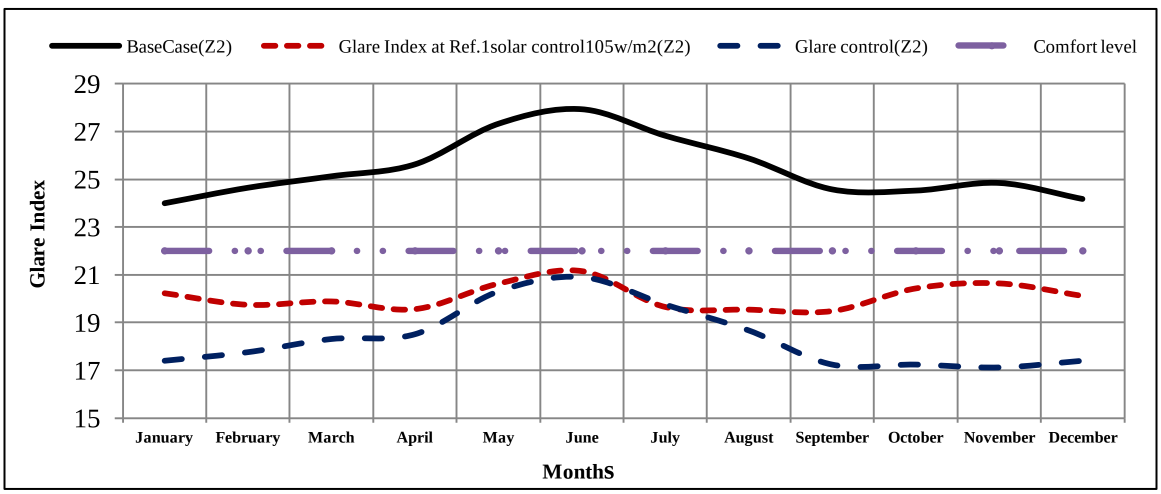


Figure 4.6: Monthly Variation of Maximum Glare Index Value for Both Control Strategies with EC in North Orientation

Figure 4.7 shows the variation in lighting, cooling and total energy consumption for different solar set points. By increasing the solar radiation value, huge amount of daylight will be drawn from outside and will be allowed to move in the interior space thereby reducing the lighting energy consumption. But on the other hand, by letting in high amount of daylight will increase the heat gain in the space which in turn increases the cooling energy consumption. So there is a need to identify the optimal set point at which the savings are high, while maintaining the glare index in the acceptable range. Total energy consumption curve can be divided into the 3 stages for different set point radiation level. First stage is categorized as phase in which the radiation level is increased gradually between 25-100 W/m^2. In this phase, the lighting energy consumption decreases but there will be slight increase in the cooling energy consumption due extra heat gain from outside. Due to this mix effect of decrease in the lighting energy consumption and slight increase in the cooling energy consumption, substantial savings in the total energy consumption can be seen with curve moving downwards. At solar radiation value of 105 W/m^2, glare index was investigated and was found to have attained the saturation point of comfort level, and further increase in the radiation value resulted in visual discomfort in the indoor environment. Second stage is the phase between 105-175 W/m^2, in this phase the savings were maximum in the overall energy consumption because by drawing huge amount of daylight will decrease the artificial lighting energy consumption to the maximum with slight increase in the cooling energy consumption but visual comfort will not be attained, because the glare index value will be increases beyond the comfort level if we increase the set point radiation value after 105 W/m^2. Third stage starts from set point radiation value of 175 W/m^2, and is described as a phase in which, with an increase in the radiation level beyond 175 W/m^2, will result in an abrupt increase in the cooling energy consumption and no further decrease in the lighting energy consumption, which is why the total energy consumption curve shots up showing an increase in the overall consumption of the building. The lighting energy consumption was reduced by 3% and End-use cooling energy consumption was reduced by 4% by using EC smart window in North orientation with solar control and set point at **105W/m^2**. Also the total energy consumption of building saw a reduction of 3%.

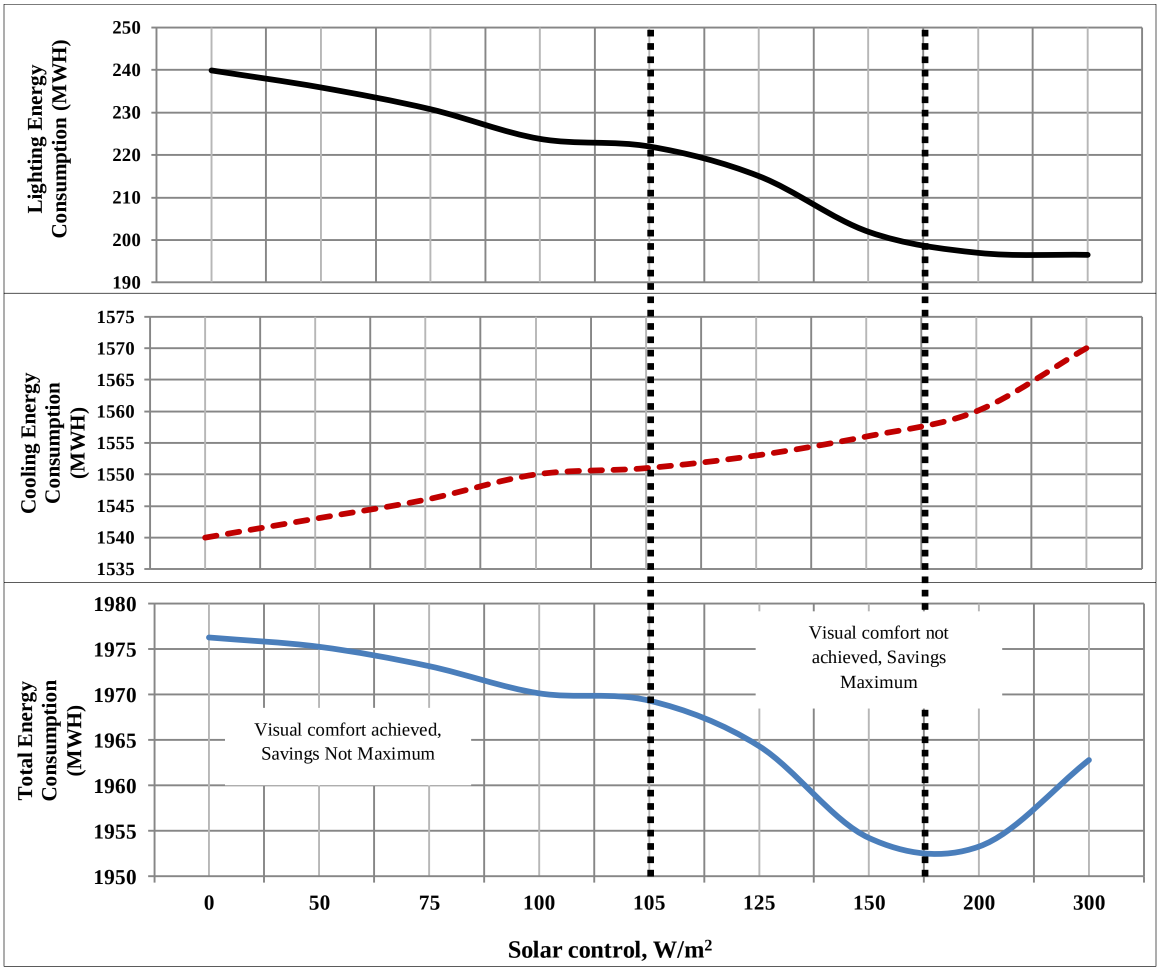


Figure 4.7: Lighting, Cooling and Total Energy Consumption for Different Radiation Level with EC in North Orientation

Energy and visual comfort performance of EC smart glass with both the controllers (Glare control & solar control) is determined. Simulations were carried out by installing the EC smart glass with glare control in the north orientation. **Table** 30 illustrates the lighting energy consumption and End-use cooling energy consumption for both controllers. It can be observed that, if solar controller is used over glare control the resultant savings will be high along with visual comfort criteria being satisfied.

Table 30: Energy Performance for the Whole Building with Both Controls in North Orientation

Energy consumption	Base case(kWh)	Solar control 105W/m^2 (kWh)	Glare control (kWh)	solar control (% Reduction)	Glare control (% Reduction)
Lighting	136,857	132,751	133,435	**-3**	**-2.5**
Cooling	1,587,191	1,523,703	1,515,767	**-4**	**-4.5**
Total	2,174,093	2,108,870	2,108,870	**-3**	**-2.7**

4.4.2 East Orientation Set Point Radiation Level

EC smart glass with solar controller is installed in the East orientation. Simulations were carried out and it is found that at solar set point value of 100 W/m^2, the energy savings were high and visual comfort was achieved. **Figure** 4.8 shows the glare index values at set point 100 W/m^2 for different months. It can be seen that during the whole year the glare index value is within the acceptable level.

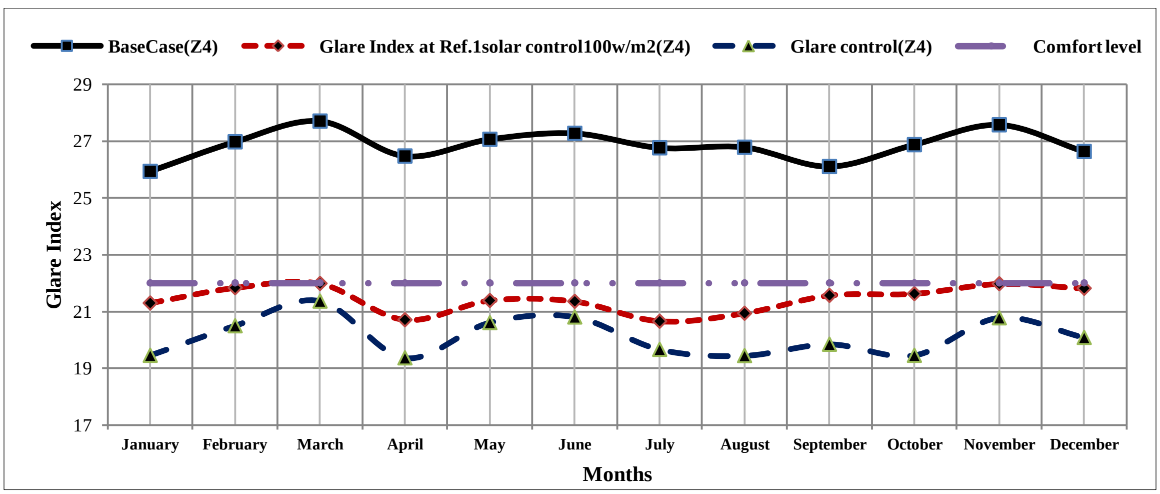


Figure 4.8: Monthly of Maximum Glare Index Value for Both Control Strategies with EC in East Orientation

Figure 4.9 shows the variation in lighting, cooling and total energy consumption for building with EC windows in East orientation at different solar set points. By increasing the solar radiation value, huge amount of daylight will be drawn from outside which will decrease the artificial lighting consumption due to the dimming effect by the control mechanism.

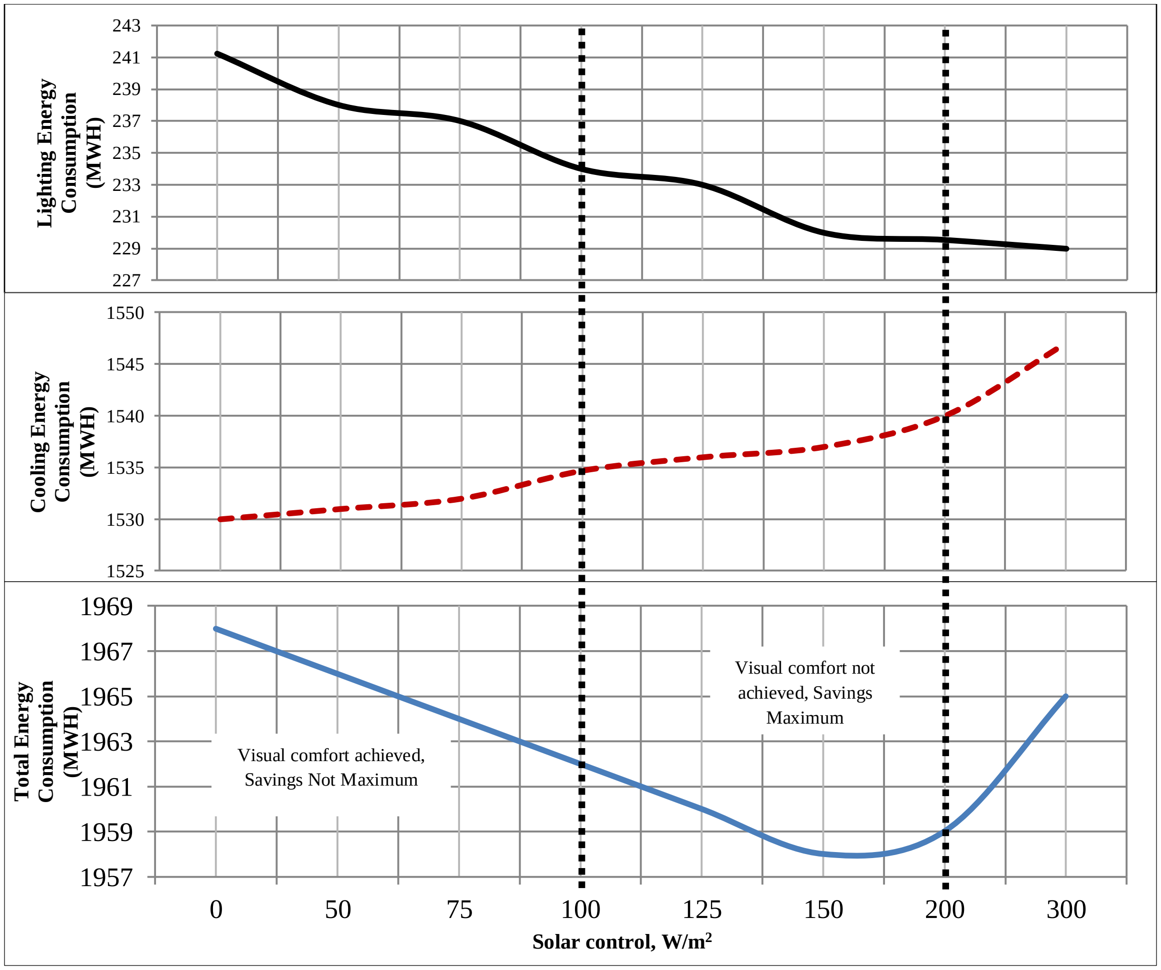


Figure 4.9: Total Energy Consumption for Different Radiation Level with EC in East Orientation

By increasing the radiation level the excess solar radiation from outside will increase the cooling load which is why the curve for cooling energy consumption increases linearly with the increase in the radiation level. The lighting energy consumption was reduced by 5% and End-use cooling energy consumption is reduced by 3% by using EC smart window in East orientation with solar control and set point at **100W/m^2**. Also the total energy consumption of building saw a reduction of 5%. Simulations were carried out by installing the EC smart glass with glare control in the East orientation. **Table** 31 illustrates the lighting energy consumption and end use cooling energy consumption for both controllers. It can be observed that if solar controller is considered over glare control the resultant savings will be high along with visual comfort criteria being satisfied.

Table 31: Energy Performance for the Whole Building with Both Controls in East Orientation

Energy consumption	Base case(kWh)	Solar control 100W/m^2 (kWh)	Glare control (kWh)	solar control (% Reduction)	Glare control (% Reduction)
Lighting	136,857	130,000	131,376	**-5**	**-4**
Cooling	1,587,191	1,539,561	1,531,646	**-3**	**-3.5**
Total	2,174,093	2,065,392	2,076,281	**-5**	**-4.5**

4.4.3 South Orientation Set Point Radiation Level

EC smart glass with solar controller is installed in the South orientation of the office building for identifying the set point radiation. Simulations were carried out and it is found that at solar set point value of 95 W/m^2, the energy savings were high with all the zones satisfying the visual comfort condition. **Figure** 4.10 shows the glare index values for every month for South orientation. It can be seen that during the whole year the glare index value is within the acceptable level.

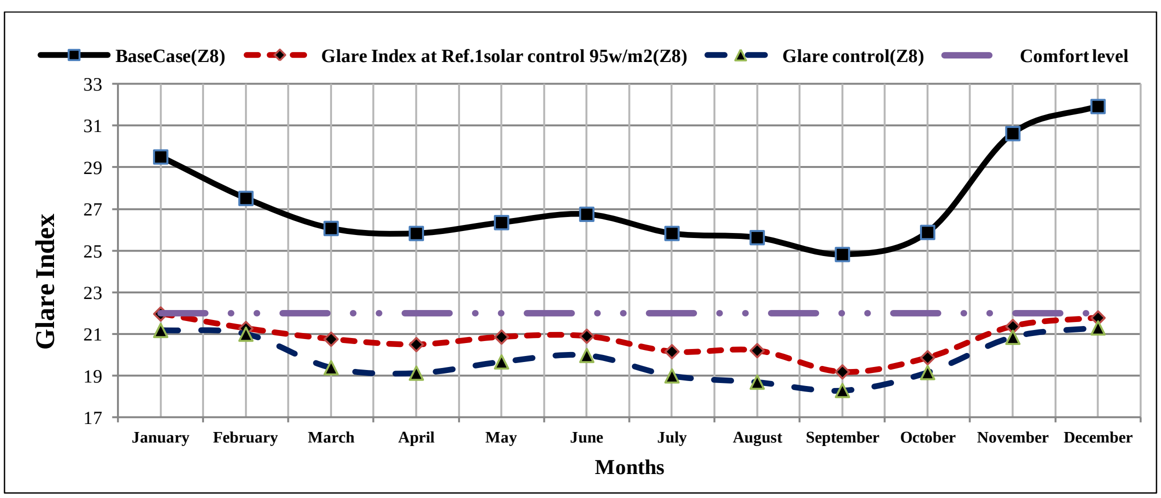


Figure 4.10: Monthly variation of Maximum Glare Index Value for Both Control Strategies with EC in South Orientation

Figure 4.11 shows the variation in lighting, cooling and total energy consumption for different solar set points. By increasing the solar radiation value, huge amount of daylight will be allowed to move in the interior space, which reduces the artificial lighting energy consumption. The lighting energy consumption is reduced by 7% and End-use cooling energy consumption was reduced by 2% at set point **95W/m^2**. Also the total energy consumption of building saw a reduction of 7%.

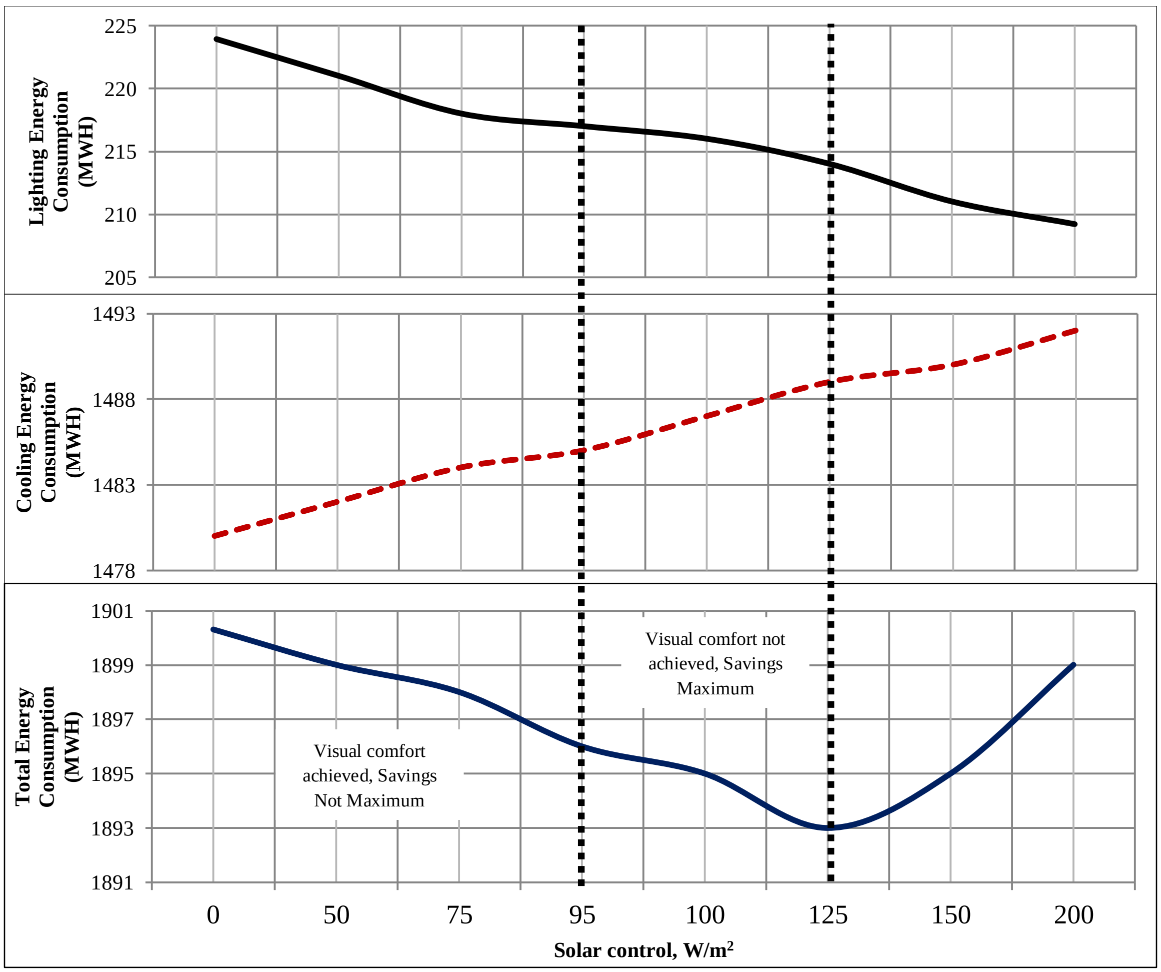


Figure 4.11: Total Energy Consumption for Different Radiation Level with EC in South Orientation

Simulations were carried out by installing the EC smart glass with glare control in the South orientation. **Table** 32 illustrates the lighting energy consumption and end use cooling energy consumption for both controllers. It can be observed that if solar controller is considered over glare control the resultant savings will be high along with visual comfort criteria being satisfied.

Table 32: Energy Performance for the Whole Building with Both Controls in South Orientation

Energy consumption	Base case(kWh)	Solar control 95W/m^2 (kWh)	Glare control (kWh)	solar control (% Reduction)	Glare control (% Reduction)
Lighting Energy	136,857	127,277	128,645	**-7**	**-6**
Cooling	1,587,191	1,555,447	1,547,511	**-2**	**-2.5**
Total	2,174,093	2,021,906	2,032,776	**-7**	**-6.5**

4.4.4 West Orientation Set Point Radiation Level

EC smart glass with solar controller was installed in the West orientation for identifying the set point radiation at which the energy savings will be highest along with satisfying the visual comfort criteria. Simulations were carried out and it was found that at 100 W/m^2, the energy savings were high with all the zones satisfying the visual comfort condition. Figure 4.12 shows the glare index values for every month for West orientation. It's observed that the maximum glare index value is within the acceptable level, during the whole year. With glare control strategy, the glare index will be adjusted and will always remain less than the maximum glare index value set at first daylight sensor.

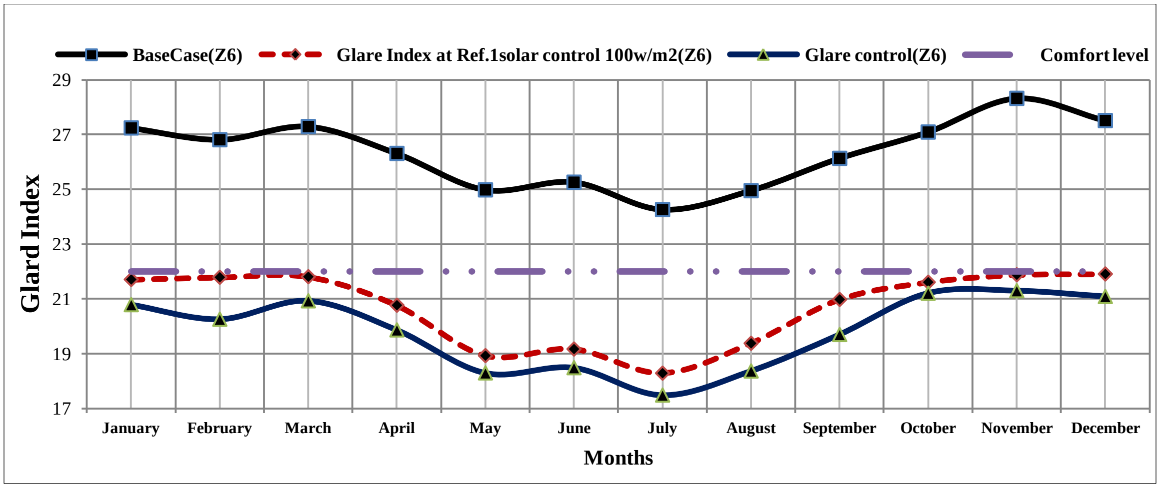


Figure 4.12: Monthly Glare Index Value for Both Control Strategies with EC in West Orientation

Figure 4.13 shows the variation in the lighting, cooling and total energy consumption for different solar set points. The set point value for West orientation was found to around 100 W/m^2.

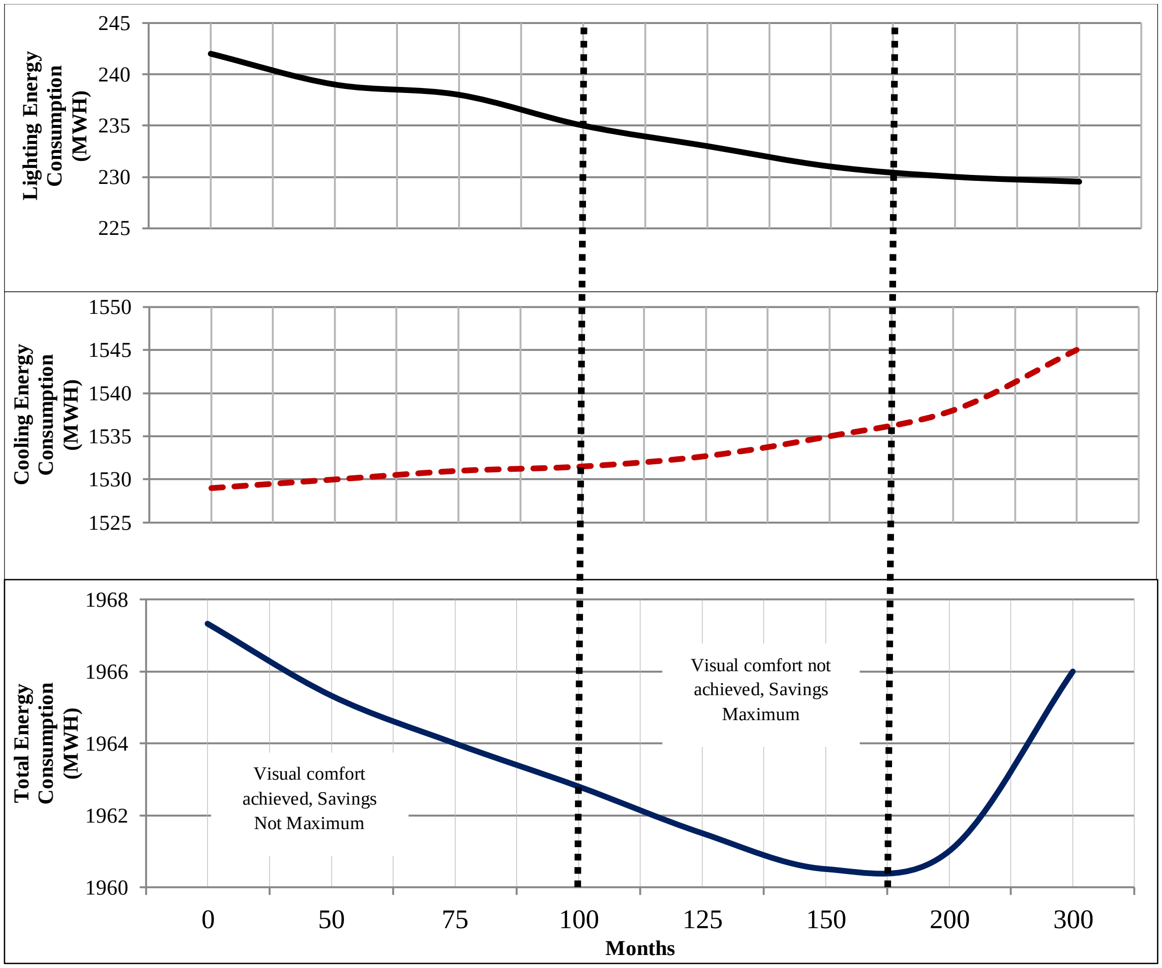


Figure 4.13: Total Energy Consumption for Different Radiation Level with EC in West Orientation

Simulations were carried out by installing the EC smart glass with glare control in the West orientation. **Table** 33 illustrates the lighting energy consumption and End use cooling energy consumption for both controllers. It can be observed that if solar controller is considered over glare control the resultant savings will be high along with visual comfort criteria being satisfied.

Table 33: Energy Performance for the Whole Building with Both Controls in West Orientation

Energy Flow consumption	Base case(kWh)	Solar control 100W/m^2 (kWh)	Glare control (kWh)	solar control (% Reduction)	Glare control (% Reduction)
Lighting	136,857	130,014	131,382	**-5**	**-4**
cooling	1,587,191	1,539,575	1,531,639	**-3**	**-3.5**
Total	2,174,093	2,065,388	2,076,285	**-5**	**-4.5**

Table 34 illustrates the scope of maximum energy savings when visual comfort is neglected for various orientations. After analyzing the results it's observed that, by installing EC smart glass with solar controller in the south orientation the energy savings were the highest when compared with the other orientations.

Table 34: Maximum Energy Savings With and Without Visual Comfort

Orientation	Maximum energy savings (No visual comfort)			Energy savings (visual comfort)		
	Lighting	Cooling	Total	Lighting	Cooling	Total
NORTH	-7	-3	-4	-3	-4	-3
EAST	-6.5	-2.5	-5.5	-5	-3	-5
SOUTH	-8.5	-1.7	-8	-7	-2	-7
WEST	-6.5	-2.5	-5.5	-5	-3	-5

4.5 Impact of WWR When Employing Solar Radiation Control

EC smart glass with solar controller was used for the admittance of daylight, the resulting total building energy consumption first decreases and then increases for different WWR. Window size is expected to have two major impacts on the energy performance of the building. As the size gets larger, more lighting energy is saved. However cooling energy is expected to increase. Simulations were carried out by varying the WWR. With increase in the WWR, the amount of daylight increases thereby reducing the load on artificial lighting. **Figure** 4.14 shows the variation in the lighting, cooling and total energy consumption for various WWR. By admitting high amount of daylight will increase the heat gain in the building, which in turn increase the end-use cooling energy consumption.

Also, it can be seen that the total energy consumption of the building for smaller values of WWR will tends to move down, this is because of decrease in the lighting energy consumption and between 50-70% WWR the lighting energy savings reaches the saturation point which is why at this point maximum savings were calculated. By increasing the WWR beyond 70%, will bring in a lot of solar radiation through the windows which will increase the End-use cooling energy consumption, and the total energy consumption will start to increase. So the results show that the potential energy savings are very high when WWR is set between 50-70%.

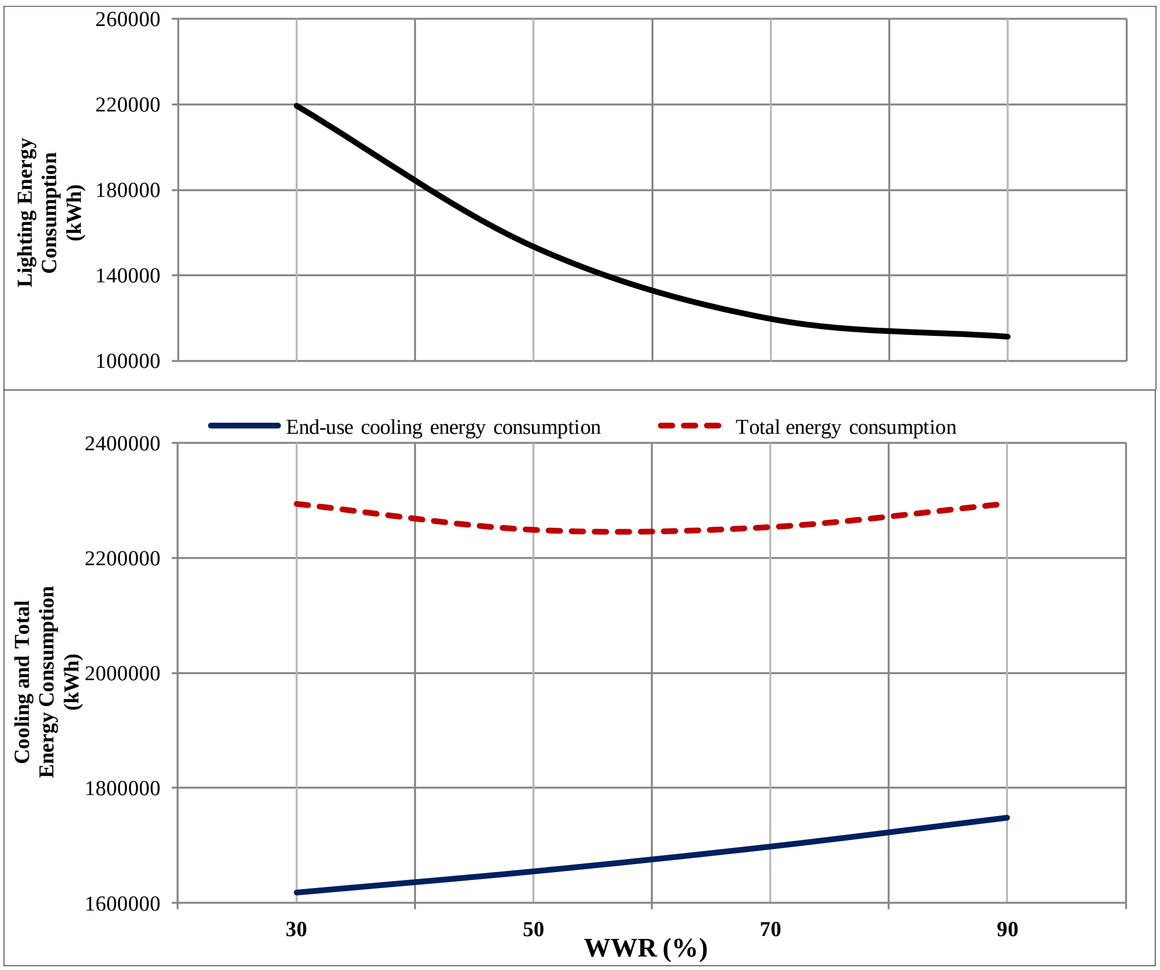


Figure 4.14: End-Use Cooling Energy and Total Energy Consumption with EC in All Orientations (Solar Control) for Different WWR

4.6 Energy Consumption with EC Windows (Solar control) in all orientations

EC smart window with solar control strategy is used to change the property of smart glass from clear state to darkened state. In the previous section it has been found that EC smart glass with daylight controller has the potential of saving a lot of energy but without satisfying the visual comfort criteria. Simulations were carried out by installing EC smart glass with glare control in all the orientations and it is found that the lighting energy consumption is reduced by 12% and cooling energy consumption is reduced by 14%. Also the total energy consumption of building saw a substantial reduction of 17% and all the space in the buildings were satisfying the visual comfort criteria. Solar controller is used as trigger to alter the properties of EC smart glass. Simulations were done to identify the set point radiation value for the various orientations and study the energy performance of the office building. For building with EC smart glass install in the North orientation the set point radiation value is found to be 105 W/m^2, similarly for building with EC smart glass install in East and West respectively the set point radiation value is found to be 100W/m^2, and for building with EC smart window install only in the South orientation the set point radiation level is found to be 95 W/m^2. An investigation was conducted by installing the EC smart window in all orientation with respective radiation level. During the simulations it was found that by using EC smart window with solar controller will result in reduction of artificial lighting energy consumption by 20%. Similarly the cooling energy consumption was reduced by 12%. Total building energy consumption was reduced by 20%. **Figure** 4.15 shows the average Daylight factor (%) which was used to reduced the artificial lighting energy consumption for various orientations.

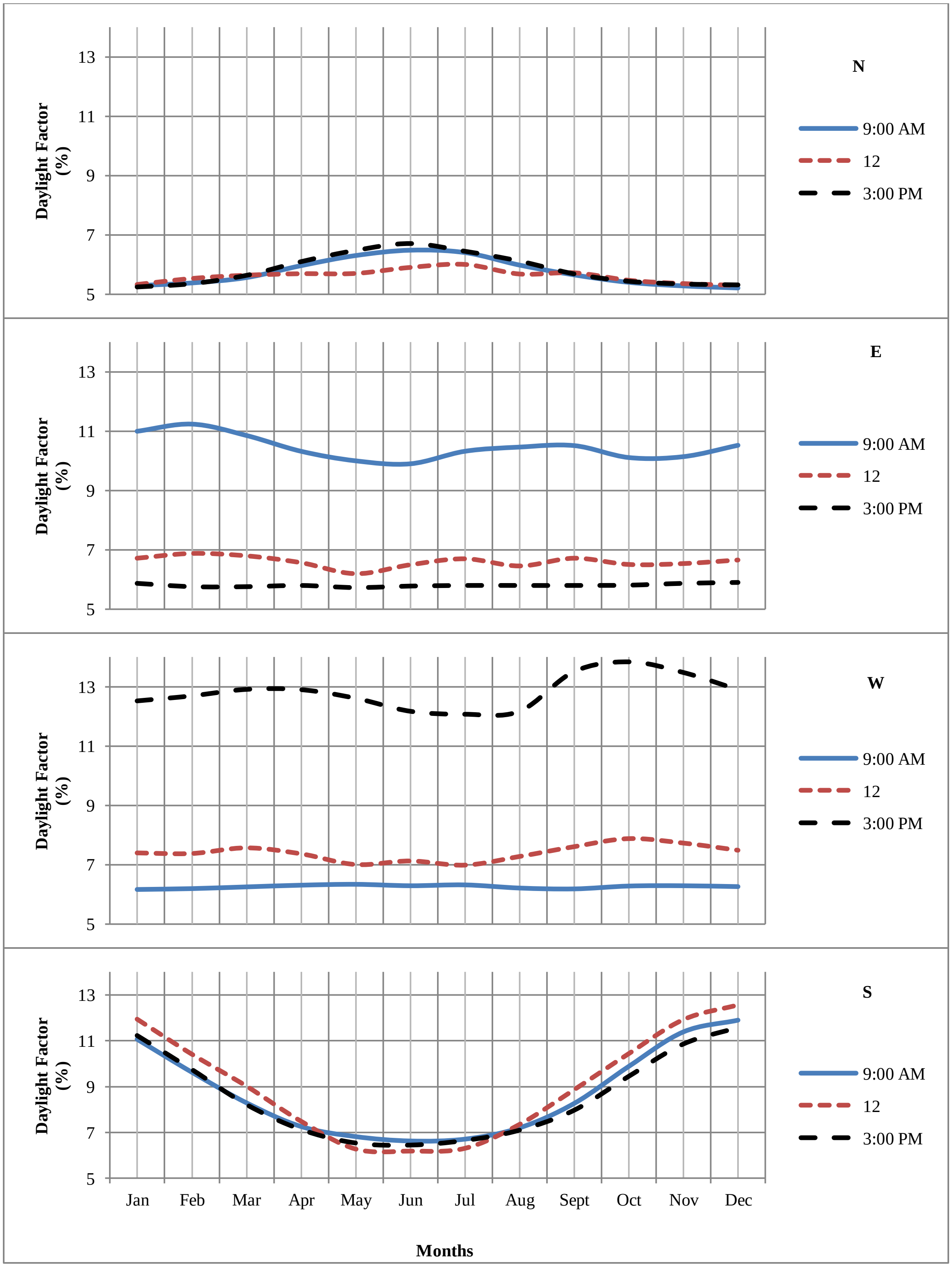


Figure 4.15: Average Daylight Factors on 21st of every month in different orientations (Solar control)

4.7 Impact of building orientation on Energy performance

Building orientation is simply what compass direction the building faces. Building orientation can be the most important step in providing a building with passive thermal and visual comfort. Orientation is measured by the azimuth angle of a surface relative to true north. Successful orientation rotates the building to minimize energy loads and maximize free energy from the sun and wind. Initially the base case model is considered to be facing North orientation. **Figure** 4.16 shows the Top view of the office building facing the North orientation.

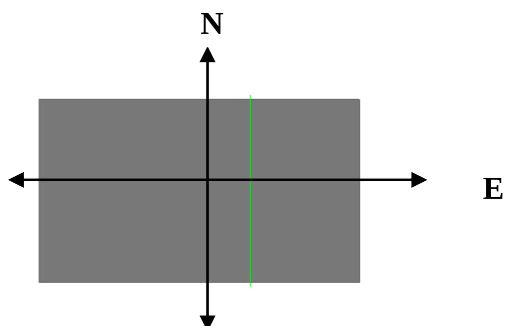


Figure 4.16: Top View of the Office Building

The lighting energy savings for building facing North with EC smart window (Solar control) was found to be 20%, where as the savings in the cooling energy consumption was calculated to be around 12%. The savings in the total building energy consumption was found around 20%.

Building is rotated by an angle of 45 degree relative to North as shown in **Figure** 4.17 and simulations were carried out. It was found that the lighting energy consumption is reduced by 20.5%, whereas the savings in cooling energy consumption has found to be around 11.5% and for the total building energy consumption the savings were accounted to be around 18.7%.

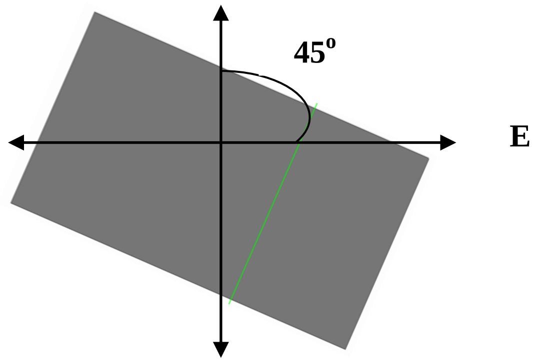


Figure 4.17: Office Building Rotated at 45 degrees

Simulations were carried out by rotating the building by 90 degrees as shown in **Figure** 4.18 and energy performance for both lighting energy and cooling energy was analyzed. For lighting energy consumption the savings were calculated to be around 22%. Similarly for cooling energy consumption the savings were found to be 10% and for overall building energy consumption the savings were 18%.

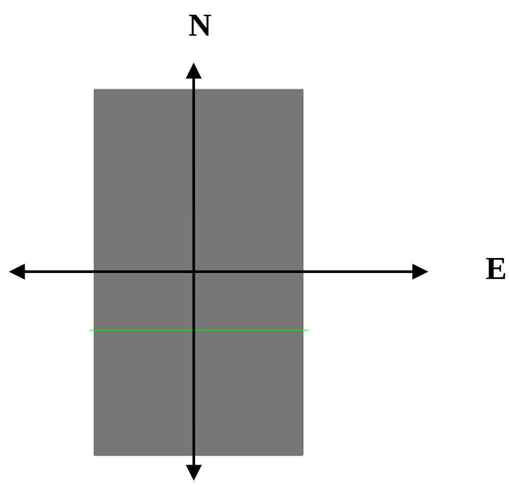


Figure 4.18: Office Building Rotated at 90 degrees

4.8 Building Energy Performance with Automated Venetian Blind

The solar control strategy adjusts blinds on the basis of climatic criteria. Depending on the season, solar radiation that causes heat is either blocked or let in. Thermo sensors are placed near the windows to measure the amount of radiation falling on the windows, theses sensors are linked to the controller of automated venetian blinds. WWR for the building is set at 50% based on the findings. Automated venetian blinds were used as interior shading unit for double glazed clear glass. From the previous section the solar set point value which is determined for different orientations are used for operating the venetian blinds. For the automated venetian blinds in the North orientation, the solar radiation set point value is set at $105W/m^2$. Similarly in East and West orientation the solar radiation set point value is adjusted to $100W/m^2$. For window in the South orientation the solar radiation value is set at $95W/m^2$. **Figure** 4.19 shows the variation in the maximum glare index over the months for building with EC smart window (Solar control) and building with automated venetian blinds in all the orientations. For both the cases the visual comfort criteria is being achieved as it is observed that the glare index is within the comfort level.

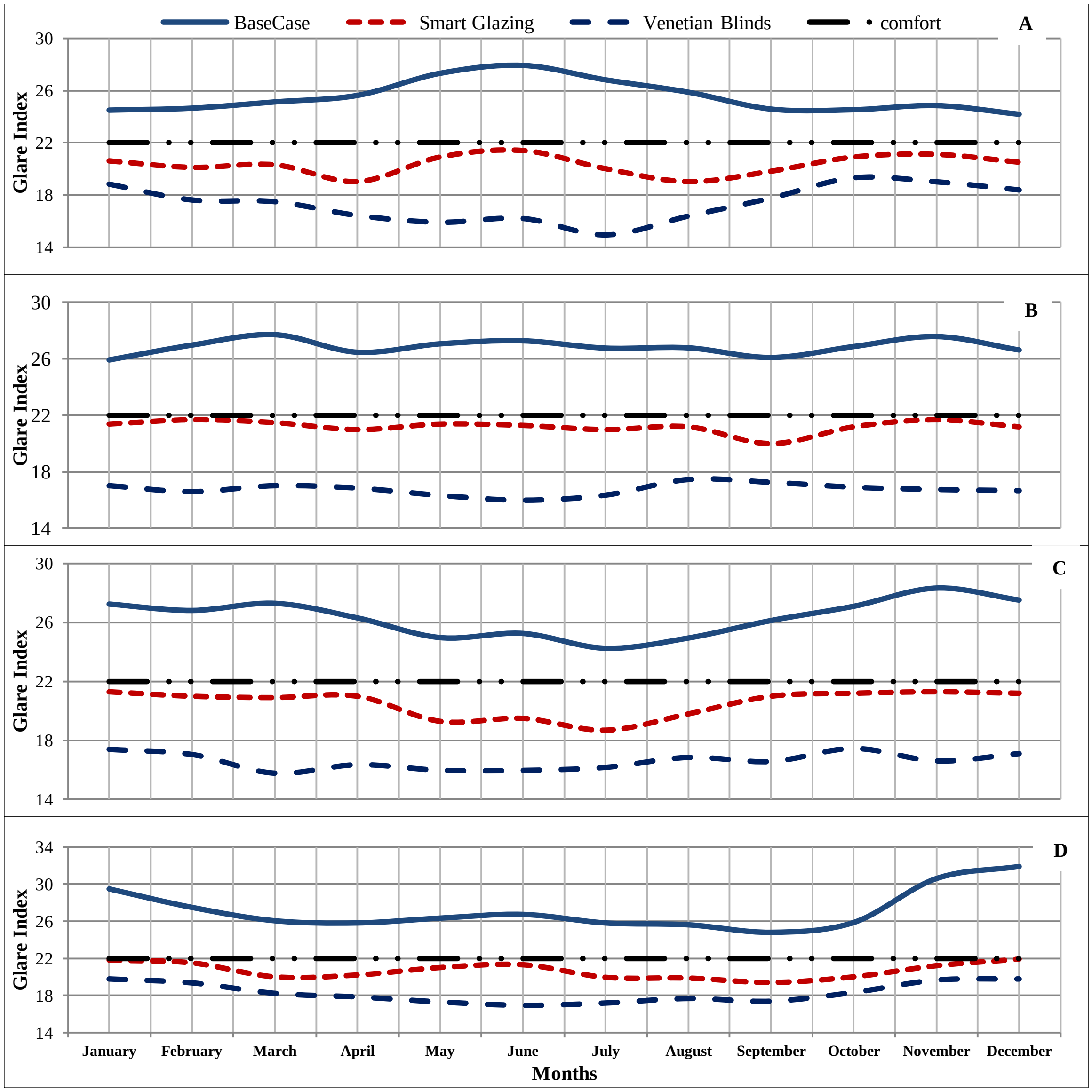


Figure 4.19: Monthly Variation in the Glare Index for Various Orientations with EC Smart window (Solar Control) and Venetian Blinds

Table 35 shows the comparison between EC smart window and automated venetian blind based on the energy performance. EC smart window with solar controller has the potential of saving 20% in building energy consumption, whereas smart automated venetian blind is capable of saving 16% of building energy consumption. The savings from both the smart windows technologies are substantial and can be used to make the design sustainable and save the money for the building owner.

Table 35: Comparison of the Energy Performance for Both Smart Windows in All Orientations

Energy Consumption	solar control strategy (%)	Percentage Reduction by using Venetian Blinds (%)
Lighting Energy	**20**	**18**
cooling energy	**12**	**17**
Total Energy	**20**	**16**

Figure 4.20 shows the average Daylight factor (%) which was used to reduced the artificial lighting energy consumption for various orientations.

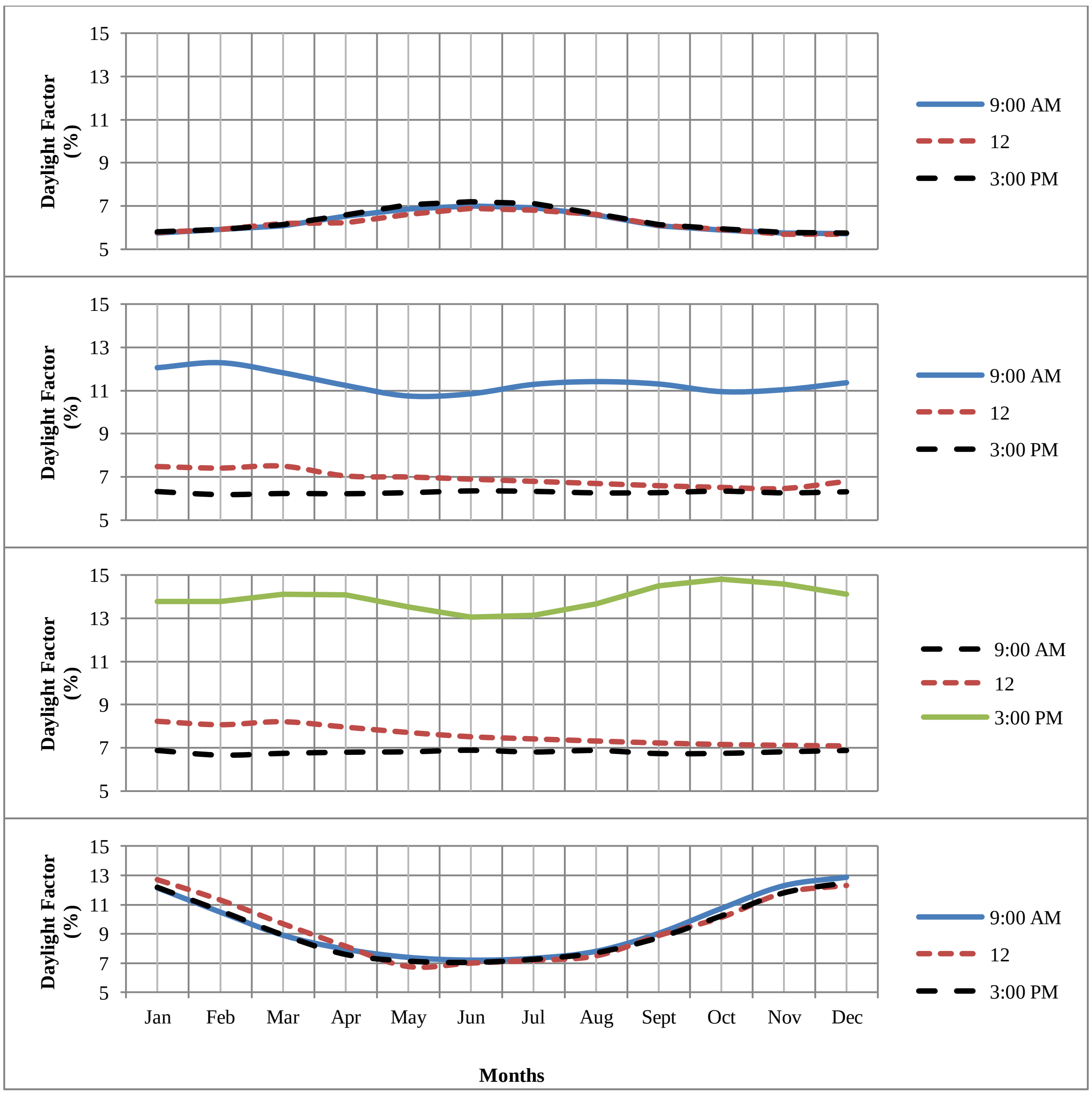


Figure 4.20: Average Daylight Factors on 21st of every month in different orientations (Automated Venetian Blinds) A. North B. East C. West D. South

4.9 Economic Analysis

Simple payback considers the initial costs, i.e. incremental initial investment cost and incremental first year utility savings. Simple payback period (SPP) can be used to measure cost effectiveness. It is determined by dividing the cost of implementing the Energy conservation opportunities with the annual energy savings. **Table** 36 shows the electricity tariff in the Kingdom of Saudi Arabia issued by Saudi Electric Company to different sectors of buildings. The energy for cooling the building and artificial lighting is provided in the form of electricity.

Table 36: Electricity Tariff in the Kingdom of Saudi Arabia [48]

Electricity in kWh	**Residential and Commercial tariff in Halala/kWh**	**Industrial tariff in Halala/kWh**
1-1000	5	12
1001-2000	5	12
2001-3000	10	12
3001-4000	10	12
4001-5000	12	12
5001-6000	12	12
6001-7000	15	12
7001-8000	20	12
8001-9000	24	12
9001-10000	28	12
Over 10000	30	12

The initial glass cost was considered per square meter of glass. The cost of double Low E and Electrochromic glass used for this study is shown in **Table** 37. The glass cost of Electrochromic glass shows the present market value.

Table 37: Cost of Conventional and Smart Glazings

Specification	**Double low E glass**	**EC glass**
Glass cost+ Installation($/m^2)	140	217
Controls and wirings	-	33
Total cost ($/m^2)	140	250

Simple payback period is calculated for all the energy conservation opportunities. The cost of EC smart glass with controller is considered to be 900 SAR/m^2. The cost of electricity is based on the data received from the Saudi Arabia electricity tariff issued by Saudi Electricity Company. From the data it is found that 0.3Halala/kWh tariff is being paid for office buildings. **Table** 38 shows the simple payback period calculations for the various energy conservation opportunities and it also shows whether the opportunity satisfy the visual comfort criteria. From the analysis it is found that by using EC smart window with daylight control, tremendous amount of energy can be saved but without satisfying the visual comfort criteria. Whereas using the glare controller for EC smart window can save 17% of building energy consumption with a payback period of 6.37 years. From the literature it is found that the service life of EC smart window is above 20 years based on the experiments conducted on the material. So the EC smart window promise to be the next major advance in energy-efficient window technology, helping to achieve the goal of improving the building energy performance by reducing both lighting energy consumption and cooling energy consumption and also maintaining the visual comfort with in the building. From the results it can be seen that due to the high cost of EC smart window, we can limit the installation to only one orientation with an improve payback period. The energy savings recorded for both lighting energy consumption and cooling energy consumption were the highest when EC smart window is installed in the South orientation. The absolute difference between the cost of EC smart window and Double low E glass window will be used for determining the cost of installation of smart window. In this case the difference value will come around 450 SAR/m^2. The estimated market cost of the automated venetian blind is considered to be around \$125/m^2.

Table 38: Energy Conservation Opportunities with Smart Windows

Energy conservation measure		Energy Reduction (%)			Visual Analysis and Simple payback period (Years)					
		Lighting	Cooling	Total	Glare Index	Average DF		Cost of Installation (SAR)	Energy Savings (SAR)	SPP (Years)
EC window with daylight control		25	8	23	x	N	5	1,004,400	194,392	5
						E	7			
						W	8			
						S	9			
EC window with glare control		12	14	17	✓	N	4	1,004,400	157,452	6.4
						E	6			
						W	7			
						S	8			
EC window with solar control		20	12	20	✓	N	4.5	1,004,400	167,870	6
						E	6.5			
						W	7.5			
						S	8.5			
EC with Glare control	N	2.5	4.5	2.7	✓	N	NA	311,850	40,228	7.8
	E	4	3.5	4.5	✓	E	NA	190,350	39,277	4.8
	W	6	2.5	6.5	✓	W	NA	311,850	69,470	4.5
	S	4	3.5	4.5	✓	S	NA	190,350	41,872	4.5
EC with Solar control	N	3	4	3	✓	N	NA	311,850	40,661	7.7
	E	5	3	5	✓	E	NA	190,350	43,257	4.4
	W	7	7	7	✓	W	NA	311,850	71,113	4.38
	S	5	3	5	✓	S	NA	190,350	43,170	4.4
Automated venetian blind		18	17	16	✓	N	4	1,046,250	136,229	7.6
						E	6			
						W	7			
						S	8			

CHAPTER 5

Summary, Conclusion and Recommendation

5.1 Summary and Conclusions

Energy consumption in the world has increased abruptly due to rapid industrialization. Office buildings are the major consumer of electric energy. Their lighting systems account for a large portion of their total energy consumption. To conserve electricity in buildings, many strategies can be applied. A smart glass window enables the user to control the amount of light, glare and heat passing through the windows by integrating the daylighting with artificial lighting through controller [42]. Energy savings from installing a smart glass not only lower the total energy consumption but also improve the visual comfort by controlling the glare index. Large windows in offices usually allow more daylight, along with excessive heat gain or loss. Smart glass window design offers a balance between lighting provision and energy consumed by lighting and cooling systems. The main objectives of this study were to investigate the impact of smart window design on energy consumption of an office building considering daylight and artificial lighting integration along with visual comfort and also identifying the potential benefits of smart window design for offices in hot climates. In order to achieve these objectives, the study comprises three phases: a literature review; Formulation of base case model based on standards and design practices of envelope design and lighting requirements in office buildings; a base case simulated with smart windows with various control triggers, and analysis of the simulation results for all the cases. From the literature review, it was found that daylight is desirable by most office building's occupants. This is because daylight provides high illuminance, good conditions for vision, and a view to the outside environment. But most of the architects ignore an important issue related to the quality of daylight which is visual comfort. Daylight can cause visual discomfort by inducing glare. With increased daylight provision, the hope for reducing in electrical lighting is often not achieved because the devices that occupants use to control visual comfort (e.g. blinds) invariably reduce the overall daylight provision. Visual comfort of daylight is measure in terms of glare index and Daylight Factor. From the review, it is found that most often, visual discomfort results from lights that are too bright or windows that let in too much sunshine.

A Theoretical office building model was developed by using the energy simulation software tool Design builder. The building model was considered to have a WWR of 50%. Investigation was carried out to determine the best glazing for the office windows. The energy performance of Clear, Tinted and Low- E glazings was done by means of simulations. During the investigation it was found that, Low E glazing with daylight integration can save substantial amount of energy by lowering the lighting and cooling energy consumption. So the base case model for the study was considered to be made of low E glazing with Daylight integration in all the orientations of the building. Model verification in this study was carried out by comparing the energy break down of the simulated theoretical model with the energy consumption of an existing building located in Hot-Humid climate. Results shows that the energy consumption for cooling represents the major part of about 52% of the total energy consumed. However, the lighting takes about 14%, and the energy consumed by the fans and pumps for air distribution is about 22% and the rest for the equipments and computers in the office.

The Energy analysis shows that, smart window can be used for the integration of daylight with artificial lighting and can save substantial amount of energy. EC smart window was used with various control techniques to minimize the energy consumption and enhance the visual comfort with in the building. Three control techniques were used and the energy and visual comfort performance is studied for the typical office building in hot-humid climate.

EC smart window was used with daylight control in all orientations. The WWR was set at 50%. There was a reduction of 23% in the total building energy consumption with daylight controller. Artificial lighting energy consumption was reduced by 25% where as cooling energy consumption was reduced by 8%. During the visual comfort analysis it was found that the maximum glare index value for all the zones in the building were beyond the acceptable comfort level. So from the view point of energy savings daylight controller can be used as a control trigger for EC smart window, but without maintaining the visual comfort in the space.

Glare control was used to alter the properties of EC smart glass in all orientations. There was a reduction of 17% in the total energy consumption with glare controller. Artificial lighting energy consumption was reduced by 12% where as cooling energy consumption was reduced by 14%. During the visual comfort analysis it was found that the maximum glare index value for all the zones in the building were within the comfort level. So EC smart window with glare controller can be used for maintaining the visual comfort and also for minimizing the building energy consumption.

Solar control was also used as trigger for altering the properties of EC smart window. From the analysis it was found that by maintaining a certain solar set point value, energy can be saved along with satisfying the visual comfort. The solar set point values were determined by carrying out the simulations, and it was found that for North orientation the set point values should be 105W/m^2, for East and West the values were determined to be 100 W/m^2, and for South the solar radiation value was determined to be around 95 W/m^2. An office building model was being developed by installing EC smart window with solar control in all orientations, and during the study it was found that by using solar control as trigger can save 20% of lighting energy savings, for cooling energy consumption the reduction was 12%, and the overall building energy consumption was reduced by 20%.

In order to improve the visual comfort for the occupants after the integration of daylight, Automated Venetian Blinds were modeled in the Design builder. Thermo sensors were linked to the controller of automated venetian blinds for its function. The solar set point for various orientations determined during the simulations is used to operate the venetian blinds. Which is for North orientation the solar set point value is set at 105W/m^2, for East and West the solar set point value is set at 100 W/m^2, and for south the value is set at 95W/m^2. During the analysis it is found that there is a reduction of 16% in the total building energy consumption. Also the glare index value for all the zones were within the comfort level.

In order to determine the feasibility of study, simple payback period analysis is carried out for various energy conservation opportunities. The average payback period found for EC smart window with different controllers is around 6 years.

5.2 Recommendations

Based on this study, the following recommendations are proposed to achieve energy-efficient integration of daylighting with artificial lighting and to utilize natural daylighting efficiently in office buildings in hot humid climates and also ways to maintain visual comfort with in the building.

1) Smart glazing with daylight control is recommended if the designer is going for high energy savings. But with daylight control visual comfort criteria cannot be achieved.
2) Solar controller is recommended over both glare control and daylight control for altering the property of smart glass, because the energy savings offered by solar controller is very high and also it maintains the visual comfort within the space.
3) Based on the result analysis, the optimal WWR for an office building with smart window was found to be in the range of 50-70%.
4) Due to the high cost of EC smart glazing, it's recommended to install them in the South orientation due to high energy savings it offers based on the result analysis.
5) The payback period calculated for smart glazing technology was below 10 years, so the study can encourage the building owners to invest in the smart window technology.
6) The best orientation for the building was found to be the one facing North. For this orientation the energy savings are high when compare to other orientations.

5.3 Recommendation for Further Research

This study has highlighted many findings that lead to future potential research. Different building geometries should be investigated to address the change from the rectangular shape. In addition, passive smart glazing's can also be investigated for different orientations. This study can be extended to address other building types, such as institutional and educational buildings, as lighting conditions are a major concern there.

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