Alternative Facades:

Assessment of Building Integrated Photovoltaic and Electrochromic Glazing—
Energy Benefits and Future Potentials in Office Building in UAE

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Dissertation submitted in partial fulfillment of
MSc in Sustainable Design of the Built Environment
December 2010

The British University in Dubai

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ABSTRACT

With the decline of conventional fossil fuels and the rapid growth of human population, the importance of curbing our energy consumption and reducing our dangerous emissions is now more obvious than ever. Since buildings are one of the top consumers of energy, it is not surprising that many designers, engineers, and architects are starting to address the significance of the building envelope in minimizing energy demands especially in office buildings. While many new alternative façades offer such energy saving benefits, the use of two particular technologies has not been studied enough in the gulf region. Building Integrated Photovoltaics (BIPV) and Electrochromic (EC) glazing are perhaps also more important because the potential of both of these technologies is very closely related to the availability of sunshine, which is very abundant in this region. Thus, the aim of this research was to explore the energy benefits and future potential of these two systems within the climatic conditions of the city of Abu Dhabi.

A computer energy modeling program was used to assess the energy performance, mainly the reductions in HVAC and lighting, of each system compared to a base case scenario for south, east, west, and north facing facades. Additionally, an economic analysis explored the feasibility of applications of these systems within Abu Dhabi's construction industry.

The result of this research showed that the BIPV is most advantageous on the south façade while the EC glazing performs best on the north facing windows. The BIPV model achieved a maximum energy consumption reduction of about 20.66%, 16.69%, 16.86%, and 1.35% for the south, east, west and north orientation, respectively against the base case model. On the other hand, the EC glazing model had much less benefit against the base case model with -2.86%, 1.35%, 0.89%, and 7.41% energy savings for the same orientations, respectively. The increase in glass shading coefficient increased the energy savings (15%) in the BIPV model against the base case. Similarly, the EC glazing showed significant improvement in energy savings (11.17%) over the base case which used higher shading coefficient. Moreover, the change in sensor location from 2m to 4m increased the energy savings for both cases, although the change was very marginal compared to the change of the glass properties.

The results of the economic analysis showed that due to high capital cost and low cost of electricity, neither system is currently feasible for investment. However, with future advances in each system and more efficient designs, the pay back periods would become tangible and therefore yield better performances.

In conclusion, using an automated light control system with dimming for both models, compared against the standard on-off lighting mechanism in the base case, the BIPV proves to have a higher energy saving potential than the EC glazing. If these two technologies were to be combined, the best configuration would be to install BIPV on the East, South, and West façade, while the EC glazing is used on the North façade.

الوجهات البديلة : التقييم الضوئي والكهربائي المُتكامِل للأبنية – فوائِد الطاقة والأمكانات المُستقبلية في تشييد المباني والمكاتب بِدولة الإمارات العربية المتحِدة.

نظراً لإنخِفاض الوقود التقليدي المُتمثِل في النفط والزيادة السريعة في التِعداد السُكاني ، فإن أهمية الحد من إستهلاك الطاقة وتقليل الإنبعاثات الخطيرة أصبح أكثر إلحاحاً من أي وقت مضى . وذلك نظراً لِما أصبحت عليه المباني من أهم مُستهلكي الطاقة ، فالعديد من المهندسين والمعماريين والمُصممين قد شرعوا في تشييد وتصميم نماذج معمارية صديقة للتقليل من إستهلاك الطاقة وخصوصاً في بناء المكاتب ذات الوجهات البديلة التى توفر الطاقة . في حين أن العديد من الوجهات البديلة الموفرة للطاقة وإستخدام مثل هذه التقنيات لم يُدرس بعد في منطقة الخليج ، فإن البِناء والتشييد بإستخدام التقنية الكهروضوئية المتكاملة أصبح ضروري وأكثر أهمية نظراً لإرتباطِها الوثيق بِمدى توافر أشعة الشمس – التى تكاد تكون ضعيفة إلى حد ما في المنطقة. لذلك فإن الهدف من هذا البحث هو إستكشاف فوائد الطاقة ومدى الإستفادة من هذه التقنية مُستقبلاً في ظل الظروف المناخية لمدينة أبو ظبــي.

تم إستخدام الحاسوب في وضع برنامج تقني نموذجي لتوفير الطاقة وتقييم آدائِها خصوصاً في الحد من الإنارة وإستخدام التكييف – مُقارنة هذا مع السيناريو المُتبع للواجهات الشمالية، الجنوبية، الشرقية والغربية . بالإضــأفة لوجود بحث إقتصــادي يوضح جدوى تطبيقات هذه النظم في برامج البناء والتشييد بمدينة أبو ظبــي .

وأظهرت نتيجة هذا البحث أن BIPV تُعد أكثر إفادة على الواجهة الجنوبية ، في حين أن EC Glazing تُعد الأفضل بالنسبة لنوافذ الواجهة الشمالية. كما أثبت البحث بأن نموذج BIPV قد حقق أقصى إنخفاض لإستهلاك الطاقة يتراوح بين 20.66% ، 16.69% و 1.35% لكل من الإتِجاهات الجنوبية ، الشرقية ، الغربية والشمالية في مقابل النموذج المُتبع. على الجانب الآخر فإن نموذج EC Glazing له فائدة أقل بكثير من قاعدة النموذج بتراوح يصل إلى 2.86% ، 0.89% و 7.41% من حيث توافير الطاقة لنفس الوجهات. إن زيادة الزجاج كعامل للتظليل أدى لزيادة توفير الطاقة بنسبة 15% في نموذج BIPV عنه في نموذج القاعدة. وبالمثل إن نموذج EC Glazing قد يُظهر تحسُن واضح في توفير الطاقة بنسبة 11.17% عنه في نموذج القاعدة الذي يستخدم مُعامل أعلى للظــل. عِلاوة على ذلك، إن تغيير موقع الإستشعار من 2 م إلى 4 م يُزيد من مدى توفير الطاقة في كُلاً من الحالتين. على الرغم من أن التغيير يعتبر ضعيفاً هامشياً مُقارنةً بِتغيير خصائِص الزجاج ؛ إلا أن التحليل الإقتصادى يوضح إرتفاع التكلفة المالية مع إنخفاض في تكلفة الكهرباء - ليس كل من هذاين النظامين يتسم بالمرونة وإمكانية الخوض في إستثماره في الوقت الراهن. ومع ذلك فإن تقدم كلاً منهما مُستقبلاً ومدى كفاءتهُما في التصميم وفترات التسديد أصبحت ملموسة وذات عائد أفضل.

وفي الخاتم، فإن إستخدام نظام آلى التحكم في الإضاءة لِكل من النموذجيـن – مُقارنة بالمعايير الآلية من فصل / تشغيل الإضــاءة بِنموذج القاعدة ، يُعتبر BIPV هو الأعلى في توفير الطاقة عن نظيره نموذج EC glazing . وفي حالة دمج كلاً من هذة التقنيات – فإن الأفضـل سيكون في تثبيت BIPV للوجهات الشرقية، الجنوبية ، والغربيــة . بينما نستخدم نموذج EC glazing للواجهة الشمالية .

ACKNOWLEDGMENT

Firstly, I would like to thank my supervisor, Dr. Bassam Abu Hijleh, for his continuous support, enthusiasm, and advice. I gained excellent knowledge into the topic of this study and building performance design through his supervision.

Most importantly, I would like to thank my wife Precious for her persistent support and encouragement for the duration of this research.

I would like to thank my employer, KEO International Consultants, particularly Bill Jolly, Andrew Halycz, Hani Ibrahim, Sujata Gupta, and Waleed Waly for their contributions.

I also wish to extend my gratitude to Mark Gifford from IES for his help with various issues during the simulation stage of the research and the early session tutorials that have helped me become more familiar with the software.

To my friends, thank you for making this journey so much more enjoyable, and forcing me to take a break when I didn’t realize how much I needed it.

Last but not least, to my parents and siblings, merci. Your love and kind words especially on the days when I had little energy kept me pushing hard until the end.

Thank you all.

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CHAPTER 1: INTRODUCTION

1.1 GLOBAL ENERGY PARADIGM

The phenomenon of global warming is a controversial topic and deserves much attention. Some claim that certain scientists have collected information based on vested interest in playing up the potential effects of this occurrence. Despite these exaggerations, the evidence of climate change can be seen by observing such examples as the average rise in earth temperature, melting of ice-caps, increase in sea-levels, and unprecedented upsurge in weather events like wildfires, heat waves, and strong tropical storms. Although the political and public debates over the main cause of this phenomenon remain unresolved, it is undoubtedly fair to claim such quick changes could have been fuelled by human activities. The use of fossil fuels has been increasing since the start of industrialization. Figure 1.1 shows that in the past few decades alone, the world's electric power consumption and CO_2 emissions have been increasing at an alarming rate.

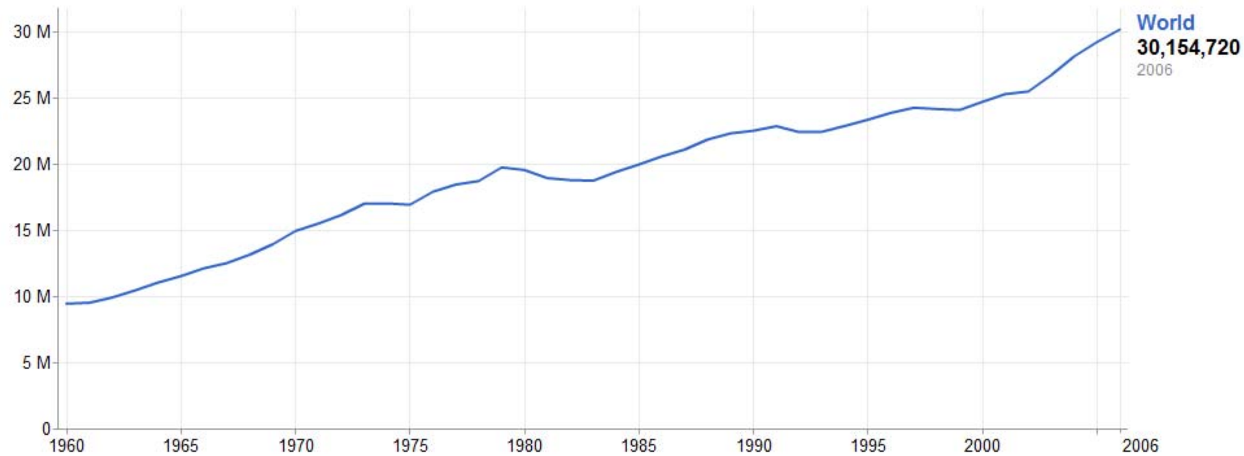


Figure 1.1 World's CO2 emissions in metric tons (World Bank, 2010)

However, with a known limited supply of fossil fuels this trend is no longer sustainable. In particular, the growing concern over the hazardous effects of excessive green house gases has turned the use of clean energy and methods of reducing energy demands into a global movement integral to our future. Such mitigation is necessary response to reduce mankind contribution to changes in the natural balance of ecosystems. There has been a tremendous increase in use of renewable energies in the past decade with solar power presenting the highest potential. Figure 1.2 shows the forecast changes in the worldwide energy consumption. One day's energy of the sun is capable of meeting world's energy demands for 27 years (Hope, 2009). Hence, it's no wonder that many areas of research and development are focusing on this aspect. One of the areas that offer high potential for energy efficiency is the building sector. Buildings are known for their high levels of resource consumption during construction and operation. According to US statistics published in Building Energy Data Book, in the year 2009 buildings were responsible for 40% of all energy use and 74% of electrical consumption (US Department of Energy, 2009).

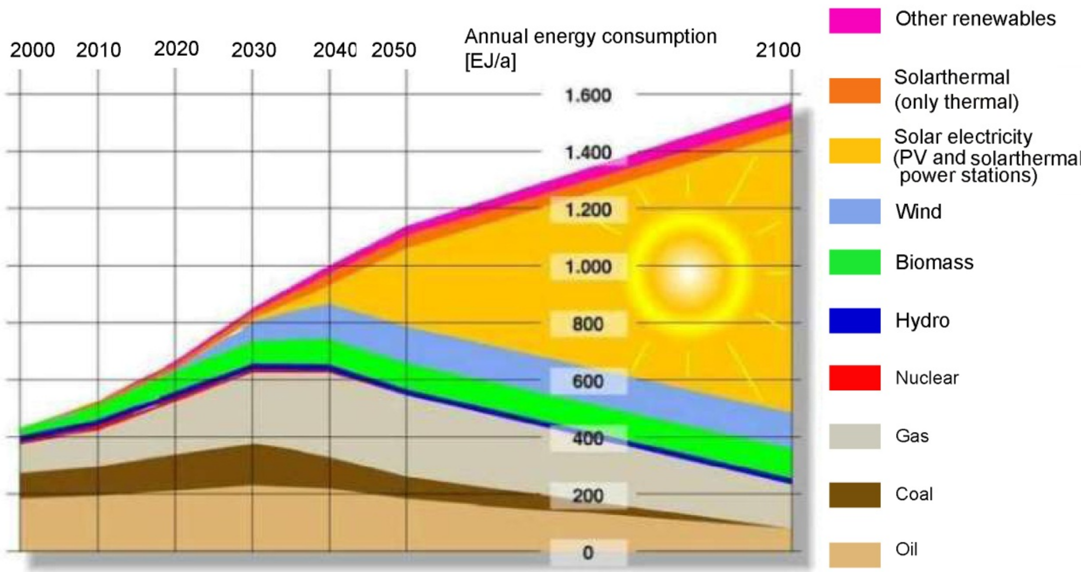


Figure 1.2 Changes in worldwide energy (global primary consumption) matrix through 2100 (Neuner, 2008)

Office buildings which rank the highest amongst all energy consumers require the most attention. In fact, the increase use of air-conditioning in office buildings accounts for a substantial part of the electricity consumption worldwide (Barnham et al., 2006). The statistics published by US Department of Energy in 2008, as seen in Fig. 1.3, showed that the US leads the word in total primary energy consumption. On the other hand, the Middle East, accounts for only 5% of this amount. However, when it comes to energy use per capita, the Middle Eastern countries, particularly the ones in the Gulf are amongst the world's top ranking energy consumers. This is not surprising when with a figure of 2%, the Middle East has the second highest annual population growth rate of any other region in the world after Africa (US Department of Energy, 2008). With such rapid expansion, it is imperative that the progress of construction and design approach in this region be monitored closely in order to minimize the massive impact of buildings on the built environment and achieve sustainability.

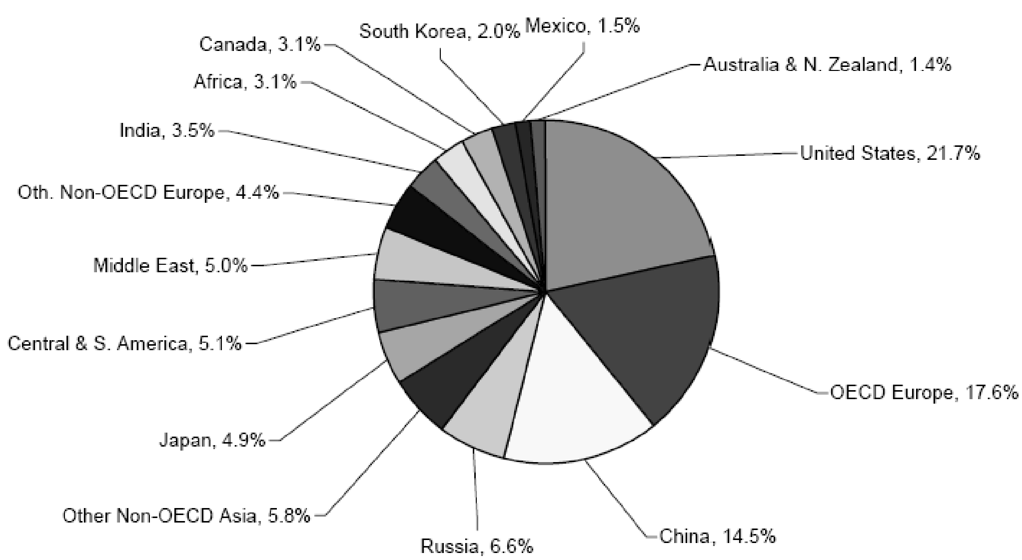


Figure 1.3 World Primary Energy Consumption by Country/Region (US Department of Energy, 2008)

1.2 BUILDING ENVELOPE AND FORM

The main role of a building is to protect its occupants from the harsh environmental elements that it is located in. The building envelope, or the façade, is the main moderator between controlling the outdoor indoor conditions (Herzog et al., 2004). Glass is one of the most popular choices for the building envelope particularly since the industrial revolution. It has always been associated with such values as modernity, openness, brightness and shine, and has become a symbol of open society and its "transparency synonymous with democracy" (Deplazes, 2009). More importantly, it offers the maximum potential of daylight deemed essential for building users productivity. This enabled Mies van der Rohe's fully glazed towers such as the Saegram Building in Fig. 1.2 to be constructed in the early 1950s to be regarded as pinnacle of modern high-rise architecture.

Figure 1.4 Mies van der Rohe, Seagram Building, New York (Wikipedia, 2010)

A comparison of the building forms around some major cities worldwide shows a surprising scenario: regardless of the climatic conditions, glass towers dominate the skyline and have become a modern architectural design trend. Although there are certain advantages to such high-rise buildings such as easy constructability and maximization of land area, they are not appropriate for all climates. The exposure of their large surfaces to climatic changes, mainly the solar impact, makes them a "vulnerable building type" and this might be regarded as a failure of modern buildings (Roaf et al., 2009).

When it comes to controlling thermal exchange, glass is unfortunately a poor insulator compared to other materials. Consequently, there is a need for other mechanical systems such as air-conditioning in order make glass a viable choice. On the other hand, the versatility of glass combined with various technologies is a promising factor for many potential markets. In the Middle East building management systems are often deemed mandatory for controlling the space comfort requirements. At the same time, this high level of automation denies individual control and limits "user interaction with the façade" (Bahaj et al., 2008). Inevitably, this encourages the use of glazing technologies that offer daylight regulation and save energy through control of solar gain thus offsetting the insulation weakness. Technological advances like variable physical configurations in addition to optical and thermal properties can allow such responsive facades to adjust to changing weather conditions, occupant preference and building system requirements (Gardiner et al., 2009). Such design breakthroughs give buildings a better opportunity to cope with conservation requirements and remain sustainable.

1.3 UAE'S SCENARIO

During the rapid construction boom, before the global economical crisis, there were approximately one third of the world's construction cranes operating in the UAE. There has been a tremendous shift in building construction over the past 40 years. In general the sunlight architecture that once tried to avoid solar gain by using small windows and appropriate shading devices has become obsolete. Other traditional elements such as the Badgir which functioned to naturally ventilate the buildings are now merely a decorative feature used for cultural association.

The vernacular architecture of this region, based on high thermal mass and natural ventilation, has been outdated with modern skyscrapers. In 2010, Dubai claimed the title for the world's tallest building with the opening of the Burj Khalifa, a massive 828 meter tall structure. The estimated 400 office towers in the dense Business Bay District follow the concept of daylight architecture and try to maximize penetration of natural light. However, these large glazed areas lead to inefficient energy consumption and high operating costs. These buildings function mainly due to heavy reliance on mechanical support particularly use of air-conditioning that runs on low cost electricity from fossil fuel (Askar et al., 2001).

One of the global issues which is challenging in the UAE is waste management. Based on work of Latham (2010) according to the Abu Dhabi Environmental Agency, UAE has one of the world's highest per capita waste productions. In a recent report commissioned by Center of Waste Management, a resident in Abu Dhabi produced 4.2kg of garbage each day, while the average of waste generated by residents of the Organization for Economic Co-operation and Development (OECD) countries is only 1.54kg (Latham, 2010). Aside from domestic waste, Fig. 1.4 shows that UAE has one the highest levels of energy consumption per capita worldwide. At the same time UAE has vast oil reserves, making the goal towards alternative energy less desirable. The high demand for electricity and water is fuelled by urban sprawl, population growth, and high per capita income (Table 1.1), poses a high pressure on natural resources.

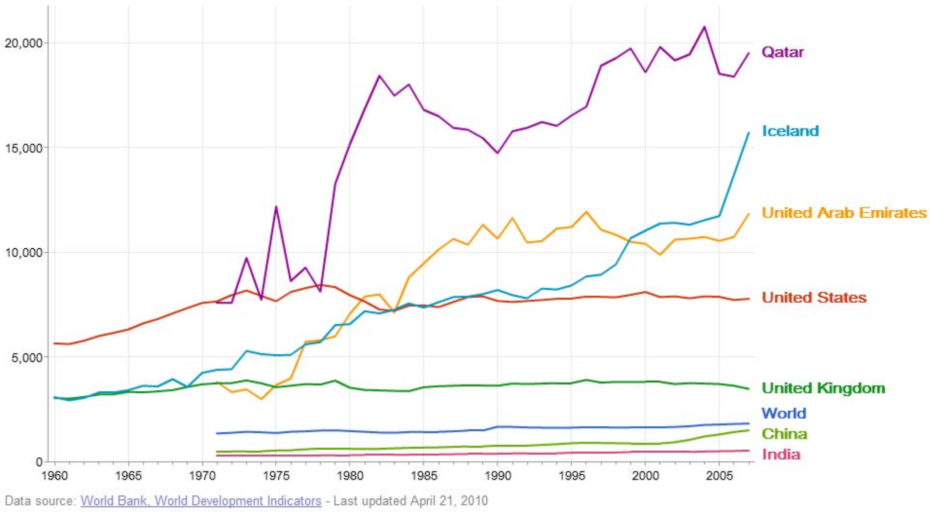


Figure 1.5 Energy use per capita: primary energy use (before transformation to other end-use fuels) in kilograms of oil equivalent, per capita (World Bank, 2010)

Table 1.1 Indicators of UAE utility sector (left) and UAE power supply and demand balance (Badih, 2010)

	2004	2005	2006	2007	2008
GDP (million Dh)	6,961	8,568	10,019	11,566	13,579
Gross Fixed Capital Formation (million Dh)	7,120	8,070	10,342	12,249	16,337
Number of workers	28,848	34,807	35,366	36,257	38,814
GDP per worker (Dh)	241,299	246,157	283,294	319,000	349,847

Balance	2006	2007	2008		
Electricity demand (TWh)	57.9	62.5	69.2		
Electricity supply (TWh)	66.2	71.9	77.2		
Forecasts	**2009**	**2010**	**2011**	**2012**	**2013**
Electricity supply (TWh)	76.5	80	85	92	98.9
Electricity demand (TWh)	67.8	70.8	74.6	79.2	82.7

However, UAE is also one of the most ambitious amongst the several oil-rich Gulf countries that have made efforts to find alternative energy sources to meet its growing need for electricity. After all, in order to maintain a life of luxury with indoor ski slopes, chilled swimming pools, and huge air-conditioned shopping malls like the Mall of Emirates and Dubai Mall, the dependency on oil primarily might not be such wise option. Looking at the country's past, the use of passive techniques such as the Badgir, and courtyard are prevalent in its architecture. Such measures were necessary for keeping comfortable environments through inducing stack effect particularly in the hotter months. Unfortunately with the accessibility to oil and introduction of air conditioning, these elements slowly faded. Today, they are the subject of vernacular architectural study of the region and regarded as the essence of sustainability.

Bahadori et al. (2008) explore the new designs of wind towers and recommends their manufacturing for incorporation into new buildings. They found that the new approach can replace the evaporative coolers usually found in hot arid regions, and have a considerable saving in electrical energy consumption. Other technological breakthroughs have aided the development of new integrated passive/active solutions also known as hybrid. Ma et al. (2006) present the performance analysis of a hybrid air-conditioning system of a green building in China. In their findings, the performance of this system is 44.5% higher than conventional vapor compression system. The work of Shaahid and El-Hadidy (2007) assesses the techno-economic viability of using hybrid PV–diesel–battery power systems to sustain the energy needs of a typical commercial building in KSA. The investigation shows a 27% fuel reduction in hybrid system compared to diesel-only situation. Furthermore, utilizing this system saves 44 ton/year of carbon emissions into the environment. In the UAE, Helal and Malek (2006) present a model for the design of a hybrid solar diesel powered mechanical vapor compression (MVC) unit in Al Ain. Because solar radiation is high all year round, it is deemed as an environmentally safe power generation source. At the same time, due to water scarcity, the use of MVC is feasible option for desalination in remote places where water and electricity are difficult to transport. In a stand-alone PV powered system, the excessive battery requirement for power storage at night become difficult. The study finds that a hybrid system is more practical with lesser environmental impacts.

Fortunately, in the UAE, there has already been a tremendous positive shift to sustainable design measures. The word sustainability and green are possibly the most known catch phrases of this decade. But what does it really mean to the people living in the UAE? Here are responses of some working professionals when asked to define the term sustainability:

> "…a way of life that ensures an organization or individual participates equally in the natural cycle of its environment--giving back the same energy and resources it takes from the environment in any useful form." –PD (Journalist)

> "…perfection of technology to minimize waste in resources" –MK (Marketing Manager)

> "…sustainability and its efforts are a rather late reaction by the human race for a planet already in ruins. A more literal understanding of the same is...Sustainability is long-term maintenance plan for the earth." –ZA (Creative Director)

> "…the ability for something to last/survive over time by changing/evolving to its surroundings." –NK (Software Business Development Manager)

> "…being sustainable, is being able to live in your bubble without taking anything from outside... having what you need to survive, and not thinking of what you want." –DM (Graphic Designer)

> "…it is about survival, and about being able to blend in with your surroundings. It is about constantly innovating yourself to be 'demanded' in every era. From a corporate perspective, I see it as being socially responsible, not because

> corporations are inherently good - but because it is what we demand of them.”
> –SB (Account Manager)
>
> “…Sustainability is the human endeavor that begins from the smallest scales to the largest scopes. It is the result of the marriage of our ever-growing societal needs with effective management of our planet's resources.” –MN (Technology Consultant)

Although all these answers are different, at the root of each is a common binding theme: these people value conservation, nature and resources. Most importantly, they are aware of the issues and this shows that there is an audience that is willing to listen to the voice that needs to keep educating the younger generation.

Note: These interviews were conducted informally and therefore not included in the list of references.

1.4 RATIONALE

The purpose of the study is to review the implications of using building integrated photovoltaic (BIPV) and electrochromic (EC) glazing as an alternative building facade and how such an implementation would affect building energy consumption. The majority of previous research has examined the extent of each technology’s benefits individually. This study will compare the two systems and assess which is more advantageous for overall building energy reductions. Further, as most of the research in this field has been carried in regions with different climate that the UAE, mainly Europe and North America, this created an incentive for the author to test whether these technologies could be beneficial in this climate.

According to Chow (2010) the main two principles in sustainable design of window systems for cooling-demand locations are:

- *To filter out solar transmission specially the infrared spectrum, but excluding the visible light range which is to be controlled well and fully utilized; and,*
- *To convert incoming solar irradiance into a source of renewable energy, and thereby reducing the room heat gain.*

The former could be studied through use of EC glazing while the latter via incorporating BIPV as part of the façade. The outcome of such a study could better direct the UAE’s activity towards a more sustainable approach in the built environment.

1.5 OUTLINE OF DISSERTATION

The dissertation is divided into six chapters as follows:

The first chapter shall provide an insight of the reason for increase in demand for sustainable energy and development of alternative facades as a mean to reduce building energy consumption and curtail the rapid growth of greenhouse gas emissions.

The literature review in chapter two shall consider the various types of alternative facades available. A brief description of each will be presented and the two selected technologies will be examined further. The literature review will continue by providing a complete overview of how BIPV and EC glazing work and ways which they can be beneficial for reducing building energy demand. It looks at previous similar studies and their finding which will form a basic understanding of the current extent of research. Further in this chapter, a background on UAE climate will provide an understanding of the environmental conditions for this research.

Chapter three describes the methodology used in this study. It elaborates the various parameters used in the modeling process. It analyzes the various research methodologies which will form the basis for the selection of methodology in this study.

In Chapter four, the details of the simulation models will be described. The configuration of the base case model and the two other models will be discussed in detail.

In Chapter five the results of the simulation will be shown. A test matrix will outline how they will be used to interpret the results. A discussion of the advantages and disadvantages of introducing each system shall be collated in Chapter five. There will be a particular focus on the cost and how the introduction could affect building energy consumption.

The economic evaluation in Chapter six shall provide a balanced view of the potential introduction of sustainable construction within the UAE.

In the final section, Chapter seven, a conclusion shall be drawn making a recommendations based on the outcome of the evaluation. It is envisaged an answer to the following question shall be presented: Would the introduction of alternative facades prove beneficial for overall building energy consumption? Further work shall be identified.

CHAPTER 2: LITERATURE REVIEW

2.1 BACKGROUND

This chapter looks at current level of knowledge in the field of alternative facades. A brief examination of daylight and performance will provide the necessary benchmark for the importance of natural light management and building energy savings. This is further elaborated with different types of alternative façade technologies, with an emphasis on two particular types which will be the focus of this research.

2.2 DAYLIGHT AND PERFORMANCE

Most building's occupants favor daylight as their primary light source however there are some challenges. One of the difficulties is that this preference is not unconditional particularly when it comes to controlling their visual and thermal comfort as well as their privacy. As soon as one of the above fails, daylight will be controlled through use of shading devices like curtains and blinds. The other difficulty is proving the financial benefits to the building owners. Although most developers understand the higher premium value that normally comes with a space with more windows, the effects of "extensive daylighting on organizational efficiency" is not as well considered (Boyce, 2005).

Amongst numerous positive effects of daylight is the benefit on occupant's performance and health. One of the most compelling studies is Heschong Mahone Group investigation showing the connection between daylight and student performance. An improvement in students test scores over the period of one year was proven to be influenced by better daylighting in classrooms. The group's findings support the notion that such performance benefits associated with daylighting can be "translated to other building types and human activities" (1999).

Other benefits include savings from operational costs due to lower electrical consumption for artificial lighting. In addition, the lower cooling load through the lower wastage of heat from these lights adds to these savings. In the end, the optimization of daylight lowers emissions through the reduction of electrical use for lighting and heating/cooling and minimizes the use of fossil fuels. These valid claims highlight the importance of new façade designs with features capable of delivering such predictions.

2.3 ALTERNATIVE FACADES

In the building sector, an increase in demand for sustainable energy and strategies for management of natural light indoors and its relationship with artificial lighting requirements has led to exploration of alternative façade designs. Although it is commonly accepted that a building's environmental impacts and energy use must be reduced, the method by which this is achieved is still debatable. In particular, the use of passive and active systems is a controversial topic and agreeing on which is most beneficial approach is still an open discussion. Mahdavi's (2010) case study presents a comparison between low-energy and passive apartments in Vienna. The primary difference aside from the fact that passive buildings have a higher insulation level is in the ventilation system. While the strategy in passive buildings is controlled mechanical ventilation, the low-energy buildings depend on natural ventilating user-operated windows. The study measured indoor environmental conditions such as indoor air temperature, relative humidity, and CO_2 concentration in the two cases over a period of five months. The results showed that the passive buildings "consume approximately 65% less heating energy and 35% less electrical energy." He concluded that resource expenditure (shown by embodied energy) and environmental impacts (shown through CO_2 emissions) are offset in short periods.

One of the most active areas in building design is advancements of technologies related to windows and specifically the glass. The driving forces behind such breakthroughs are issues related to interior day-lighting enhancement, maximizing occupants view and comfort, and reducing operational costs. Consequently these also have an environmental impact which makes the focus on glass worthwhile. In addition, other factors such as cultural mentality, health regulation, and occupant expectations have added to the momentum towards "healthy buildings" through use of unconventional façade designs (Sullivan and Horwitz-Bennet, 2008).

Alternative facades can optimize control over sun and shade to help save energy, improve the economic efficiency of the building and create a more pleasant, healthier place to live and work. Several breakthrough building façade technologies present opportunities that can help achieve these objectives. Following is a short list of some available technologies and an overview of their aim to accomplish lower building energy consumptions.

2.3.1 Double-façade systems

Normally the selection of a shading system would depend on factors such as building type, climate, cost, orientation, and function. For example in hotter regions, they would be placed outside to block solar gain. Double skin facades are essentially sophisticated shading devices with intermediate shading between the glass panes and can be used in various climatic areas (Tzempelikos et al., 2010). This system improves thermal performance and helps to achieve transparency. This is the opposite of other similar systems that aim to attain good thermal requirements but at the expense of blocking the visual connection. These facades typically incorporate a built-in shading device such as venetian blind that absorbs solar heat gain and re-radiates it to the surrounding environment. They can contribute to winter heat gain or induce ventilation air flow in summer (Hanby et al., 2008). Shown in Fig. 2.1, it utilizes both stack and cross ventilation to naturally vent the hot air through high level vents.

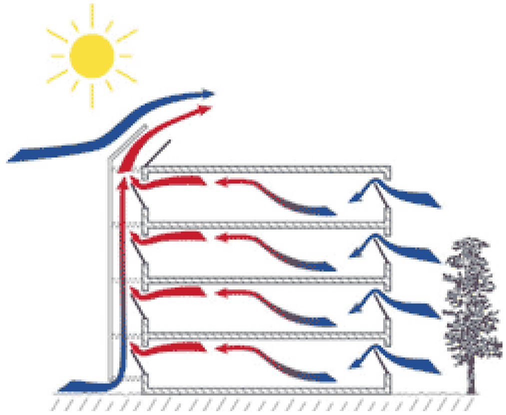


Figure 2.1 Schematic of double-façade system (Dyer Environmental Controls Ltd., 2010)

A standard recommendation is to provide single glazing on the exterior buffering skin, and double glazing on the interior layer. Although this approach might work for hot or temperate climates, in colder regions, double glazing is used on outside and single glazing on the inside skin (Boake et al., 2010). These systems can also prove beneficial for buildings in areas of high traffic noise for example adjacent to roads. An example of a double-skin system in the UAE can be found in the striking 0-14 commercial tower seen in Fig. 2.2. This 22-story commercial tower employs this technique by featuring a unique 16-inch-thick concrete facade perforated by 1,000 circular openings. The facade is against a window wall enclosure. A one-meter space between the facade and the glass surface creates a chimney effect to allow hot air to rise for passive cooling. The perforations provide light, air, and views while the facade acts as a sunscreen.

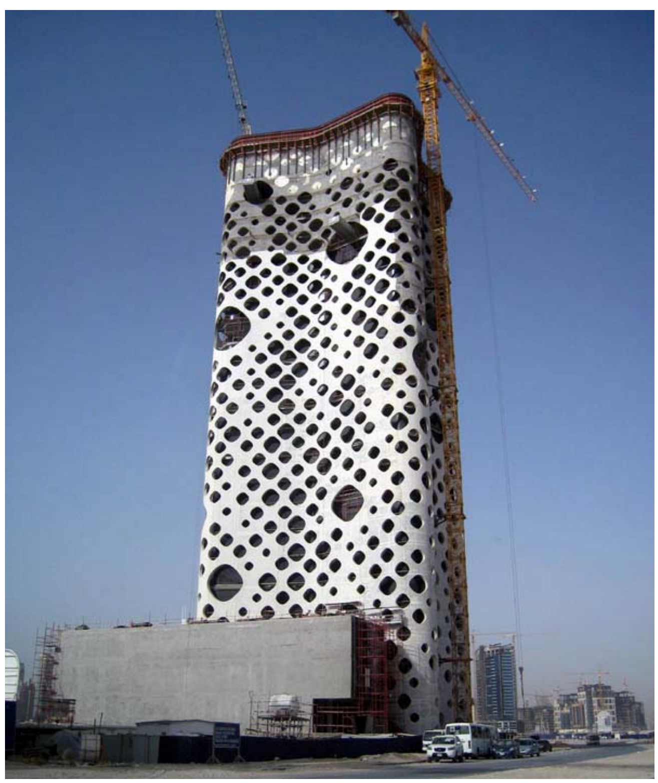


Figure 2.2 The 0-14 Tower under construction in Business Bay district (*Luecke, 2010*)

The advantages and disadvantage of this type of construction can be summarized as follows (Poirazis, 2004):

Advantages:

- Lower construction compared to other smart window systems like electrochromic
- Acoustic insulation achieved through minimum of 100mm gap beneficial in high traffic areas
- Thermal insulation in winter is improved from increased external heat transfer resistance; in summer due to stack effect, hot air to rises and takes additional heat out
- Night time ventilation that is protected against weather and more secure from intruders
- Energy savings and reduced environmental impacts achieved through minimizing solar loading at the building perimeter and extending period which natural ventilation is possible
- Improved protection of shading devices in the intermediate cavity from wind and rain
- Reduction of wind pressure effects facilitated by buffer effect of the intermediate space
- Transparency in architectural design and aesthetic desire of a fully glazed façade
- Natural ventilation leading to energy savings and increase in occupant comfort
- Thermal comfort during winter from higher temperature maintained in interior part of the facade

Disadvantages:

- Higher construction cost compared to conventional façade
- Fire protection is not clear due to lack of information on this type of façade during a fire
- Reduction of rentable office space caused by façade protection ranging from 20cm to several meters
- Additional maintenance and operational cost compared to cleaning and servicing of single skin façade
- Overheating problems caused by inadequate cavity width and size of ventilation openings
- Increased air flow speed specially in high rise buildings
- Increased structural weight which requires higher construction cost
- Daylight quality reduction caused by additional external skin

Currently, the most common types of shading devices used in office buildings are Venetian blinds and roller shades. These will be used in the benchmark model of this study in order to compare the benefits of other systems.

2.3.2 Low-E Glazing

Low-Emittance (Low-E) films are applied to one of the glass surfaces that face the inner air gap. They retard radiant transfer between double-glazed windows. In addition to helping reduce HVAC loads, they minimize UV transmission which helps to protect building furniture and colors. Three types are used depending on the climate. High transmission Low-E is used in cold areas where low U-factor and high SHGC trap infrared inside the building envelope. The overheating in summer can be avoided through well designed external shadings. Selective transmission Low-E used in moderate climates combines low U-factor and low SHGC. While the low-e coating applied to the closest exterior glass surface blocks infrared from entering, the reflectance of infrared cause heat buildup that is then carried by convection. In places that get plenty of clear day skies and experience high intensity illumination most of the year Low transmission Low-E is used. This type uses low U-factor and low SHGC as well as low VT and is used in the UAE where the sun is mainly undesirable.

2.3.3 Evacuated Glazing

The permanent vacuum between the glass panels created during manufacturing increases energy performance. This low pressure vacuum ensures no conductive or convective heat transfer (Fang et al., 2007). This type of glazing provides architectural possibilities in area of building conservation, and can even replace single glazing in thin frames but with a much better performance. Unfortunately, however, the thermal bridge caused by the spacers between the panes of glass, seen in Fig. 2.3 can reduce its overall effectiveness.

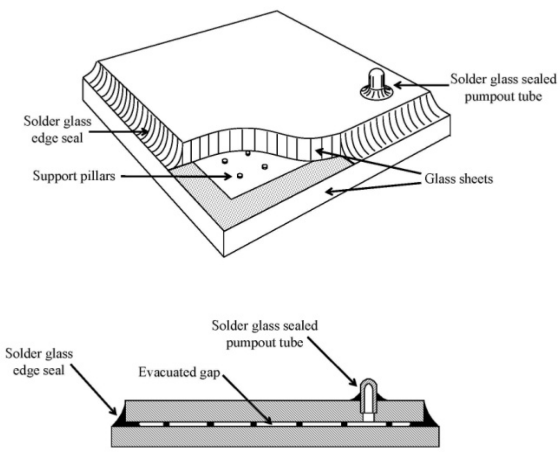


Figure 2.3 Schematic of evacuated glazing (Fang et al., 2007)

2.3.4 Windows with built-in blinds

Some windows are equipped with built-in blinds or louvers. These specialty windows offer a more efficient insulation compared to the standard internal shading devices such as curtains. The shading feature is sandwiched between two panes of glass, as seen in Fig. 2.4, and uses a slide feature to lower them either manually or with remote control. One of the main benefits is that internal heating is reduced which avoids expensive air conditioning costs. In addition to lower energy gains, another advantage is that the blinds do not collect dirt. This also keeps the blinds looking newer. However, maintenance is more difficult and small defects may require entire system replacement. Dalal et. Al (2009) conducted a numerical study for a double pane window with internal pleated shades based on models found in North America. The results showed that convective heat transfer can be reduced through shorter pleat length, while the angle of the pleat is less critical for the performance. One manufacturer (Unicel Architectural, 2010) uses this specialty glazing as partial louvers that act as a light shelf, reflecting natural light further into the building. This approach provides energy savings, due to reduced need for artificial lighting resulting in an important decrease in annual operational energy cost.

Figure 2.4 Insulated glass with internal blinds (A.S.P Glazing, 2008)

2.3.5 Self-cleaning glass

The surface of the glass panel can be engineered to respond according to sunlight or rainwater. Pilkington Activ brand by Pilkington is claimed to have the first self-cleaning glass product with a thin titanium dioxide (TiO_2) layer causing a photo-catalytic reaction when glass is exposed to UV rays. After installation, the special coating needs 5 to 7 days to activate fully. The reaction consequently causes any dirt or organic materials on glass to decompose thus reducing the adherence of inorganic dirt (Sullivan and Horwitz-Bennet, 2008). Figure 2.5 illustrates that any dirt particles on the glass are picked up by water and washed off the glass leaving a remarkable difference.

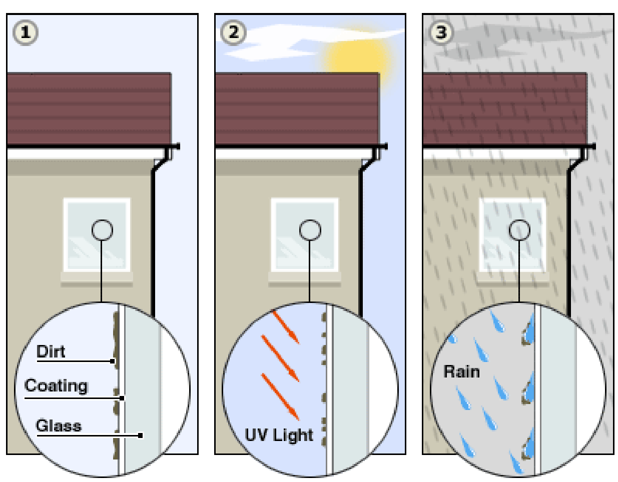


Figure 2.5 Photo-catalytic process in self-cleaning glass (Twist, 2009)

2.3.6 Decorative Glass

The importance of graphics and rise in adequate signage and brand identity has led a growing trend in use of decorative glass. This is also the result of good lighting designs, and creates a vast potential for glass to become a canvas to project colors and images. Different methods are used for lighting up buildings. In Seoul, South Korea, the Galleria West shows off electronic façade technology developed by UN Studio and Arup Lighting. The shopping mall's whole façade is covered with 5000 glass discs that are hung from a metal sub-structure that is directly mounted on the existing concrete cladding of the department store. Each disc is 80 millimeters in diameter and is made of sandblasted laminated glass. They each play an integral part in the perpetually-changing appearance of the building. As seen in Fig. 2.6, the building undergoes a complete transformation during the day and evening. The color of the façade changes from green to amber, depending on the position of the sun and the viewing position. In the evening, the LEDs light the frosted glass discs. "The subtle daytime looks of the building changes to something completely expressive and outgoing during the night," says lighting designer Rogier van der Heide (PenWell, 2005).

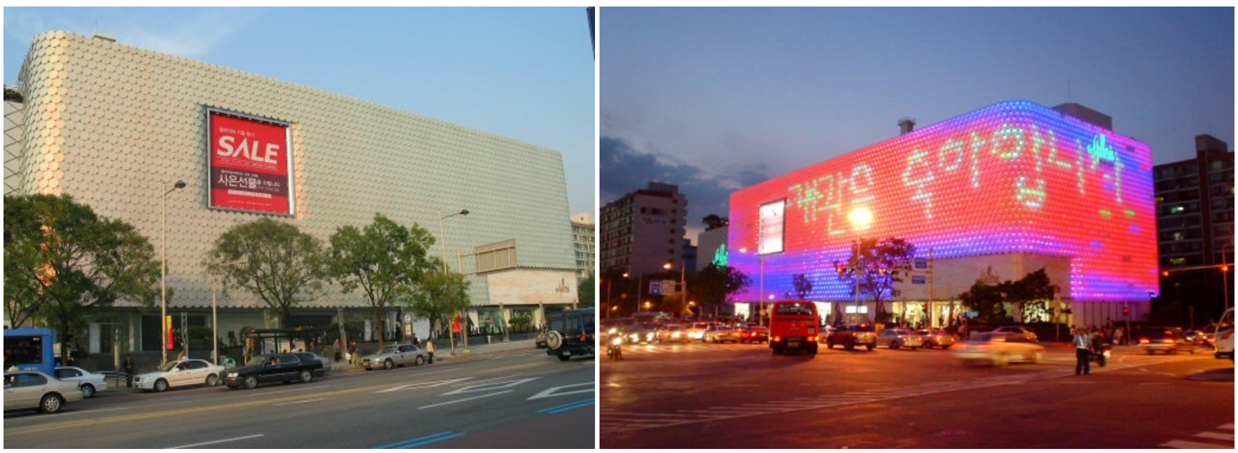


Figure 2.6 Galleria West building day and night view (PenWell, 2005)

The glass discs have a special dichroic foil. This is based on nano thin film technology, where a very thin controlled oxide can be produced on aluminum foil, shown in Fig. 2.7. When metalized, bright pastel colors are achieved by optical interference. The shift in color or dichroism can be viewed from different angles. This is similar to the effect that produces the colors seen in thin films of oil on water, but much brighter. A comparable result is used in security applications and banknote anti-counterfeit features (Ball, 2005).

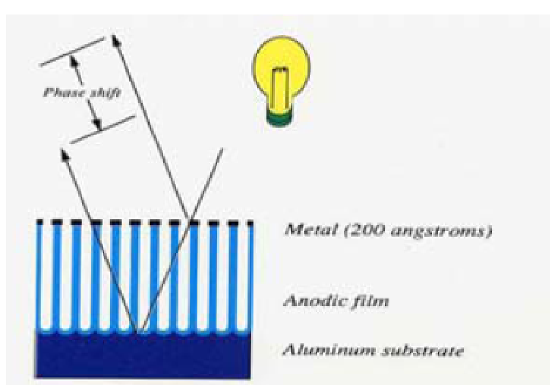


Figure 2.7 Schematic of interference coloring mechanism (Ball, 2005)

2.3.7 Water-flow windows

As illustrated in Fig. 2.8, this type of window contains a water circuit which lets a stream of clean water flowing upward inside the cavity of between the two panes of glass. Studies indicate that such water flows can effectively minimize the temperature of the inner glass pane, and reduce room heat gain in the room hence cutting down on air-conditioning loads (Chow, 2010). These systems have good potential in buildings with constant hot water demands such as apartments, hotels, and sports centers.

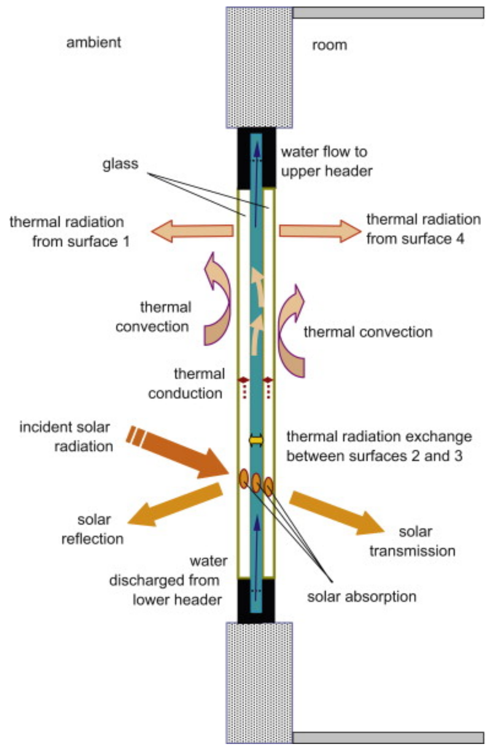


Figure 2.8 Energy flow paths at water-flow double-pane window (Chow, 2010)

Despite the ongoing research and development of many of these new technologies, many of them fall short of the architects and client's level of expectations. This is mainly due to difficulty of satisfying both the environmental performance and system reliability with the financial implications. The next two sections will elaborate on two newer types of alternative facades which are the focus of this study, building integrated photovoltaics and electrochromic glazing. This is followed by the findings of previously done research on their benefits.

2.4 BUILDING INTEGRATED PHOTOVOLTAICS

2.4.1 Solar Energy Potential

The use of PV power system is increasing worldwide. This technology once only available for space travel is now becoming an everyday energy source and a big stake holder in the market. Looking at the world map for annual solar radiation in Fig. 2.9, a common misconception is to assume that hotter regions such as the Middle East are one of the most ideal locations for PV.

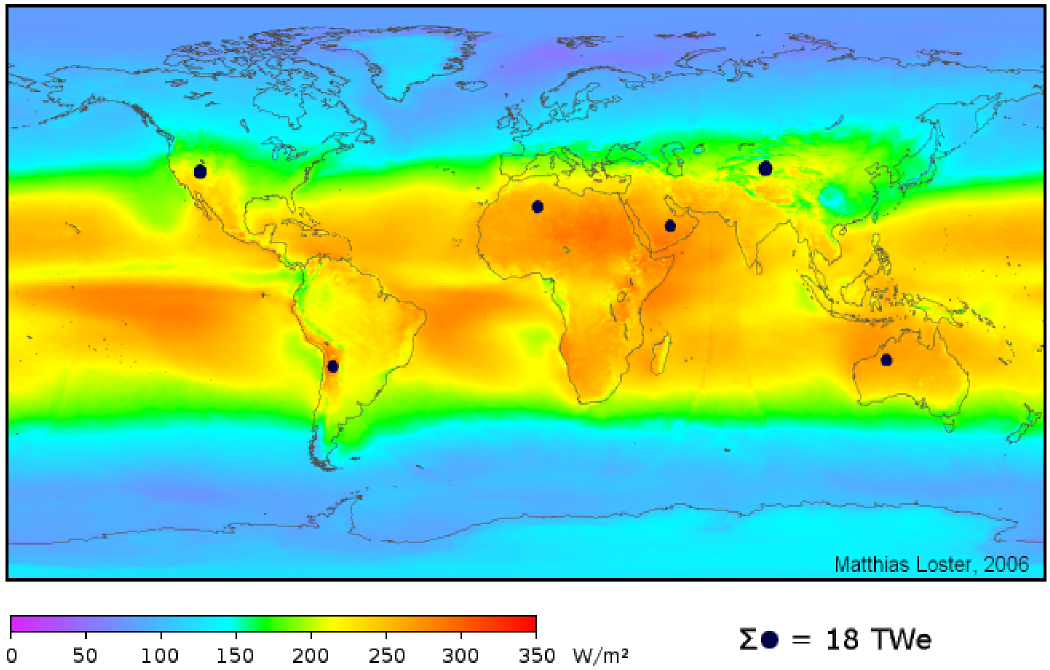


Figure 2.9 Net surface solar radiation (Wikipedia, 2010)

However, this is not the case. In fact, the countries where solar panels have fared well are not always in the sunniest places. Figure 2.10 shows the World's solar insolation versus solar installation in 2005, where the three countries US, Germany, and Japan, accounted for 90% of the 3705 megawatts of installed photovoltaic capacity. PVs actually perform better in cooler regions because as electronic devices relying on light not heat for electrical generation, they "operate much better at cooler temperatures" (Sullivan, 2008). Furthermore, the advancement of technology, the availability of alternative energy sources, regulation, awareness, and the commitment of the environment all contribute to the viability of solar energy in a given location.

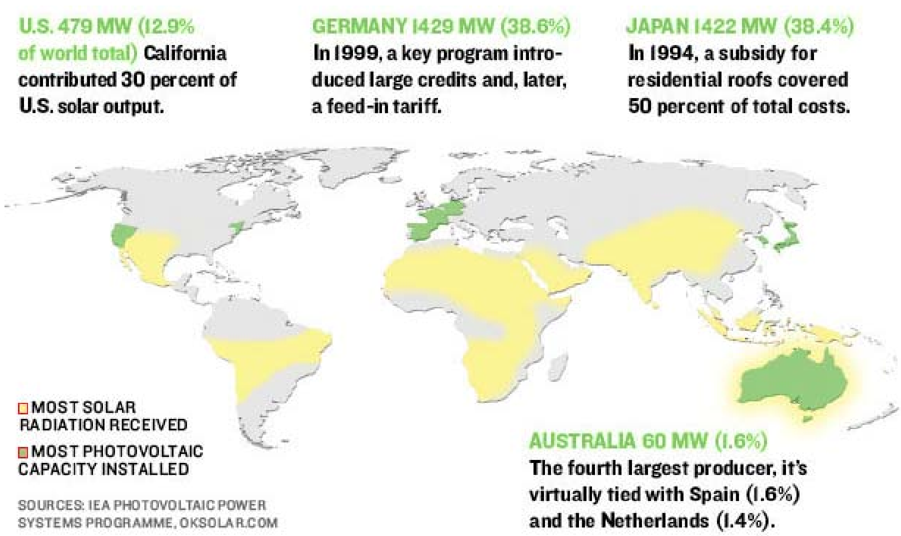


Figure 2.10 Photovoltaic hot spots (Upson, 2007)

2.4.2 Solar Energy Systems

There are three basic types of solar-energy conversion systems, flat-panels, thin-films, and concentrators. The following is a summary of the current state of each system, recent innovations, and some future developments.

Flat-panel PV systems

Most people associate solar energy with these systems. They are based on crystalline silicon solar cells that convert the sun's rays directly into electricity. The two types of these cells are mono-crystalline and poly (multi)-crystalline. The easiest way to visually identify the difference between them is that the polycrystalline has a shattered glass look, while the mono-crystalline cells tend to be uniform in appearance (Fig. 2.11). The price and performance of polycrystalline silicon solar module is lower than that of mono-crystalline and they are the most common type of these cells. Mono-crystalline cells are cut from silicon chunks grown from a single crystal. Their applications are for more expensive types of solar panels and are more efficient in converting the sun's rays to electricity. A polycrystalline cell is cut from multifaceted silicon crystal. More surface area is required due to inherent flaws and these panels are less efficient in converting the sun's rays. However, polycrystalline technology has closed up the performance gap in recent years with nominal efficiency of 15% compared to 17% in mono.

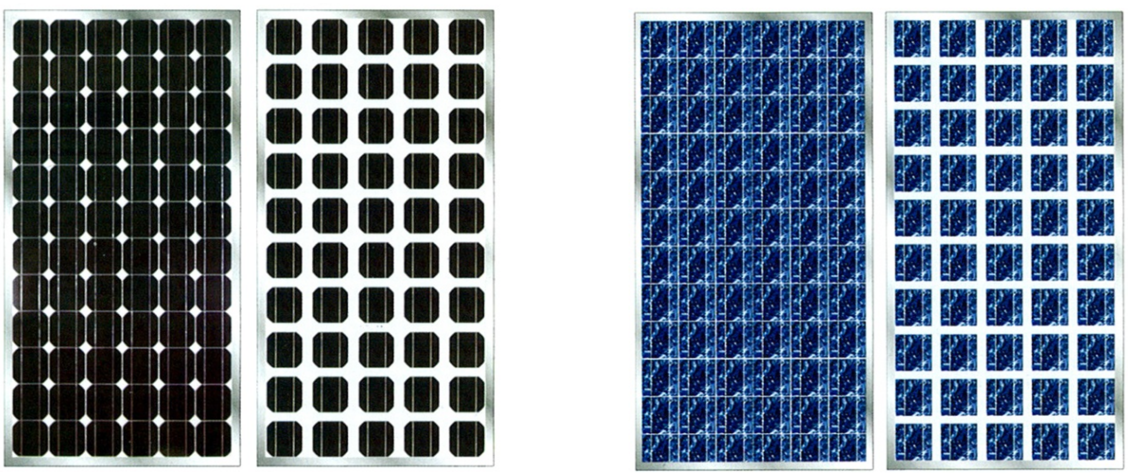


Figure 2.11 Opaque and semi-transparent mono-crystalline (left) and polycrystalline PV module (RHC, 2008)

Even in comparison to all other types of solar cells, the mono achieves the highest conversion efficiency yields. However, they also have the highest cost due to large quantity of raw material used. Since they have been in production the longest, they can give the most guaranteed performance proven for 25 years, and thus get the most funding. These types of cells are not transparent, however, the distance between the cells can be adjusted to allow light to transmit as seen in above figure. This has made their application as building integrated more difficult.

Thin-film solar system

They are based on nanotechnologies using extreme thin layers of solar-conversion materials. Then later they are applied to a thin layer of flexible backing, typically a metal. They are made thin by addition of tiny hole patterns on the cells. By adjusting the amount of these holes, the solar transmittance can be changed. Therefore, as illustrated in Fig. 2.12 the “power output reduction is equivalent to visual transmittance” (Chow, 2010). As the percentage of the openings reduces, the g-value, also known as the solar heat gain coefficient (SHGC), drops and the power output is increased. Similarly, with more light transmission, and higher SHGC, power output is lower.

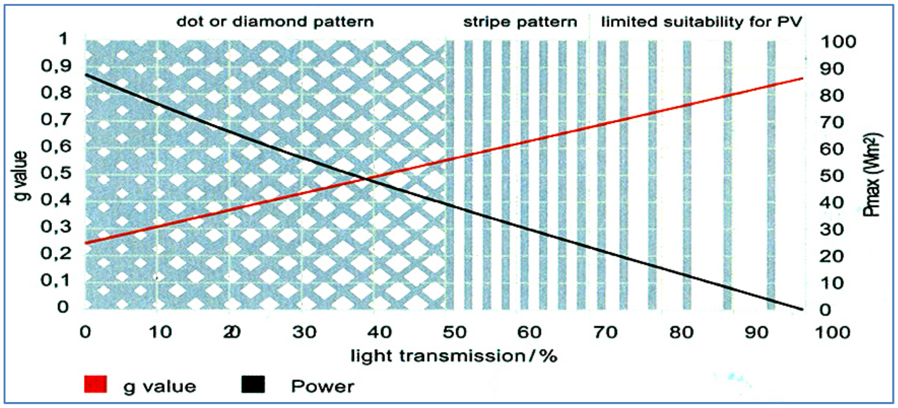


Figure 2.12 Semi-transparent modules: g value and power as a function of light transmission (RHC, 2008)

Masseck (2005), showed a case study of innovative transparent and colored amorphous silicon PV façade in the rehabilitation of a five-story staircase and the adjacent zones of an office building in the Barcelona. As seen in Fig. 2.13, since they are flat, they require less space vertically and are easier to install. Further they offer a low cost per square footage as they don’t rely on scarce polysilicon material, which is used to manufacture silicon PV modules. However, this economy of manufacture is outweighed by lower electrical production. There are mainly three types of thin film solar cells, amorphous silicon, CIS (copper, indium, and selenide), and CdTe (Cadmium Telluride). The uniform transmission of visible light makes them desirable for offices. Further because of their performance, high efficiency (maximum 13% nominal efficiency), and low cost, they are identified as the most potential PV cell to invest for the future (Green, 2002). A company, Nanosolar, has developed a “printing-press-like process” for mass production and low per-unit cost making thin film very cost competitive (Higgins, 2009).

Figure 2.13 Interior view (left) and exterior of finished façade with amorphous silicon PV (Masseck, 2005)

Concentrator solar systems

The two types of these systems are thermal-concentrators and concentrator PVs. The former, shown in Fig. 2.14, functions by concentrating the sun's rays on a media, like water, that can retain heat and produce steam to run generators for electrical production. The latter, seen in Fig. 2.15, uses the same principle onto PV cells to produce power, saving money by requiring less PV material and installation space. At IBM, the same technique used to cool computer chips is used to cool solar cells to withstand intense heat from the concentrators. They claim that this adaptation of liquid metal cooling technique can "remove roughly three-quarters of the heat generated by a CPV system" (La Monica, 2008). At MIT, engineers have developed a concentrator that can be useful for office buildings. It moves sunlight to window edges where "conversion materials" produce electricity and allows the window to still serve its normal functions (Higgins, 2009). As illustrated in Fig. 2.16, the glass is coated with careful mixture of dyes that absorb light and re-emit the energy onto the glass edges where the solar cells are placed. This method allows smaller solar cells to effectively harvest the same amount of solar energy as the larger more costly cells (Currie et al., 2008). The complete lecture about the luminescent solar concentrators by Marc Baldo, the leader of the electrical engineering group from MIT, can be seen at http://mitworld.mit.edu/video/689.

Figure 2.14 Dish engine systems eliminate the need to transfer heat to a boiler by placing a Stirling engine at the focal point (Wikipedia, 2010)

Figure 2.15 CPV arrays use lenses and mirrors to magnify light onto solar cells that convert light to electricity (La Monica, 2008)

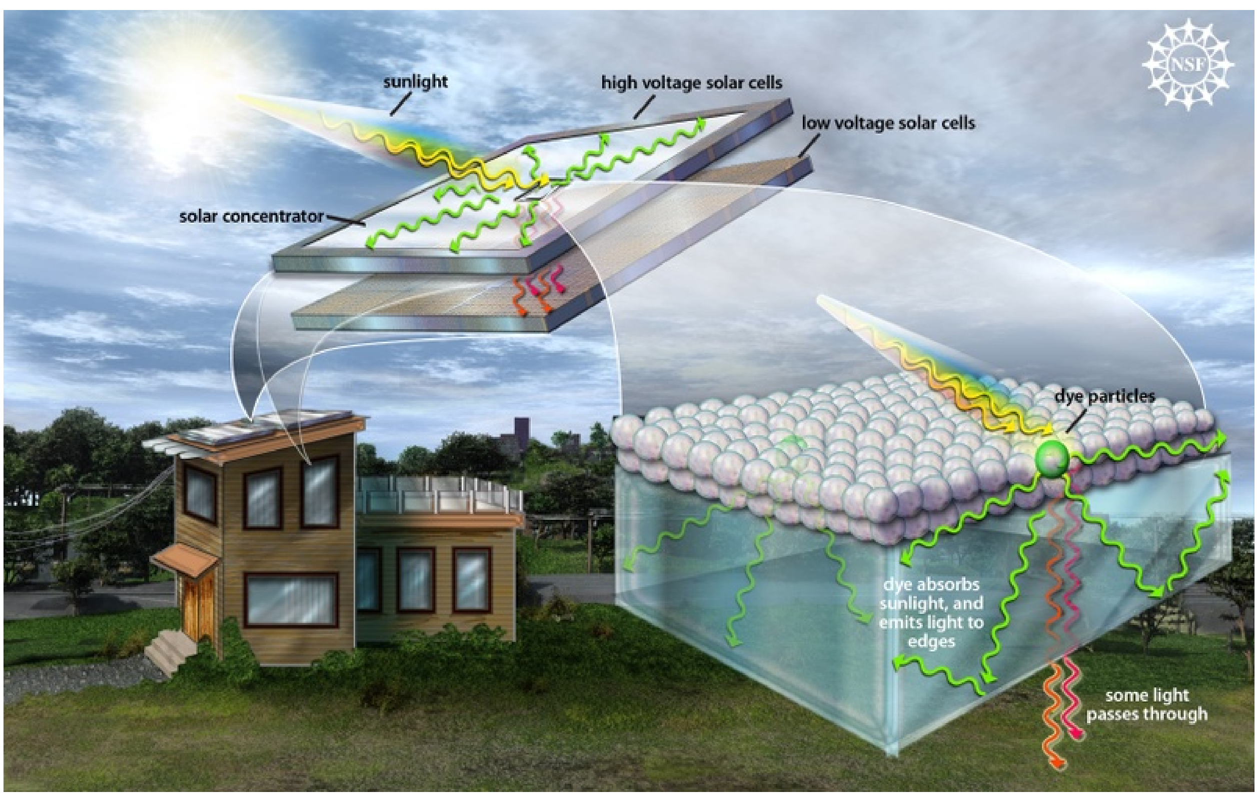


Figure 2.16 Solar concentrator (Madrigal, 2008)

Table 2.1 provides a comparison summary of all the different solar cells based on current market data. The information is provided from RHC catalog, a manufacture of BIPV. Aside from cell efficiency, and production cost discussed earlier, few other criterions are important when choosing appropriate PV cell. One of the most important criteria is the integration effect in the building. For example, the thin film cells can achieve a uniform look on the façade whilst the crystalline cells will be less appealing by a checkered pattern. Furthermore, thin films, the CIS cells in particular, will be more advantageous in areas of low sun intensity as their performance is less affected at low irradiances (Jardine, 2001). Stability performance is another important consideration which characterizes any attenuation in voltage production. The thin films also achieve a better interior light (optic performance) compared to the crystalline cells during weak lighting conditions. Therefore, they will require less need for artificial light and save more energy.

Table 2.1 Characteristics of Solar Cells (RHC, 2008)

Type of Cell	Nominal Efficiency	Production Cost	Performance at low illumination intensity	BIPV Building Effect	Stability Performance	Optics performance in weakening light
Monocrystalline	14-17%	High	Poor	Checkered	Stable	Poor
Polycrystalline	10-15%	High	Poor	Checkered	Stable	Poor
CIS	11-13%	Low	Excellent	Uniform	Stable	Good
CdTe	8-10%	High	Poor	Uniform	Stable	Good
Amporphous silicon	6-8%	Low	Good	Uniform	Attenuation	Good

According to Higgins (2009), the factors that will enhance solar generated power to become more cost competitive are innovations, state requirements and tax incentives. Firstly, the economies of scale encouraged from new innovations will push the costs down in manufacturing. As mentioned earlier, investments from companies like IBM which are non-energy based will boost the market confidence. Second, making the use of alternative energy sources mandatory will enable smaller solar companies to reach their capability and encourage future research. For example, the government could pass a legislation to push a utility company such as DEWA (Dubai Electricity and Water Authority) to achieve a percentage of its sources from renewable energy. This would create more incentives for small companies to enter the market which would otherwise not thrive in the current circumstances. Third, government tax credits can encourage businesses and consumers to install alternative energy sources like solar. By utilizing areas with high intensity sun, the government can help in leasing these lands to businesses with the technology to tap this vast “power of sunshine.” Fortunately in the UAE there are plenty of unused lands which can be harvested for this purpose. The issue in UAE is however of the detrimental effect of sand and dust on the cells. This along with other issues will be discussed in a later section which focuses on finding of previous research.

2.4.3 BIPV Applications and Design Considerations

PV can be used in a variety of ways on a building surface, combining energy production with other functions of the building envelope such as façade and roof integration, sun shades, and balcony rails. Some of these applications, as seen in Fig. 2.17, are more efficient in terms of power output than others.

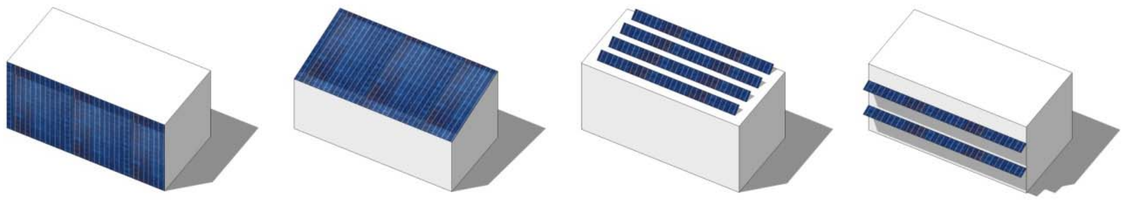


Figure 2.17 Applications of PV in buildings: façade (a), Sloped roof(b), Flat roof (c), and Awning (d)

A type of PV application is Building integrated photovoltaic (BIPV) which is an ideal solution to reduce peak grid-supplied power dependency, and provide new façade design. As seen in Fig. 2.18, the CIS Tower in Manchester, England, combines aesthetics and functions. However, the energy efficiency of BIPV, for example placed as spandrel glass panel, is 50% less compared to “optimally placed PV module” such as roof-mounted angled arrays used primarily for power generation (Sullivan, 2008). Table 2.2 shows the output efficiency of a PV panel based on different orientations and tilt angles simulated based on the climate of Abu Dhabi. This information was received through personal correspondence at the Abu Dhabi World Future Energy Summit (Noble, 2009). It is important to consider that completely horizontal installation is inadvisable since dirt will collect and will not be washed away by rainwater. This aspect will be discussed further in the section that elaborates the findings of previous researchers.

Table 2.2 PV power generation based on Orientation and Inclination for Abu Dhabi (Noble, 2009)

Inclination	**Orientation**				
	South	**SE/SW**	**E/W**	**NE/NW**	**North**
0 Horiz	1620	1620	**1620**	**1620**	**1620**
10	1690	1660	1600	1530	1500
20	**1730**	**1680**	1560	1420	1350
30	1720	1660	1490	1280	1170
40	1680	1600	1410	1140	989
50	1590	1510	1310	1000	827
60	1450	1390	1200	861	669
70	1280	1250	1070	727	518
80	1080	1080	925	600	384
90 Vert	863	893	778	484	281

Note:

1. Figures in kWh / kWp / year for 7m^2 facade based on Monocrystalline cells
2. Actual generation quoted after allowances for temperature effect, reflectance, cable, inverter losses and dirt allowance
3. Generation of up to 250kWh / m^2/ year

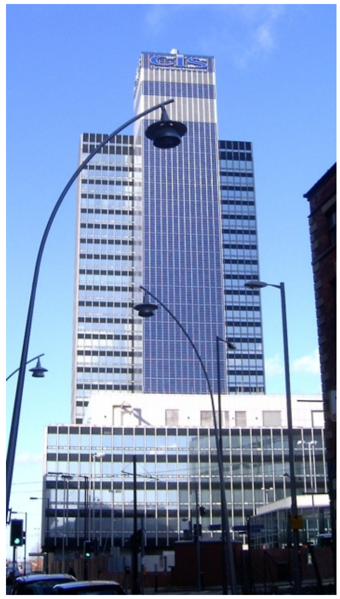


Figure 2.18 BIPV in façade of CIS Tower in Manchester England (Wikipedia, 2010)

According to the International Energy Agency (IEA), in order to assess potential of BIPV, an analysis of building skin suitability is required (Hope, 2009). This can be defined as two categories: architectural suitability taking into account limitations due to constructions, shading, and available surfaces, as well as solar suitability which considers amount of incident solar flux on the surface based on orientation, inclination and location and performance of characteristic of the BIPV system.

One of the advantages of BIPV as an alternative façade is that is produces electricity while allowing daylight to penetrate the internal spaces. This will further reduce building energy consumption by providing diffused light that will ultimately reduce need for artificial lighting and hence air-conditioning. It offers a variety of possibilities for building integration seen in Fig. 2.19, given that the panels have the best orientation toward the sun, usually south facing in the Northern hemisphere.

a b c

Figure 2.19 BIPV applications in facade (a), skylight (b), and exterior shading like canopies(c)

Besides good orientation, which ensures optimum solar irradiance, another critical design issues is adequate ventilation. Without sufficient air gaps on the back of the modules, overheating of the modules causes reductions in outputs. Figure 2.20 shows output reductions based on a temperature-dependent behavior of thin film cells. The standard test condition (STC) often used in labs is based on the most optimum scenario, which is usually at 25˚C and 1000W solar irradiation.

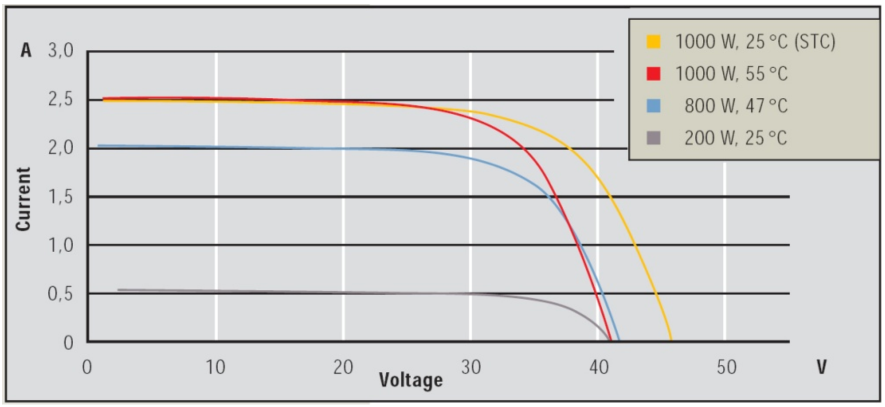


Figure 2.20 Intensity and temperature-dependent behavior (Wurth Solar, 2010)

Another important concern is maintaining a clear obstruction from surrounding building parts or trees that may cause shading. This is crucial for a continuous optimum performance. Any part that is shaded will reduce the overall module efficiency. These design considerations will be examined more closely in the coming section which deals with previous research studies.

2.4.4 BIPV system components and configuration

Hope (2009) describes a complete BIPV system includes the following components:

- PV modules (thin-film or crystalline, transparent, semi-transparent or opaque)
- A charge controller to regulate the power into and out of battery storage bank (in standalone systems)
- A power-storage system (either utility grid itself or batteries, which is the case in UAE)
- Inverter for converting DC output from modules to usable AC current
- Back-up power supplies like diesel generator
- Appropriate support and mounting hardware, wiring, and safety disconnects

The configuration of this product, shown in Fig. 2.21, reveals that tempered glass is laminated as a sandwich with ethylene vinyl acetate (EVA) or polyvinyl butyral (PVB) foil and solar cells laid within the unit. Although PVB foils are more advantageous due to safety reasons, they have a tendency to cloud up if they absorb moisture (Sullivan and Horwitz-Bennet, 2008). Furthermore, depending on the type of cell embedded within the glazing unit, the perceived building exterior as well as interior look can be altered. These various methods will be discussed in the methodology chapter for choosing an appropriate type of cell for optimum test results.

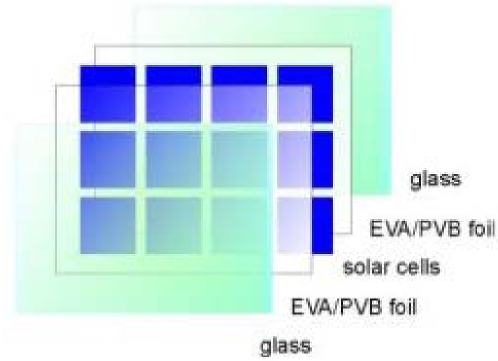


Figure 2.21 BIPV laminate (Lenardic, 2010)

2.4.5 BIPV Future Outlook

Despite all of its benefits, however, this technology has discouraged investors due to high initial cost and long payback periods. The PV modules normally account for half the total cost of a system, while the inverter, support structures, and installation account for the rest. Thus, most projects so far have been relying on incentives such as government subsidization, and gaining social stature through the building image in order to use BIPV. The use of intelligent grids can further enhance the chance of this renewable energy which is often dismissed due to intermittency problems (Barnham, 2006).

In the UAE, with new interest over winning the bid for hosting new headquarters of the International Renewable Energy Association (IRENA), some of the stumbling blocks for BIPV can be overcome. A considerable step in Masdar City project, seen in Fig. 2.22, shows an objective to make Abu Dhabi a developer of this technology rather than an importer. The project is the first carbon-neutral and zero-waste city in the world, and is head- quarters of the IRENA (Masdar, 2010). With such ambitions to become a leader in alternative energy, and with “commitment to 7% renewable energy in electricity by 2020,” the indications of shift in energy paradigm are strong (Pelosse, 2010). In the lecture by Pelosse (2010) overcoming the issues of maintenance and grid connectivity are described as the top priority in future development of solar energy in this region.

Figure 2.22 Masdar City has the first grid-connected solar plant in the UAE with 10MW capacity (Hope, 2009)

2.5 ELECTROCHROMIC GLAZING

2.5.1 Smart Window Technologies

A new type of dynamic glazing can play a significant role in architecture. This type glazing, also called smart window, can change transparency in response to external changes. There are three technologies that work on this principle: liquid crystals, suspended-particle devices, and chromic materials. They are all compared based on certain specific factors. The following are the most important attributes for potential users (Baetens et al., 2010):

- Transmittance modulation range of visible and solar spectrum
- Lifetime expectancy and period without any degradation
- Switching time (needed to reach 90% of maximum range) and consistency of tint
- Window size and energy usage
- Operating voltage and temperature range

<u>Liquid Crystals (LC) device</u>

As shown in Fig. 2.23, these devices work by applying an electric current between two conductive electrodes which results in changing the liquid crystal molecules orientation (Doane et al., 1987). The switching time is fast, however, a constant power is necessary to keep the device in this state which results in high power consumption. The LC glass is limited to interior privacy applications because it only scatters light rather than block it.

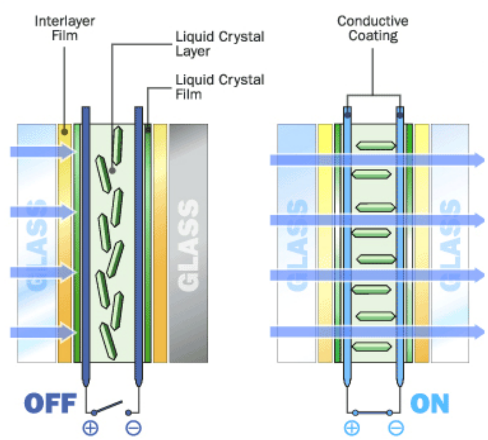


Figure 2.23 Liquid Crystal Window working mechanism (Bonsor, 2010)

<u>Suspended-particle device (SPD)</u>

The particles in this device are randomly positioned when turned off, and absorb the light. However, as seen in Fig. 2.24, an electric current triggers them to align allowing higher light transmission. Through simple adjustment of this current manually or automatically, the amount of light passing through SPD-glass can be controlled instantaneously. There is little knowledge about the recent findings of SPD due to patent restrictions (Vergaz et al., 2008). Similar to the LC, the SPD requires a continuous power for passing the light.

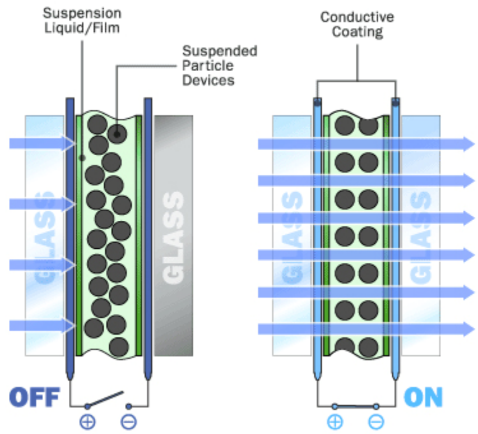


Figure 2.24 SPD Smart Windows working mechanism (Bonsor, 2010)

<u>Chromic device</u>

There are four categories of chromic devices: electrochromic (EC) which responds to electrical voltage, thermochromic that responds to heat, photochromic which responds to light (Granqvist et al., 2009) and gasochromic that reacts to oxidizing gases like H_2 (Wittwer et al. 2004). This paper will focus on electrochromic type which can be used to control heat and light in windows.

2.5.2 Configuration of EC Glazing

EC glazing is part of a new group of technologies called switchable glazing or smart window. Its energy reduction potential can be achieved through control of solar heat, daylight and glare. There are various types of EC windows. One of the most common one is metal oxide EC such as tungsten. Tungsten oxide (WO_3) is well known for it good EC properties and stability. Figure 2.25 shows the configuration which is a five-layer WO_3 coating sandwiched between two glass panes.

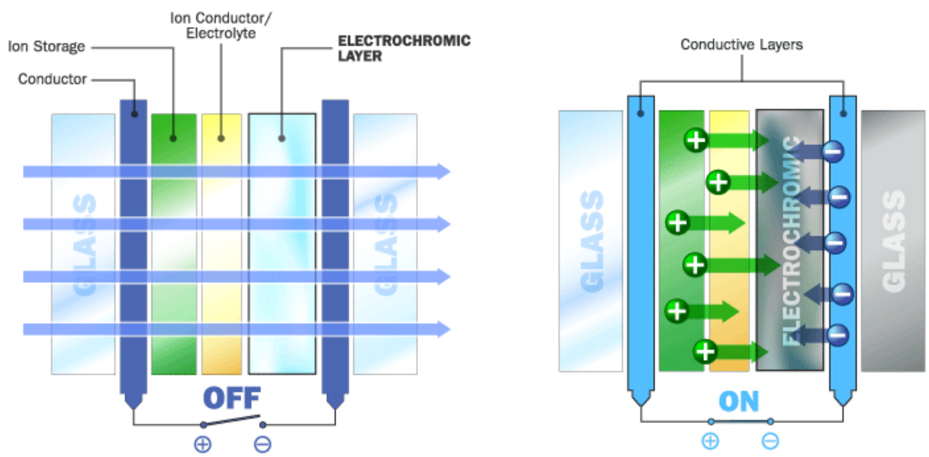


Figure 2.25 Layers of EC glazing and the working mechanism (Bonsor, 2010)

This technology works by passing a low-voltage electric current across a microscopically-thin coating on the glass surface. This activates the EC layer that causes its color to change from clear to dark, hence changing the window's transparency. A product by one of the leading manufactures has a dynamic range of 3.5-64% (SageGlass, 2010).

This means that on the low (dark) end, it blocks all but 3.5% of incoming visible light and most of the heat, while on high (clear) end, it blocks only 36% incoming lights, and allows in more solar heat. Figure 2.26 shows how EC windows can be used to eliminate the need for blinds and shades.

Figure 2.26 Century College, Minnesota – Clear (a) and Tinted (b) glass in student library (SageGlass, 2010)

One of the advantages EC glazing is that it only requires electricity to change its opacity but not to maintain a particular shade. It has a good durability and can be cycled from clear to tinted over 100,000 times without any functional loss (Rudolph et al., 2009). Another advantage is that unlike Low-E coatings that are only appropriate for one type of climate, this type of smart glass can regulated depending on the specific needs. Further, in contrast to blinds, they are capable of partially blocking light while giving a clear view of outside.

A performance characteristic of ECG that might limit its use is its switching speed. Because this transition takes three to five minutes, the amount of light entering the room is limited by the delay in the response of the window. Due to this time needed to tint the glass, the “standard use is to control the system for two states: clear and fully tinted” (Rudolph et al., 2009). Another disadvantage is the inconsistency in the tint change. This is known as the “iris effect” where color change begins at outer edges of the window and slowly towards the center (Sottile, 2008).

2.5.3 EC Glazing Future Outlook

Surveys taken of US architects and LEED accredited professionals, showed more positive attitude toward use of EC glazing. While it is not surprising that main issue of importance was energy efficiency, some of the other desired properties included: durability, integration with other coatings like low-E, glare reduction, consistent tint, high UV blockage, fast switching speeds, and variable solar heat gain control (Sottile, 2007). Despite all this understanding, the lack of knowledge about category of product, perceptions of high material cost, and doubts over service life are inhibiting factors for architects to specify smart windows (Baetens et al., 2010). This technology is well suited for locations with intense sunlight thus making them appropriate for UAE. Further, because most buildings do not have heaters in UAE, a combination with low-E coating ensures good insulation in winter.

In addition to energy savings, EC glazing can have a role in architectural aesthetics. In an anonymous article, Transparent Technology, in Lighting Design + Application magazine, the Chanel Ginza building in Tokyo is featured using a triple glazing with LEDs and automated interior shading from switchable optics, see in Fig. 2.27. The LED technology that appears transparent during the day allowing the office workers a clear view to outside. Whereas at night the glass turns translucent and LEDs switch on to transform the building into a large scale screen. The building's "media skin" can display unlimited choices of arts and imagery as seen in Fig. 2.28.

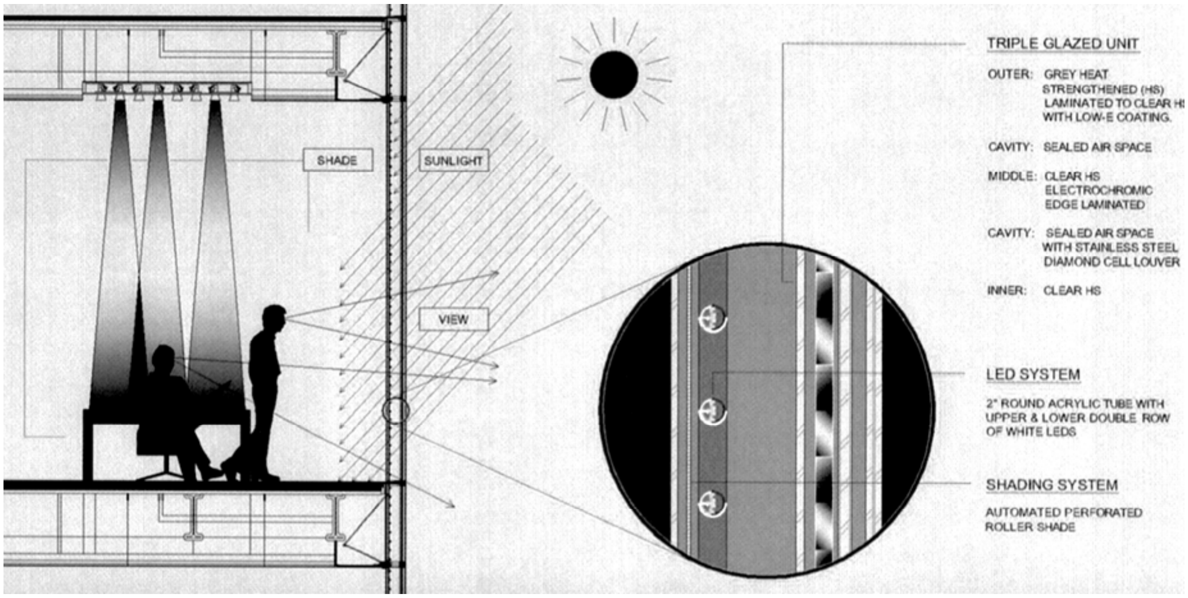


Figure 2.27 LED EC wall in daytime mode (Lighting Design + Application, 2006)

Figure 2.28 Chanel Headquarters' curtain wall (Peter Marino Architect, 2010)

Other developments include a self-powered photovoltaic EC device in the US (Deb et al., 2001). The preference for this is its elimination of external wiring requirements. However, Baetens et al. (2010) claim possible system implications include PV generated energy loss in larger windows, limited range of "optical modulation" and "low transmittance in clear state." Sullivan and Horwitz-Bennet (2008) recall another new development by Lawrence Berkley National Laboratory is a "switchable-mirrors technology," that uses transition metals instead of earth metals harder to acquire. Consequently the cost of production is expected to reduce. In addition, the cost of this type of glazing is expected to lower, with continued increase in volume and manufacturing refinements.

2.6 RESULTS OF PREVIOUS RESEARCH

This section will review the findings of previous published scientific studies. The key issues which will be explored are BIPV and EC glazing systems, control mechanism strategies (energy versus lighting optimization), human comfort, and orientation. This discussion summarizes fifteen research papers covering a period from 2001 to 2010. The purpose of this exploration is analyzing how these factors can be manipulated for efficient system utilization and ultimately maximum energy savings in office buildings. Finally, a comparison of the results will identify any gaps in the research and give a better understanding of required work for additional investigation. This section is divided into three parts, mainly because all except one of the papers examines these two systems separately.

2.6.1 Studies on EC Glazing

Gugliermetti and Bisegna (2005) analyzed the integration of EC windows or double-glazed systems equipped with motorized internal shading devices when combined with light control system. The advance package IENUS (Integrated Energy Use Simulation) was used to run simulations testing two types of control strategies shown in Fig. 2.29 in typical Mediterranean climates. Whilst, the On/off control strategy works by quickly changing the EC device from bleached to colored state, the linear strategy requires two set points to define a range for the variation in EC transparency.

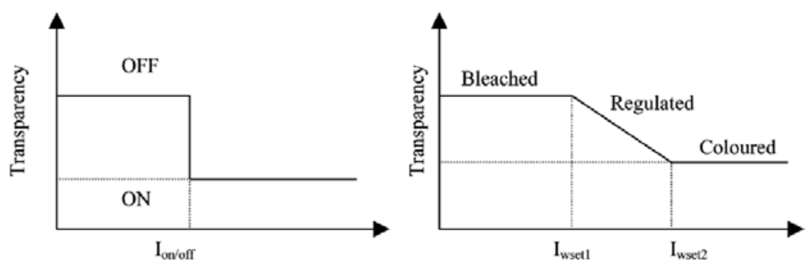


Figure 2.29 On/off (left) and linear (right) control strategy (Gugliermetti and Bisegna, 2005)

The occupant's actions are the main cause of reduced benefits of daylight control systems (Gugliermetti et al. 2001). However, because their behavior is not predictable, the possibility of EC control system override to suit their needs was not considered. Therefore, daylight was regulated through an open-loop feedback, where light sensors detect only daylight and are insensitive to artificial light. The control system was triggered when photo-sensors measured sunlight hitting the exterior glass surface for the EC model and direct radiation transmitted for the reference case with blinds. In an earlier study, Gugliermetti and Bisegna (2003) discovered that a comfort based approach, aimed at minimizing glare, can produce only a slight increase in minimum energy requirements. Thus, this approach was once again adopted for the EC case. Also, Gugliermetti and Grossi (2000) suggest that when using On/off control method in motorized shading systems, closing the shading device is necessary once the glazing transmits radiation above $30W/m^2$. In addition, the values for the linear control were assigned to range from $30W/m^2$ to $150W/m^2$ for the two set points I_{wset1} and I_{wset2} respectively.

The study measured the annual illuminance distributions of the darkest point in a typical office model of 5mx7mx3m. Three types of double-glazed window systems were selected: a system of two clear glass panes with external panel coated with EC device (EC1); EC1 with internal panel coated with low-e (EC2); and a reference clear double-glazed system (REF). For the REF, various types of blinds with different transmittance characteristics were tested, labeled REF1, REF2, and REF3. The analysis looked at various control strategies, window orientations, and control systems for the three selected Italian cities. The results show that EC window systems are more appropriate for "low illuminance requirements" compared to the REF systems that lose efficiency from the frequent closing of the curtain caused by significant occurrence of daylight illuminance (Gugliermetti and Bisegna, 2005). In comparing the three cities, an increase in latitude indicates a loss of EC efficacy in terms of visual point of view. Further, as the North side is characterized by diffuse solar radiation, the EC windows lose benefit of linear regulation. As Fig. 2.30 illustrates, there is a loss of daylight illuminance from changing the orientation. Hence, it is economically more advantageous to use traditional window systems than EC systems on north orientation.

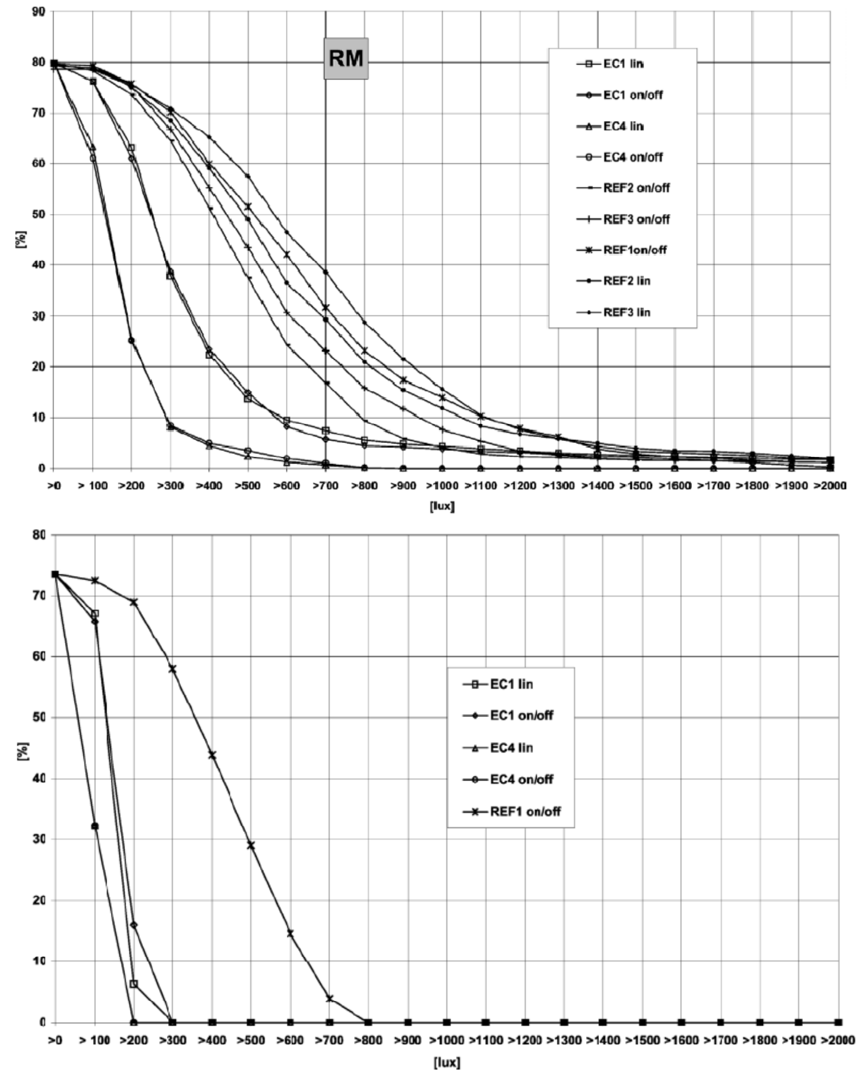
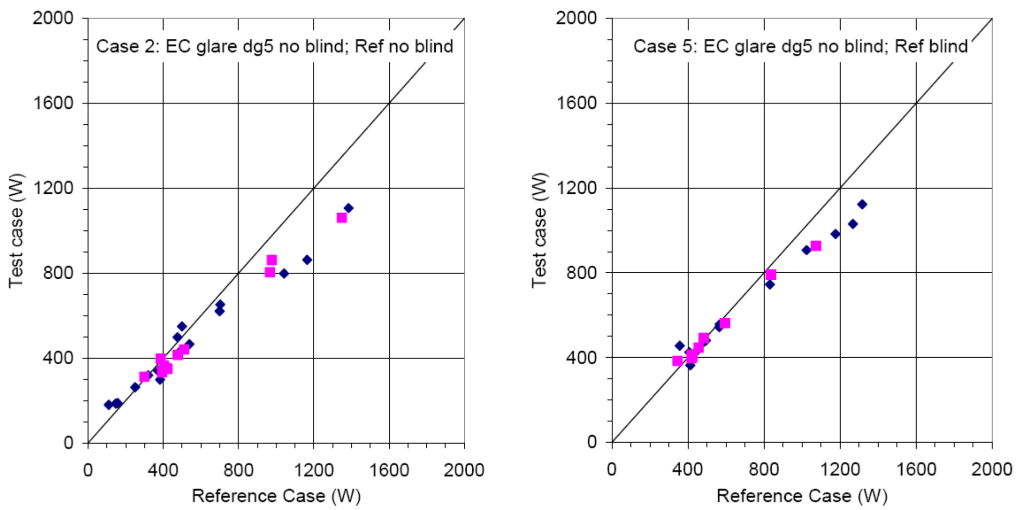


Figure 2.30 Rome's South (above) and North (below) annual cumulative daylight illuminance distribution (Gugliermetti and Bisegna, 2005)

Furthermore, whilst REF1 showed most number of hours with curtain closed, the EC models showed a lower number of hours with complete darkening. Therefore, the use of EC systems allow for more connectivity and less risk of feeling secluded for the users. However, it is accepted that the best approach to understanding privacy and seclusion is through field analysis intended to identify a “typical worker” behavior (Gugliermetti and Bisegna, 2005).

Lee et al. (2006) published results of a 20-month field-study of large-scale commercial electrochromic windows by the Lawrence Berkeley National Laboratory. Their findings, which are a guide for architects and engineers, are prepared as a report for the California Energy Commission with the following summaries:

- At temperatures above 10˚C switching time ranges from 6-7 minutes, while at colder temperatures and lower solar irradiance, the switching period reaches 40 to 85 minutes.
- A high average daily light energy savings of 44% can be achieved compared with a base case with fully lowered blinds and no daylight controlled electric lighting, which is the current norm in building practice.
- Greatest energy savings in warm to hot climates where large-area-windows are used.
- Lower energy savings in cooler climates, built-up urban areas casting shadows, and for small windows.
- A 26% and 19% peak cooling load reductions due to solar heat gains compared to an unshaded and fully shaded reference case if the EC window is controlled to its most colored state (Fig. 2.31).



a) Reference with no blind b) Reference with blind

Figure 2.31 Field measured hourly peak cooling load due to heat gains compared to reference case without (a) or with (b) fully lowered Venetian blinds (Lee et al., 2006)

These findings indicate that the maximum energy benefits through use of EC windows requires controlling window and lighting systems to minimize lighting energy loads than reducing cooling load through solar heat gain control. In addition to energy savings, EC windows offer better visual comfort than normal windows with raised blinds. A simulation study was undertaken for blind use pattern based on occupant’s control to achieve visual comfort. The results, as see in Fig. 2.32, showed a greater percentage of occupant’s view to outside compared to reference case with interior Venetian blind. The x-axis indicates days of the year with left edge at 0 and right edge at 365. The black means there is no blind required. It is speculated that EC windows lead to greater occupant satisfaction and even “increased productivity and a more healthful environment” (Lee et al., 2006).

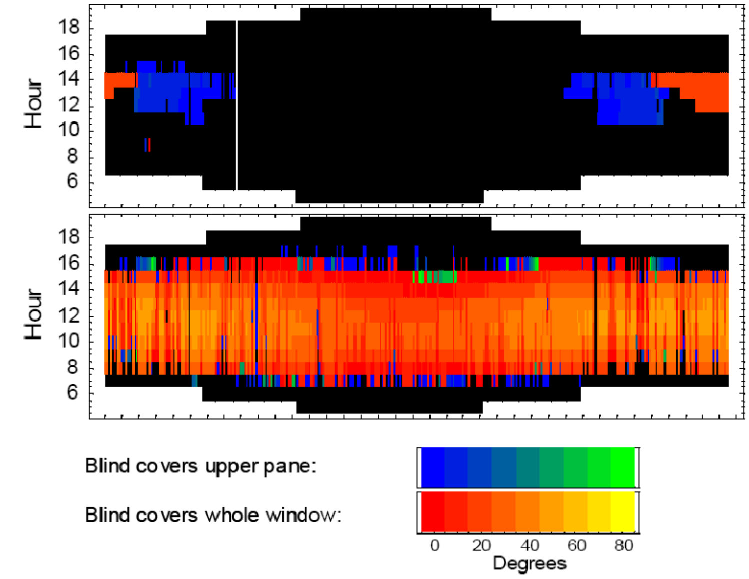


Figure 2.32 Annual blind use pattern. EC window (top) and reference window (bottom) (Lee et al., 2006)

Fernandes et al. (2006) conducted a lighting simulation to evaluate lighting energy savings of EC window systems controlled to meet visual comfort conditions. They defined an algorithm shown in Fig. 2.33 for the control of Venetian blinds and EC windows for the reference case model as well as the EC model. The transmittance of the EC varied between 5% and 60%, while the reference case was constant at 60%. The optimization target for the working plane was 600 lux.

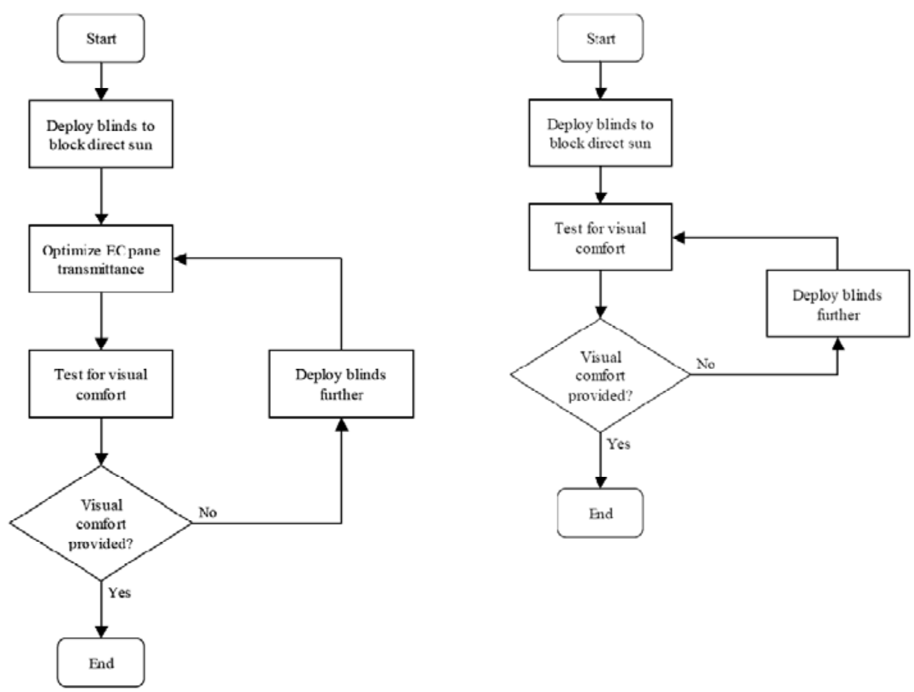


Figure 2.33 EC case (left) and reference case (right) control algorithm flow charts (Fernandes et al., 2006)

The results in Fig. 2.34 showed that annual lighting energy use for EC window is higher than the reference case. Also the use of an overhang results in slightly higher energy use for both cases. Given that the EC window provided lower illuminance levels than the reference window, it was decided to test the effect of higher work plane illuminance set-point for the EC case. This analysis showed an increase to 1000 lux in optimization will bring the energy performance of EC to levels much closer to the reference case, although at the expense of visual comfort.

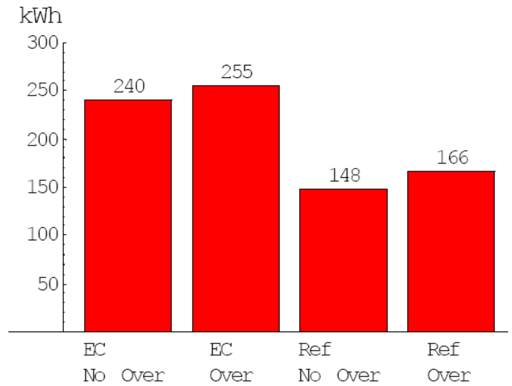


Figure 2.34 Annual lighting energy with hourly blind control for EC and reference windows (Fernandes et al., 2006)

The study found that the hourly adjustments of the blinds were not deemed as accurate depiction of daily office blind control. This parameter was reinvestigated since studies showed that most office users tend to leave the blinds down for the remainder of the day once they have lowered them. With the new blind control algorithm, adjusting daily instead of hourly, the EC window energy use became much lower shown in Fig. 2.35. The comparison in energy savings showed that the EC gained advantage over the reference case in the early morning and late afternoon hours particularly in the summer months.

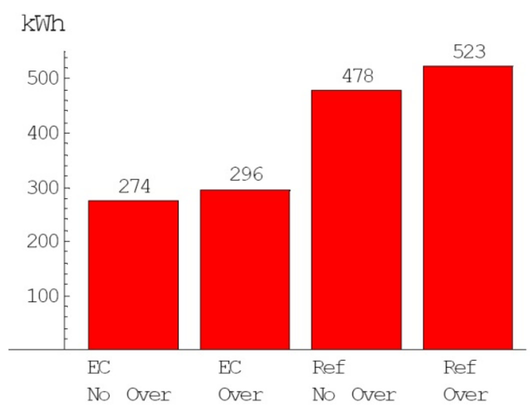


Figure 2.35 Annual lighting energy with daily blind control for EC and reference windows (Fernandes et al., 2006)

It must be taken into account that since EC works by absorbing light, and Venetian blinds by redirecting it, then ordinary glass will not outperform EC if the "interior shading is not light-directing, such as with fabric shades" (Fernandes et al., 2006). Finally, the study acknowledges the notion that although only one position for the occupant's eyes was considered, people are constantly moving and looking around. Also the sensitivity to glare varies depending on the individual. Therefore, by adding more viewing positions which require additional weeks of computation, a more realistic picture in terms of daylighting and visual comfort would be attained.

Bahaj et al. (2008) identified advanced glazing and solar control technologies as keys to achieving good quality performance. They claim that although changes in the "built form" are happening slowly, these improvements are an important step toward sustainable highly glazed towers. Table 2.3 shows an overview of the emerging glazing technologies undertaken in their research. They categorize the issues for electrochromic glazing as follows:

Technical issues:

- Switching time: typically 5 to 10 minutes from fully colored to bleached
- Glare: many switchable facades may need additional glare protection specially for offices
- Color rendering: large contrast in luminous color compared to normal spectrum can be considered unsuitable in many applications since it creates a blue light when in solar control mode

Non-technical issues:

- Cost: higher premium in comparison to low-e double glazing
- Lifetime: higher risk with only a five year warranty on switching performance compared to 30 years lifetime of traditional façade technology

Table 2.3 Evaluation of glazing technologies in terms of performance and risk criteria (Bahaj et al., 2008)

Matrix of Facade Technologies

		Solar Control	Daylighting	Glare Control	View to Exterior	Maintenance	Availability	Lifetime
Emerging Glazing Technologies	Aerogel Glazing *	–	+	–	o	+	–	o
	Vacuum Glazing *	–	+	–	+	o	o	o
	Switchable Reflective Glazing	+	+	o	o	o	–	–
	Electrochromic Glazing	+	o	o	o	o	o	–
	Suspended Particle Devices	+	o	o	o	o	o	–
	Reflection HOE	o	+	–	o	o	–	o
	Photovoltaic Facades	o	o	–	o	o	+	o
State of the Art	Low-e Glazing	o	+	–	+	+	+	+
	Tinted Glazing	o	o	o	o	+	+	+

Legend
+ good performance
o intermediate, moderate performance
– poor or unknown performance

* without additional low-e coating

Two hotel developments in Dubai, Jumeirah Beach hotel and Burj al Arab Tower, were used as the case studies to base the modeling approach. In order to estimate the air conditioning load, a computer model of 3 x 3 array of thermally linked rooms shown in figure 2.36 was created. The EC glazing was simulated by keeping same glazing U-value but with different g-values. The study of performance was modeled based on switching threshold of 200W/m^2 external horizontal irradiance between bleached and colored states. The results showed substantial reduction in air conditioning loads (45%). Further, in the case of PV facades, they claim a higher potential in the application of thin film technologies. Their simulation results showed that using new generation of cells, capable of achieving 60% or greater efficiency (Green, 2002), covering 40% of the south façade of a full glazed tower would "yield a net energy gain over air conditioning loads" (Bahaj et al., 2008).

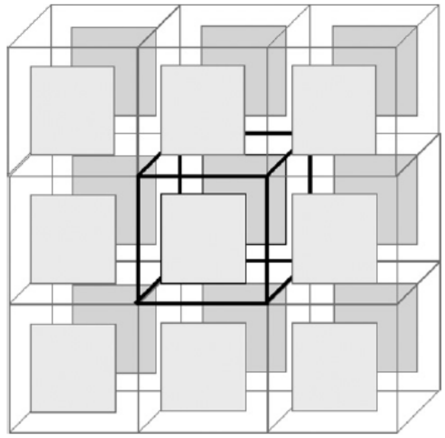


Figure 2.36 A 3 x 3 array of thermally linked rooms, with highlighted central room being used for air conditioning requirement analysis (Bahaj et al., 2008)

Jonsson and Roos (2009) evaluated the heating and cooling need of the building in different climatic conditions. They investigated four control mechanisms using EC glazing in combination with other solar glazing, solar control and low-e. These strategies are listed below:

- Energy optimization mode: keeping windows in a state best from heating and cooling perspective. During simulation, windows are kept in low-transparent state when there is a need for cooling and high-transparent state for heating requirement.
- Daylight optimization mode: windows are kept in state optimized from a daylight perspective defined as direct solar radiation regulated by EC coating to a maximum of 200W/m^2 that helps reduce glare.
- Office 1 mode: windows in “daylight optimization” mode during office use (from 7am to 6pm) and otherwise in “energy optimization” mode
- Office 2 model: windows in “daylight optimization” mode during half of the office use on weekdays and otherwise in “energy optimization” mode. This is a simple way of reflecting that office occupancy is only 50% of the time.

The objective of their study was to investigate the methods and compare strategies, and not to evaluate the performance of actual products. The results for the cooling energy balance for Miami, one of the three climatic conditions similar to UAE with large cooling needs and non-existing heating, are shown in Fig. 2.37 for different orientations. The cooling need is primarily due to solar heat gain through the window and only slightly by thermal conductance (Jonsson and Roos, 2009). The graph’s negative values indicate an energy cost due to the window that requires air-conditioning to maintain comfort indoor temperature. It was concluded that EC windows always yield a lower need for cooling than other static alternatives. The control strategy was the most important factor, with “energy optimization” mode being the best in all cases.

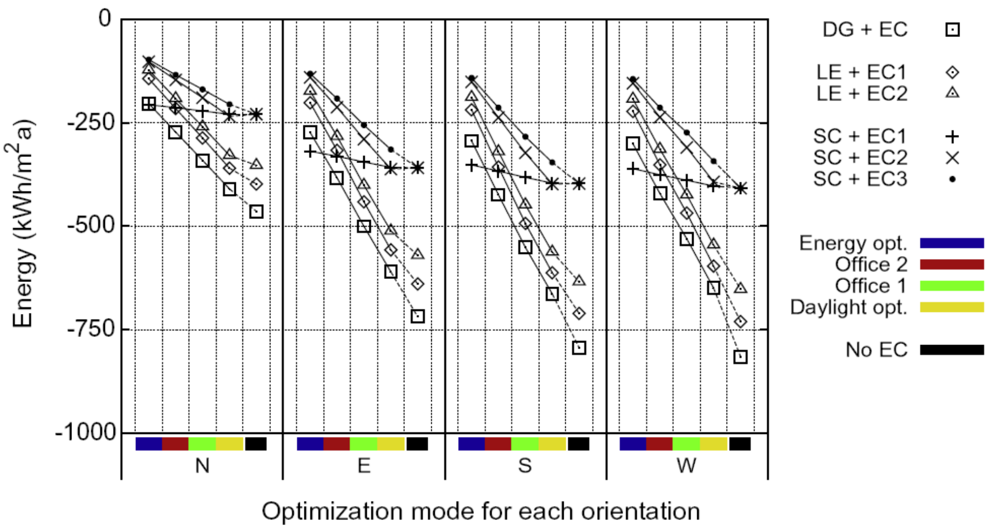


Figure 2.37 Cooling energy balance of studied window combinations for four orientations in Miami (Jonsson and Roos, 2009)

For the other climatic condition sites, the results of the total energy balance were slightly different. This shows the need to consider different windows and control strategies for EC window combinations based on typology and activity. For example, in Stockholm, with large heating needs and with moderate cooling needs, EC windows always outperform other types in “office 2” mode. On the other hand, in Denver, with moderate heating and cooling requirements, “energy optimization” mode using low-e was the best choice.

Further, the authors discuss “presence detection” as an important factor in the study. The claim a considerable potential of energy saving if the “control strategy switches to energy optimization as often as possible” (Jonsson and Roos, 2009). They also acknowledge that aside from the visual and energy performance, durability has to be considered as a critical factor for window glazing combinations. Although not accounted for in their study, they emphasize the use of protected surfaces for sensitive coatings, and low solar absorptance glazing to “avoid heating of the panes” (Jonsson and Roos, 2009).

Piccolo (2010) carried out a small scale experimental test supplemented with computer simulation to evaluate the EC window performance with respect to solar control in buildings of a cooling dominated climate. In an earlier similar experimental study, he suggests that EC windows are unable to protect against such effects of direct sunlight like “disability glare and high-luminance spots” (Piccolo et al., 2009). Here, he claims that such unwanted effects can only be reduced but not removed through implementing EC device switched to its darkest state. In fact, the complete control of high illuminance levels requires the device switching to “very low visible transmittance states” lower than 1% (Moeck et al., 1998). A positive contribution of EC glazing can be toward the reduced need of “traditional shading devices” (Clear et al., 2006). Piccolo’s study includes test conducted under clear skies and monitoring environmental parameters for different switching strategies of a double-glazed EC window for two orientations, south and west. Table 2.4 shows the various glazing properties used for the simulation.

Table 2.4 Thermophysical properties of selected glazing for simulation (Piccolo, 2010)

	Glazing	τ_e	g	U (W m^{-2} K^{-1})
(A)	EC-DGU (bleached): (K-glass 8 mm, Clear 4 mm)	0.46	0.53	2.2
(B)	EC-DGU (coloured): (K-glass 8 mm, Clear 4 mm)	0.033	0.12	2.2
(C)	Float S: (Clear 4 mm)	0.85	0.87	5.8
(D)	Float DG: (Clear 4 mm, Clear 4 mm)	0.74	0.79	2.8
(E)	Reflective low-e	0.27	0.36	1.1
(F)	Absorbing Bronze: Bronze 4 mm, Bronze 4 mm	0.51	0.59	2.9
(G)	low-e DG: (Clear 4 mm, SnO_2 4 mm)	0.59	0.74	1.85
(H)	AR low-e DG: (Clear 4 mm, AR + SnO_2 4 mm)	0.63	0.78	1.85

These glazing types can be identified where S means single, DG means double glazing, low-e means low emissivity, R means reflective, AR means anti-reflective, and the air gap in the DG unit is 12mm. The results for blocking of direct solar radiation show that the west facing window has a greater temperature reduction. Therefore, compared to the south orientation, there is more benefit for cooling energy reduction. Further, as shown in Fig. 2.38, this potential difference is boosted with an increase in the window/front-wall area ratio.

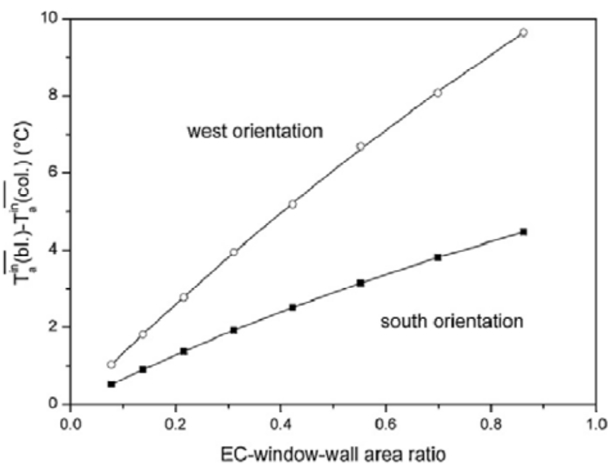


Figure 2.38 Mean differences between the internal air temperatures relative to full bleached and full colored states as a function of window/front-wall ratio (Piccolo, 2010)

Additional analysis shows due to the absorption characteristic of the EC, the average temperature of the EC device (outer pane) is considerably higher than outdoor environment especially in the darkest state. This is used to justify the placement of the EC on the outer pane, which results in rejection of absorbed heat to external environment. Consequently, this could lower the risk of thermal discomfort originating from “radiative exchange between a hot absorbing window surface” and the users (Piccolo, 2010). Figure 2.39 shows the total heat loads that affect the test-cell for both orientations using the different glazing combinations from Table 2.4. At its lowest transmitting state, the EC-DGU has the maximum heat load reduction about 50% for west and 60% for south orientation. Further, the dynamic mode test, where the EC window transmittance is modulated by the controller according to the control strategy, shows a 31% reduction for the south orientation that is similar to a reflective low-e glazing. The percentage of the heat load reduction normalized respect to a clear float glass is also indicated for each glazing.

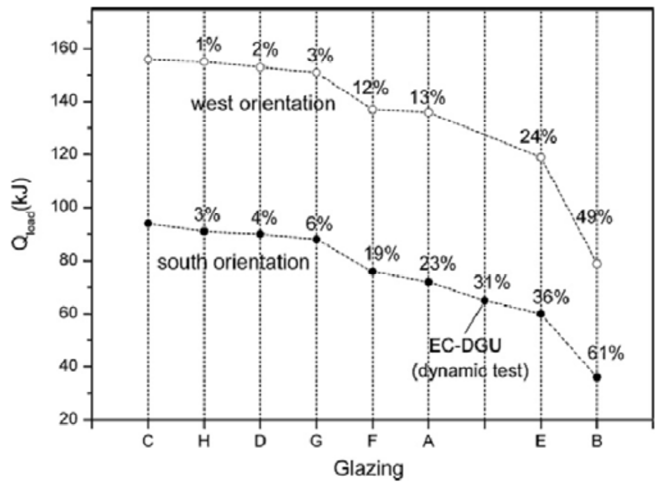


Figure 2.39 Heat loads affecting the test-cell for various glazing (Piccolo, 2010)

In summary, the Piccolo reveals that the analysis of this small scale experimental study, did not consider artificial lighting energy consumption. However, despite the full coloring control strategy which reduces the work plane illuminance associated with increase artificial lighting, or the in-effective blocking of direct-sun that causes glare and need for additional shading devices, the EC smart window could be useful to employ mostly during unoccupied hours.

Johnsson and Roos (2010) investigated the visual and energy performance of EC glazing using antireflective (AR) coatings. Their objective was not figuring out what is the best window configuration, but rather to evaluate ways of improving the performance. The energy calculations were performed for an office and a residential building using simulation tool Winsel for three different climate locations, Stockholm, Denver, and Miami. With the use of presence detection control system, an energy optimization strategy was set up where the glazing is kept in state most optimum from a heating and cooling perspective, ignoring the need for artificial lighting. Thus, whenever there is a need for cooling, windows are kept in high tint mode, while for heating they become highly transparent. Table 2.5 shows the five various configurations used in the simulations. The research found that use of AR coatings in switchable windows during clear state increases the light transmission which is very important for acceptance of this type of glazing. In terms of energy balance, the office building showed less difference in performance between the AR coated EC window and the non-coated version compared to the residential building. The study did not consider any cost implications but acknowledged that although EC technology is currently too expensive in the market, it can play a significant role in the reduction of air-conditioning.

Table 2.5 Optical and energy related parameters for the window glazing simulated (Jonsson and Roos, 2010)

Window	Short name	EC coating	T_{sol} (%)	R_{sol} (%)	A_{sol} (%)	T_{vis} (%)	R_{vis} (%)	U (W/m^{2}K)	g-Value
Low-e EC combination	EC	Light	49	15	36	63	19	1.6	0.59
		Dark	9	11	80	10	11	1.6	0.16
Low-e EC + 2 AR coatings	AR	Light	54	12	34	71	12	1.6	0.63
		Dark	10	11	79	11	11	1.6	0.17
Low-e reference	LE	No	60	15	25	75	17	1.6	0.72
Solar control reference	SC	No	34	41	25	63	25	1.3	0.38
Double pane reference	DG	No	69	13	18	80	15	2.8	0.75

2.6.2 Studies on BIPV

Gan and Riffat (2001) use field measurements and computational fluid dynamic (CFD) modeling to evaluate the thermal performance of a PV integrated atrium, seen in Fig. 2.40. The aim through their study was to test the effectiveness of ventilation strategies for cooling the PV arrays of an existing atrium roof to avoid overheating and increase the efficiency. Further, the air quality of space below is monitored for comfort. The results of the measurements identified several key variants. The radiation exposure was higher in the slightly pitched roof pitch than a horizontal plane. The PV temperature decreased with increasing ventilation, and increased with increasing external air temperature and solar radiation. In addition, the temperature was higher than that of a bare glass roof. These findings were used as boundaries for the simulation. Even further modeling tests were done to explore effects due to opening location and size, ventilation rate, and heat flux. The work demonstrates that applying cool external air from an opening close to roof would cool the PV arrays effectively and maintain a desirable thermal comfort level for occupants. However, since the external flow of air from only one inlet to the space, to guarantee good performance of cooling the arrays, the design of the inlet opening must be "a forced supply outlet under the roof" (Gan and Riffat, 2001).

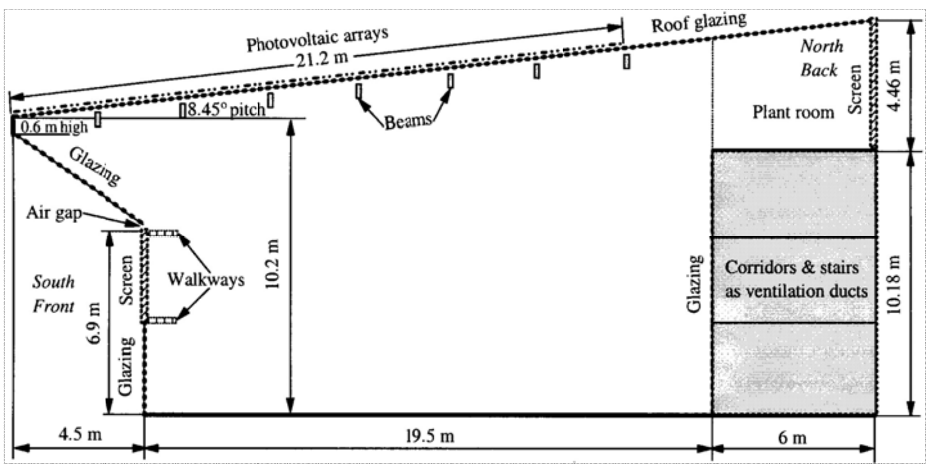


Figure 2.40 Schematic diagram of the atrium (Gan and Riffat, 2001)

Jardine et al. (2001) compared eleven PV technologies in two locations in northern and southern Europe shown in Table 2.5. The PV arrays in UK produced 60% of the energy of those in Mallorca. Figure 2.41 shows the difference in average daily power output. The best performance of arrays in UK is during summer when days are longer due to high latitudes. The a-Si modules outperformed other technologies in terms of specific yield. For example, they have a linear response to insolation compared to c-Si modules that have an S-shaped profile and show efficiency drop-off at high insolations. The a-Si is less susceptible to high temperatures at intense light levels, and performs more efficiently under overcast low insolation conditions. Figure 2.42 shows that since the low powers are produced at low insolations, the majority of power is produced at insolation between 500 and 900 W/m^2. On the other hand, the CIS modules showed improvement at low operating temperatures combined with low light level performance, thus making them the best yielding technology in UK.

Table 2.6 Normalized power outputs from the Mallorcan and the UK arrays (Jardine et al., 2001)

Sub-array		kWh/kWp Mallorca (h)	kWh/kWp UK (h)	%
Unisolar US64	a-Si	1429	838.6	58
ASE 30 DG-UT	a-Si	1706	968.8	56
Solarex Millennia	a-Si	1555	904.1	58
Intersolar Gold	a-Si	937	479.2	51
Evergreen	mc-Si	1265	841.4	66
Astropower	mc-Si	1036	736.3	71
Solarex MSX 64	mc-Si	1201	765.9	63
ASE 300 DG UT	mc-Si	1352	784.7	58
BP Solar 585	sc-Si	1341	773.8	58
Siemens ST40	CIS	1590	1003.9	63
BP Solar Apollo	CdTe	1007	558.8	56

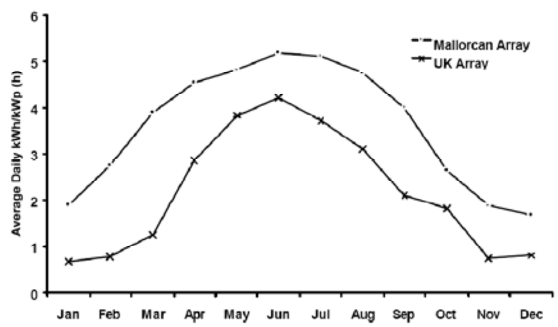


Figure 2.41 Average daily kWh/kWp of the UK and Mallorcan Arrays (Jardine et al. 2001)

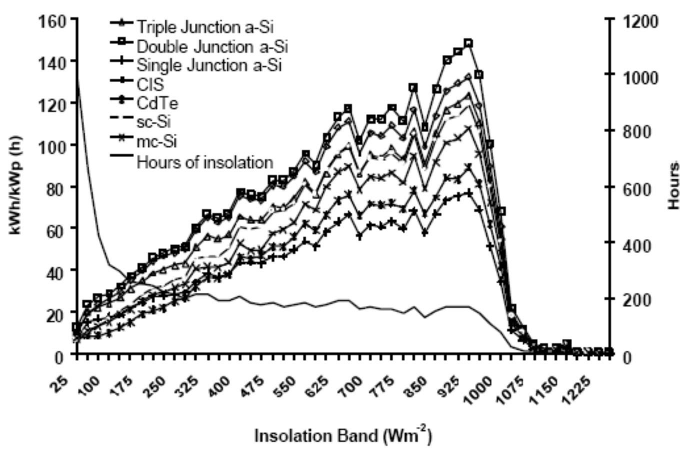


Figure 2.42 Variation of energy output with insolation for representative sub-arrays (Jardine et al., 2001)

Maurus et al. (2003) discussed various BIPV installations with particular focus on the latest thin film technology. There is an energy yield distinction between amorphous silicon (a-Si) and crystalline silicon (c-Si). The a-Si modules show only a minor power output reduction at higher temperatures and lower light intensities than other PV technologies. They claim that based on conducted studies (Jardine, 2002), a-Si modules produced an average 22% and 17% in Mediterranean and UK climate respectively, compared to c-Si. Figure 2.43 shows the power output monitored for over nine years. The reduction caused by light-induced degradation known as Staebler-Wronkski effect, reaches a photo-stabilized value after one year exposure in European outdoors (Maurus et al., 2003).

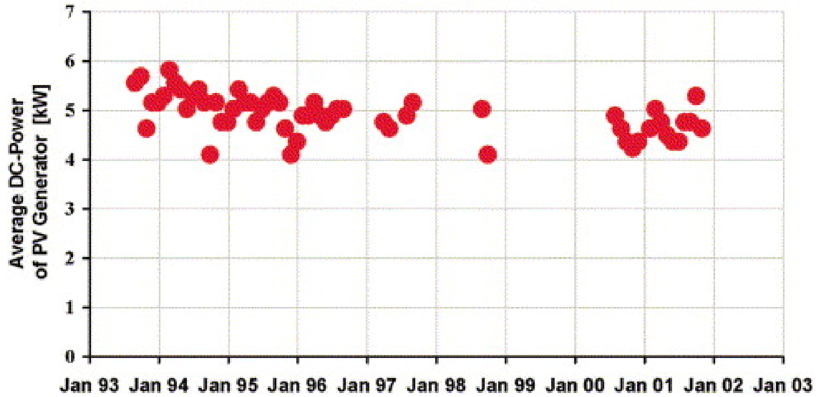


Figure 2.43 Power output of the façade of Bavarian Ministry of Environmental Protection (Maurus et al., 2003)

Although, the percentage of optical transmission reduces the efficiency of semitransparent a-Si modules, there are other advantages particularly for buildings with low power requirements. For example, a double-glazed unit integrated with semitransparent a-Si module can reduce the total energy transmittance (g-value) to 10%, not achievable from conventional shading systems like venetian blinds. Moreover, the U-value is comparable to conventional double-glazed unit normally 1.2W/m^{2}K. When it comes to the architecture, the conventional methods of laminating techniques or mounting procedures for incorporating the a-Si modules offer a high level of design flexibility. Hence the application lends itself to various building elements from façade to window and doors. In addition to power output, the façade of the building in Fig. 2.44 built with a-Si double-glazing unit provides thermal insulation, interior shade, and glare protection.

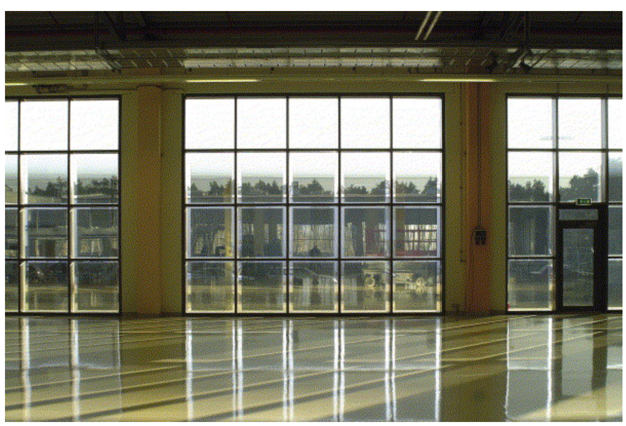


Figure 2.44 South façade of RWE SCHOTT solar production facility in Alzenau (Maurus et al., 2003)

Mallick et al. (2005) analyzed the difference between a non-concentrating and an asymmetric compound parabolic photovoltaic concentrator (ACPPVC). An advantage of concentration of solar energy is that it increases the illuminated flux on PV surface and therefore it reduces the need for expensive PV material. As Fig. 2.45 shows, in this outdoor experimental characterization at University of Ulster's Center for Sustainable Technologies, both systems have the same number of PV cells connected in series in each system. Their study concluded that even though the non-concentrating PV panel has a lower power output per unit area of PV, it has a higher efficiency compared to the ACPPVC. It was found that the solar to electrical conversion efficiency of 8.6% and 6.8% was achieved for the non-concentrating panel the concentrating system, respectively (Mallick et al., 2005).

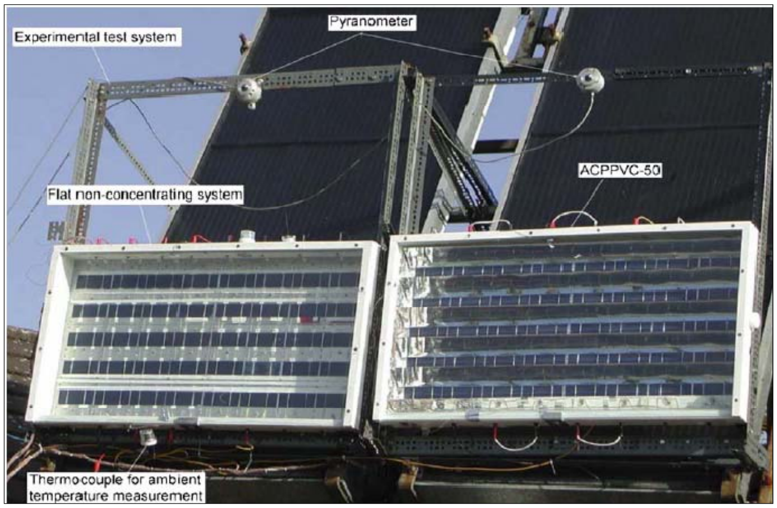


Figure 2.45 Non-concentrating and ACPPVC (Mallick et al., 2005)

Clark et al. (2008) explored the effects of shading on BIPV. Usually PV modules produce electricity in forward bias by connection of a several cells in a row. However, slight shading of an array can reverse this. Consequently, the dissipation of heat from unshaded to shaded cells causes uneven voltage and the failure of the cells (Kovach and Schmid, 1996). The two causes of shading PV façade are urban features, like trees and buildings, and protruding bay windows running alongside of PV array as seen in Fig. 2.46. The study presents two models that integrate the effects of shading by these two causes. In this study, two models, the integrated slope irradiation model (ISRM) and sky radian distribution model (SRDM), were validated by collected data. In conclusion, the SRDM model is the preferred alternative. Unlike the ISRM model that can only fit simple shading geometries, it takes into account the "sky-diffuse component of solar radiation," computing the size of sky blockages through mapping of the horizon for each PV panel, thus resulting in a more accurate prediction (Clark et al., 2008).

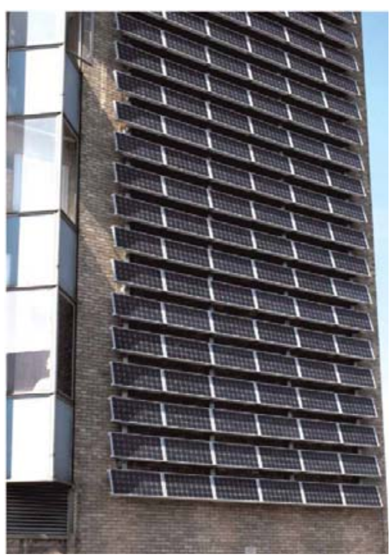


Figure 2.46 Bay windows casting shadows across the façade (Clarke et al., 2008)

Chaar et al. (2008) discusses the effects of wind-blown sand and dust on PV arrays in the UAE. Despite the good sunshine conditions in UAE, Chaar highlights the other climatic conditions such as high temperatures and occasional strong winds that cause perpetual sandstorm. Because these factors tend to produce different results than performing laboratory testing, hence the application of PV arrays must be studied for its feasibility in such extreme environment. In this environment, the effects of wind borne particles are categorized depending on its lasting disturbance. Temporary instabilities include dust or sand deposited on the PV array, and in case of rainfall, a "caked surface" clouding the surface. On the other hand, permanent disturbances are damages from large particles in sandstorm that break the fragile glass surface.

Chaar further discussed the theory of "weakest link" where just a single cell can cause degrading effect for overall module efficiency. For example, the shading of a single cell, not only stops its power output, but also behaves as a high resistor and "tends to be reverse biased by other cells" (Chaar et al., 2008). Figure 2.47 shows this effect on a module made of 36 mono-crystalline, all of which are completely under direct sun except for one cells that is 75% under shade.

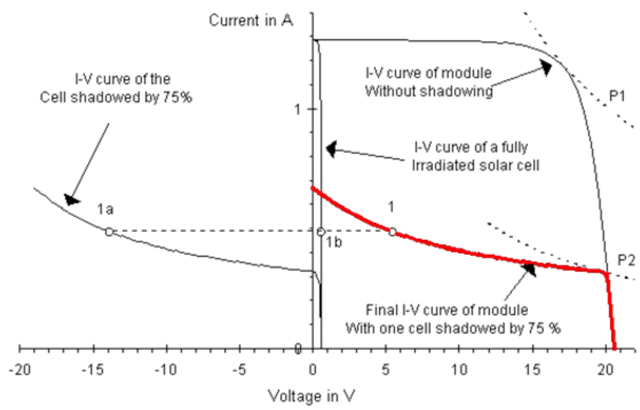


Figure 2.47 I-V curve of module with one cell shadowed by 75% (Chaar et al., 2008)

Other influencing factors that influence PV array performance are temperature. The peak temperature of the day occurs when light intensity is at maximum. This reduces the power output potential of the PV panel. As shown in Fig. 2.48, substantial reductions in PV output are associated with temperature rises particularly when reaching the peak mark of 40˚C for the site tested here.

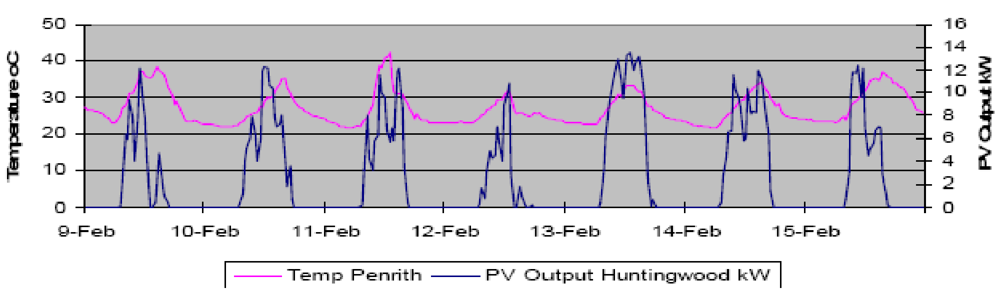


Figure 2.48 Effect of temperature on power output of PV array (Chaar et al., 2008)

Chaar and Lamont (2009) analyzed solar radiation for five different sites in Abu Dhabi to study the potential of PV application technology in this region. The results of their data which was collected over a period of three years showed high measurement of global horizontal irradiation (GHI) particularly in summer. In addition, the daylight hours shown in Table 2.7, and the daily, monthly and annual clearness index were calculated to investigate the frequency of cloudy days. With a high average of 82% clear days in one year, seen in Fig. 2.49, the study showed that the pursuit of solar energy and PV in particular in Abu Dhabi has a bright future.

Table 2.7 Average daylight hours in Abu Dhabi (Chaar and Lamont, 2009)

Month	Average daylight hours
January	10.6878
February	11.20107
March	11.88231
April	12.59827
May	13.19577
June	13.47368
July	13.33593
August	12.82337
September	12.10818
October	11.39402
November	10.80012
December	10.53767

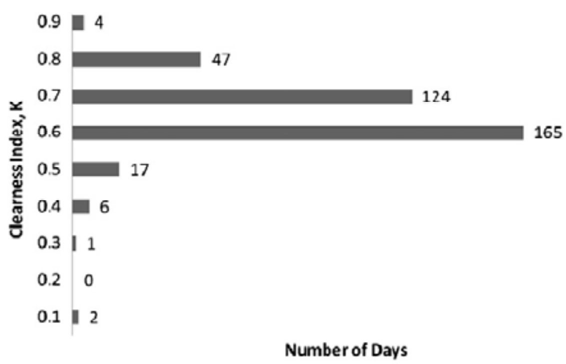


Figure 2.49 Graphical representation of the frequency of daily clearness index (Chaar and Lamont, 2009)

Yalcintas and Kaya (2009) study makes a comparison between energy conservation, which reduces energy demand versus renewable energy through PV that reduces dependency on fossil fuels. Their work analyzes four cases studies in Hawaii and argues that before installation of PV or any other renewable resource, retrofitting of inefficient building equipment is a better method for achieving energy efficiency. Figure 2.50 shows how a reduction in chiller power is observed before and after the retrofit.

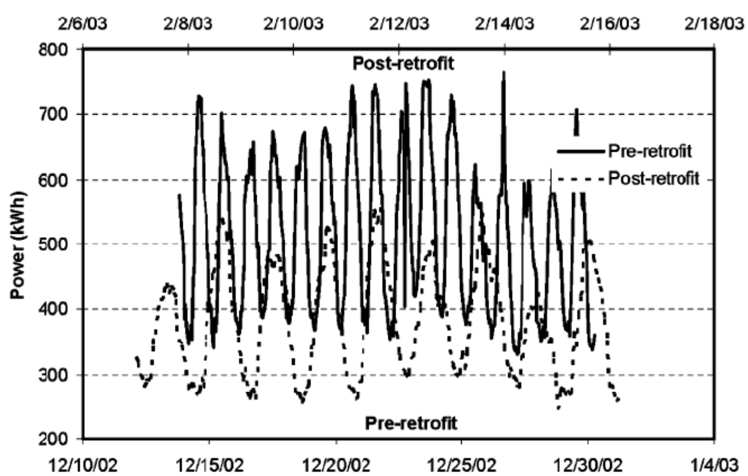


Figure 2.50 Pre- and post-retrofit period chiller power monitoring (Yalcintas and Kaya, 2009)

The study suggests that even though payback periods might be very long in some cases, renewable energy has environmental benefits and “incentives are necessary for long-term objectives” (Yalcintas and Kaya, 2009).

2.6.3 Studies on EC Glazing and BIPV

Nabil and Mardaljevic (2008) assessed the potential energy benefits of façade photovoltaics and EC glazing in non-domestic buildings. With the aid of computer simulation models, this study examined 56 combinations of four orientations and fourteen climatic conditions, using a fixed proportion of façade. In fact, the comparative assessment evaluated the benefits based on common measure of per meter width of façade. The building model is illustrated in Fig. 2.51. In the base-case, a typical perimeter office with clear double-glazing, venetian blinds are used with lights that have an on/off switch to provide 500 lux. Although clear glazing is not appropriate for regions with high sun intensities, an earlier study (Nabil and Mardaljevic, 2005) discovered that when combined with blinds, clear glazing has lower electrical lighting energy demand than medium or dark tint glazing. In the advance glazing case, EC glazing replaces the standard and a dimming control responding to daylight fluctuations provides necessary artificial light to supplement available daylight to reach 500lux. Finally, in the PV case, the façade’s opaque spandrel section is modeled as a BIPV array.

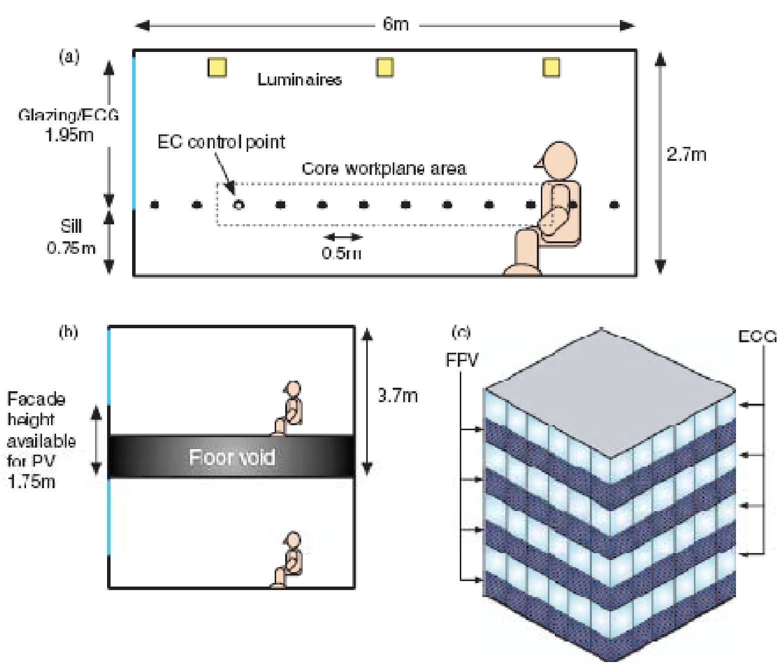


Figure 2.51 Building model and design variants (Nabil and Mardaljevic, 2008)

The operation of blinds in the base-case would be triggered by automatic sensors determining daylight levels going above 2000lux. And whenever illuminance levels are below this value, the blinds would be retracted. Although this automated control does not match accurate human behavior, it will primarily be used as a comparison benchmark. This comfort limit is used by Nabil and Mardaljevic (2005) in creation of a new daylight design paradigm entitled “useful daylight illuminance.” The sensor location for the EC case was placed at 1.25 m away from the window.

This control strategy was chosen because previous studies using sensors in the middle or back of the room showed high illuminance levels creating uncomfortable conditions for the front occupants. The PV arrays were assumed to be naturally cooled, hence dissipating all the heat to the ambient environment.

Figure 2.52 shows that the PV energy benefit has a direct linear relation to the vertical total annual irradiation (VTAI). More importantly, the results indicate that for most of the facades with VTAI levels below 1000kWh/m^2, the energy saved by using EC glazing is higher than energy output from the PV. In fact, only in few instances the façade PV exceeded the EC glazing in energy benefits. The study further calculated the energy benefit derived from application of either technology on more than one façade using an incremental additive approach. It was found that deployment of either technology is most advantageous on one façade alone, with the EC glazing being more beneficial across all four facades in saving energy.

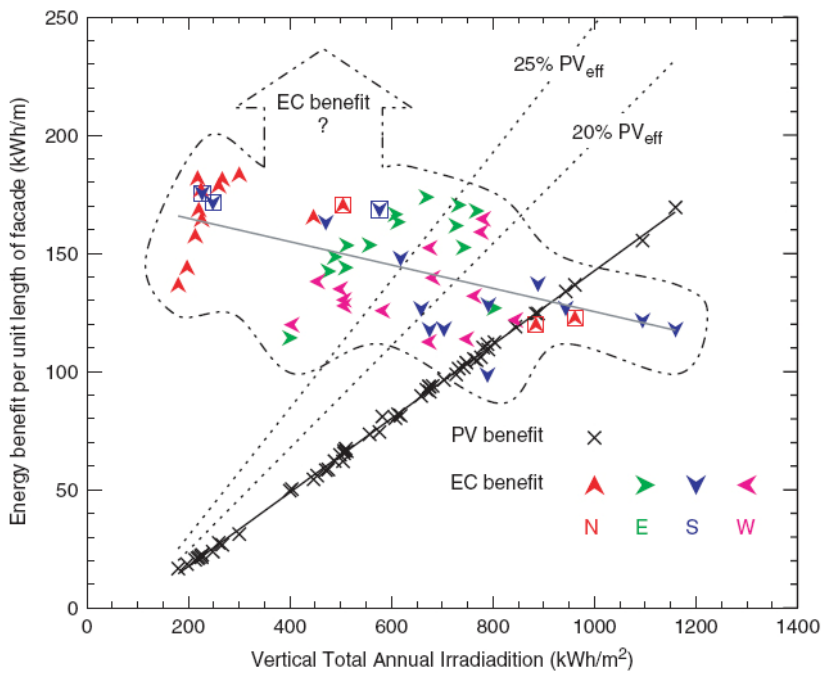


Figure 2.52 Energy benefit from ECs and façade PVs (Nabil and Mardaljevic, 2008)

In response to their study, and in the same published article, Reinhardt suggests that the occupant behavior which has great influence on the electric light usage be taken into account. He claims that EC glazing benefits can vary given this uncertainty, whilst PV power output is not occupant dependent and “guaranteed.” Moreover, EC glazing without glare control from additional shading devices are usually not accepted by private offices users (Clear et al., 2006). It is found that EC glazing offer the best energy savings in areas at lower end of the experienced range in VTAI and ,therefore, they are “better suited to less sunny climates” (Nabil and Mardaljevic, 2008).

2.7 ABU DHABI-UAE: GEOGRAPHY AND CLIMATE

As the capital of the UAE, Abu Dhabi is also the largest of the other six emirates (Dubai, Sharjah, Ajaman, Ras Al Khaima, Um Al Quwain, Fujairah) seen in Fig. 2.53 that form the country. This emirate includes major cities including Abu Dhabi capital city, Al-Ain, Liwa, Al-Ruwais. It is known for its vast oil reserves accounting for the high GDP per capita income. Geographically located at 24˚28'0'' North and 54˚22'0"East, it straddles the tropic of cancer on north-eastern part of the Gulf shown in Fig. 2.54. The hot arid climate means that the temperatures vary from warm in winter to hot in summer. Most of Abu Dhabi is on an island with some suburbs on the main land. The highest point is in garden city of Al-Ain which rises about 1,340m. Only 30% of the emirate is inhabited, with desert and arid land covering the remaining vast expanses.

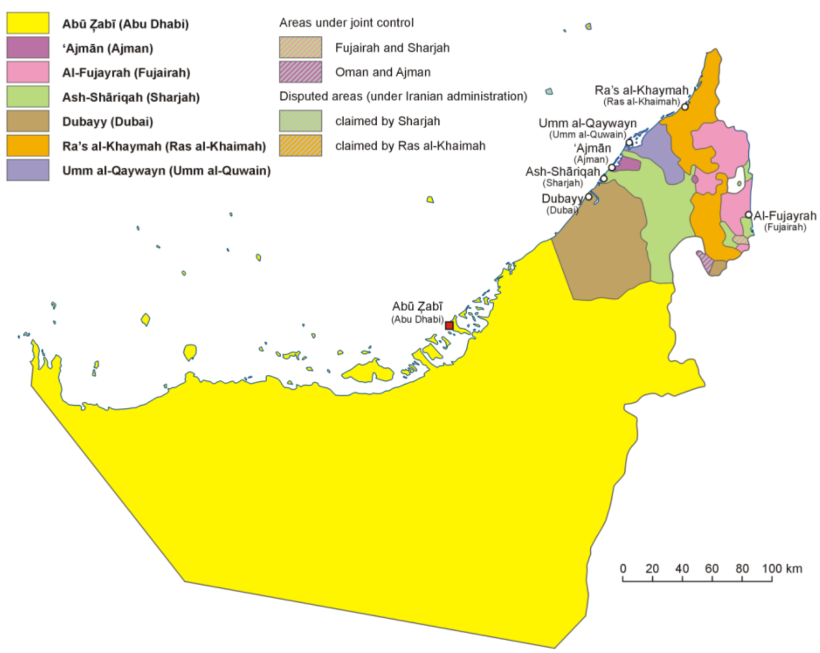


Figure 2.53 Emirates of the UAE (Wikipedia, 2010)

Figure 2.54 Map of the UAE (Google Earth, 2010)

The data in this section is extracted mainly from IES Virtual Environment weather database.

Temperature

Figure 2.55 shows the fluctuations of temperature throughout the year. The peak temperatures occur in July and August reaching over 45˚C on several occasions. The temperature between the months of May and September (summer) can be unbearably high with an average daily high of 40˚C and average daily low of 26˚C. In the winter months, from December to February, the temperatures can drop as low as 10˚C, but are mainly around the comfort zones of 25˚C.

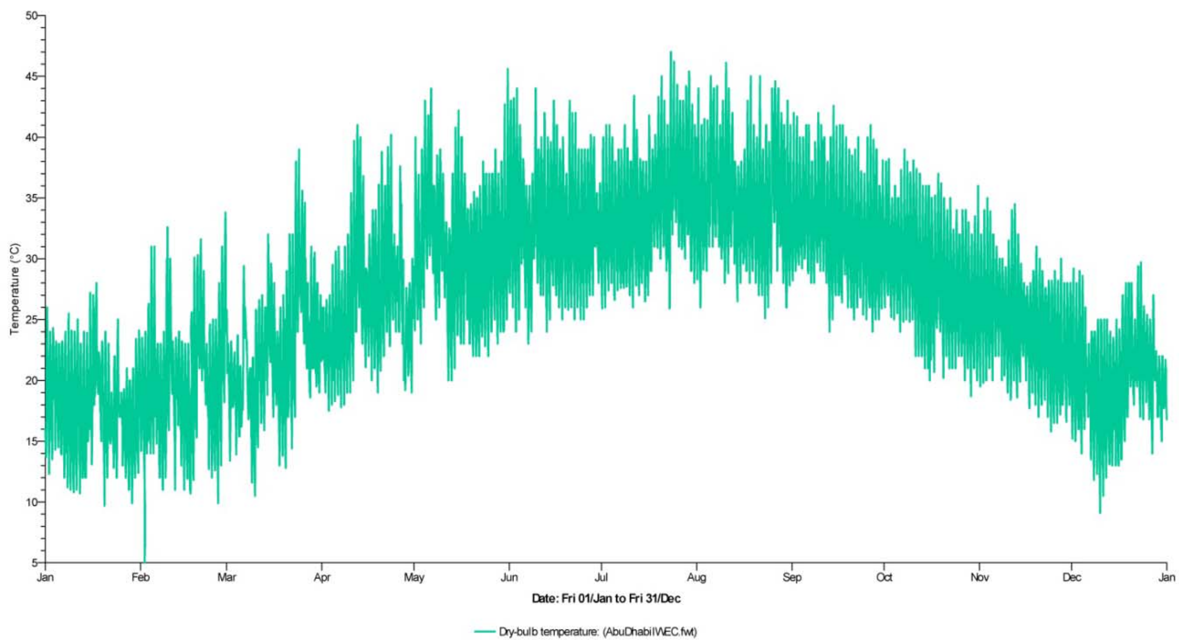


Figure 2.55 Abu Dhabi Annual Temperature (IES-VE Database)

Precipitation

Rainfalls is almost non-existent in the UAE. However, when it occurs, they are in the form of heavy sudden bursts lasting only a few hours leaving streets and even some highways flooded. Table 2.8 shows the statistical data from World Meteorological Organization for Abu Dhabi. The average number of rainy days is only about 12 days in a total year. The average yearly rainfall is about 90mm which happens mostly in February and March.

Table 2.8 Abu Dhabi Climatological Information* (World Meteorological Organization, 2010)

Month	Mean Temperature °C		Mean Total Rainfall (mm)	Mean Number of Rain Days
	Daily Minimum	Daily Maximum		
Jan	11.8	23.8	3.9	0.8
Feb	13.2	24.6	42.0	3.5
Mar	15.8	28.6	24.8	3.9
Apr	19.1	33.4	7.3	1.4
May	22.8	38.4	Trace	0.0
Jun	24.8	39.6	0.0	0.0
Jul	27.6	42.0	Trace	0.0
Aug	28.7	41.5	0.1	0.1
Sep	25.6	40.1	Trace	0.0
Oct	21.8	35.8	0.0	0.0
Nov	17.5	30.6	1.8	0.2
Dec	14.1	25.7	9.0	2.1

*Remarks:

- Climatological information is based on WMO Climatological Normals for the 10-year period 1982-1991
- Mean number of rain days = Mean number of days with at least 0.2 mm of rain
- Trace = Mean total rainfall less than 0

Relative humidity

The highest levels of humidity are in the winter months. Figure 2.56 shows that on many occasions, the humidity reaches level of 100%. Al-Ain has one of the lowest levels of humidity. Hence, the dry desert air and cooler evenings make it a popular retreat from the intense summer heat and year round humidity of the capital city (Wikipedia, 2010).

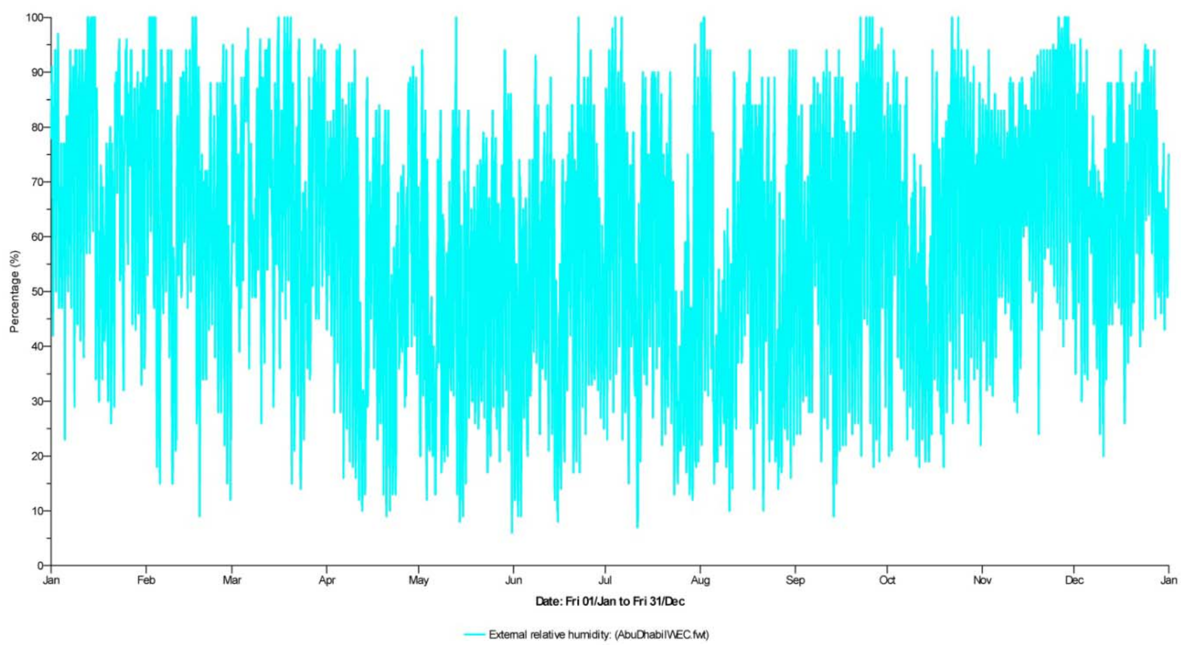


Figure 2.56 Abu Dhabi Annual Humidity (IES-VE Database)

Solar radiation

Figure 2.57 indicates that the direct solar radiation is high throughout the year. A record maximum level occurs on February 9th at 1pm and it reaches up to 967W/m^2. Table 2.9 shows that over 25% of the total hours in year have direct solar radiations above 600W/ m^2. Further, as shown in Table 2.10, the maximum occurrence of radiation profiles is within the 800-900 range, hence validating the high percentage of solar irradiances in this region. Generally as seen in Fig. 2.54, summer months have lower values of diffused solar radiation compared to periods from February to April. Figure 2.55 shows that the maximum number of clear skies is found in summer months, particularly from mid May to late July.

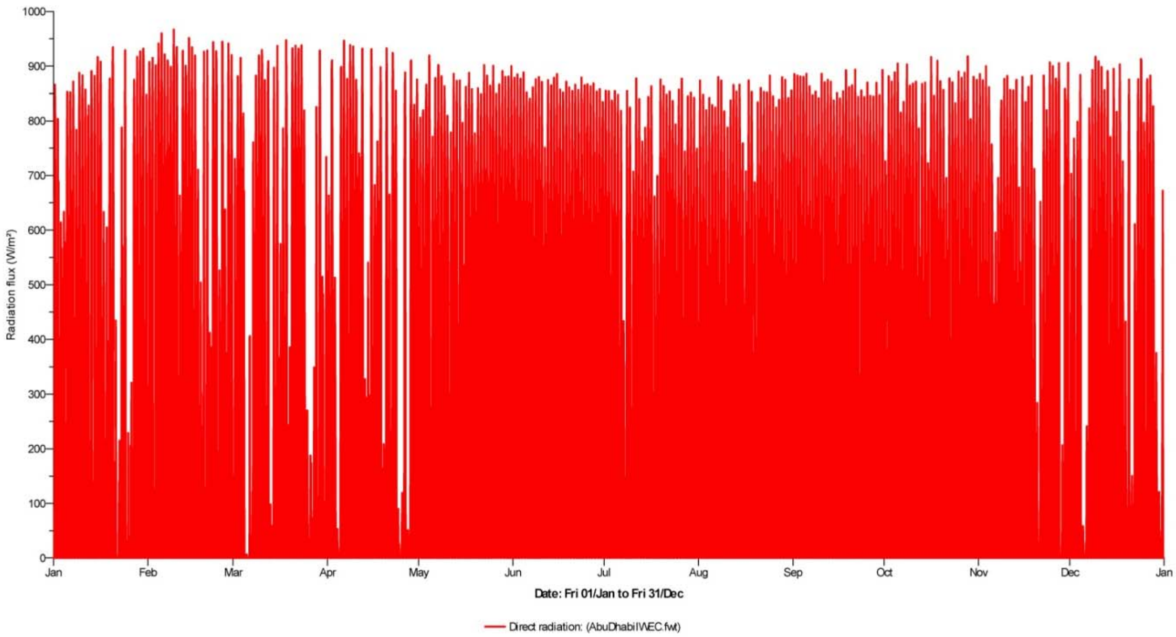


Figure 2.57 Abu Dhabi Annual Direct Solar Radiation (IES-VE Database)

Table 2.9 Annual Solar Radiation Range Percentages

Direct Radiation (W/m2)	Total Hours	Percentage
>900	162	2%
>800	1135	13%
>700	1723	20%
>600	**2207**	**25%**
>500	2498	29%
>400	2829	32%
>300	3116	36%
>200	3344	38%
>100	3831	44%
>0	8760	100%

Table 2.10 Annual Solar Radiation Range Percentages

Direct Radiation (W/m2)	Hours in Range	Percentage
>1000	0	0%
900 – 1000	156	2%
800 – 900	**976**	**11%**
700 – 800	588	7%
600 – 700	484	6%
500 – 600	292	3%
400 – 500	331	4%
300 – 400	289	3%
200 – 300	225	3%
100 – 200	486	6%
0 – 100	4933	56%
0 – 1000	8760	100%

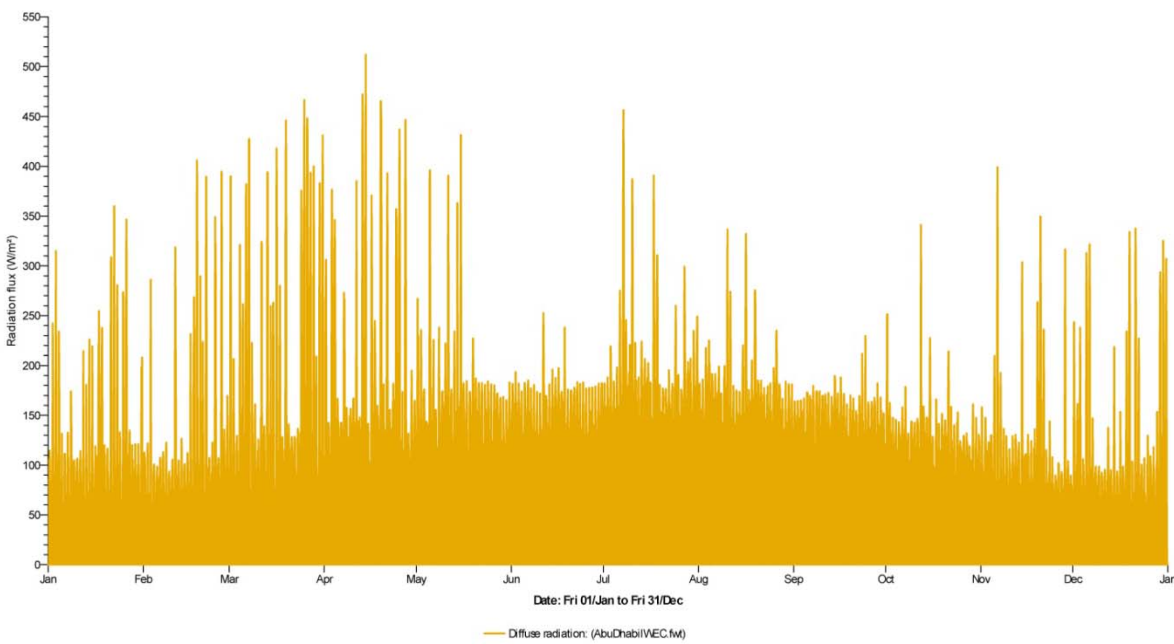


Figure 2.58 Abu Dhabi Annual Diffused Solar Radiation (IES-VE Database)

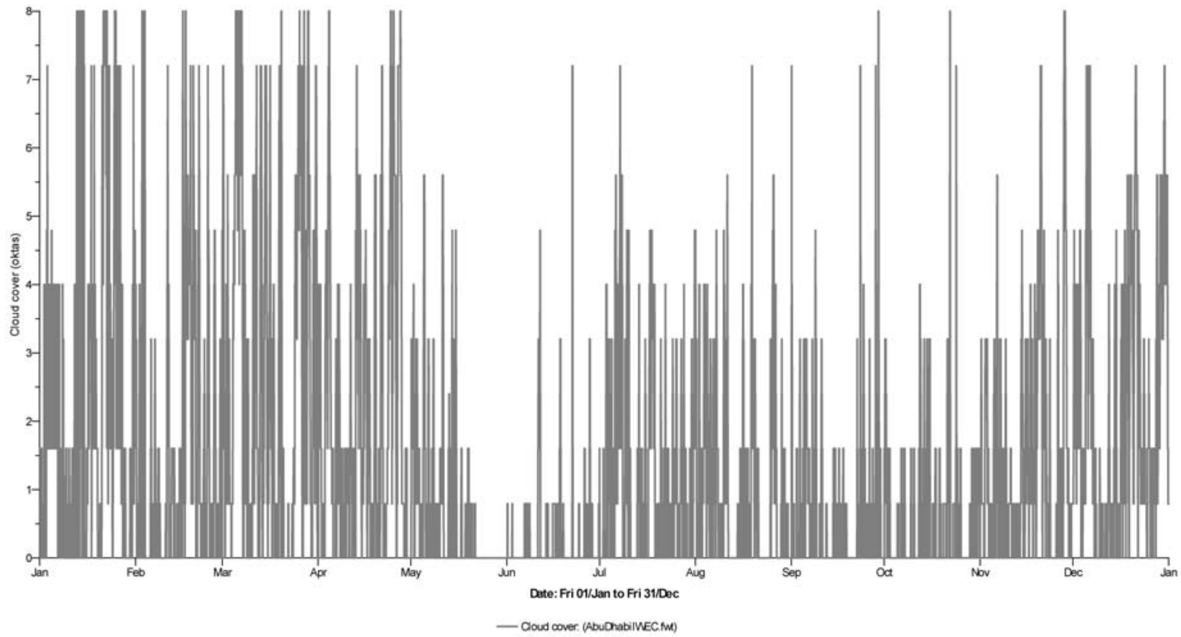


Figure 2.59 Abu Dhabi Annual Cloud Cover (IES-VE Database)

Wind speed and direction

The prevailing wind is from the North West direction with an average speed between 2 to 6 m/s. As shown in Fig. 2.56, a maximum wind speed of 24 m/s was recorded in January.

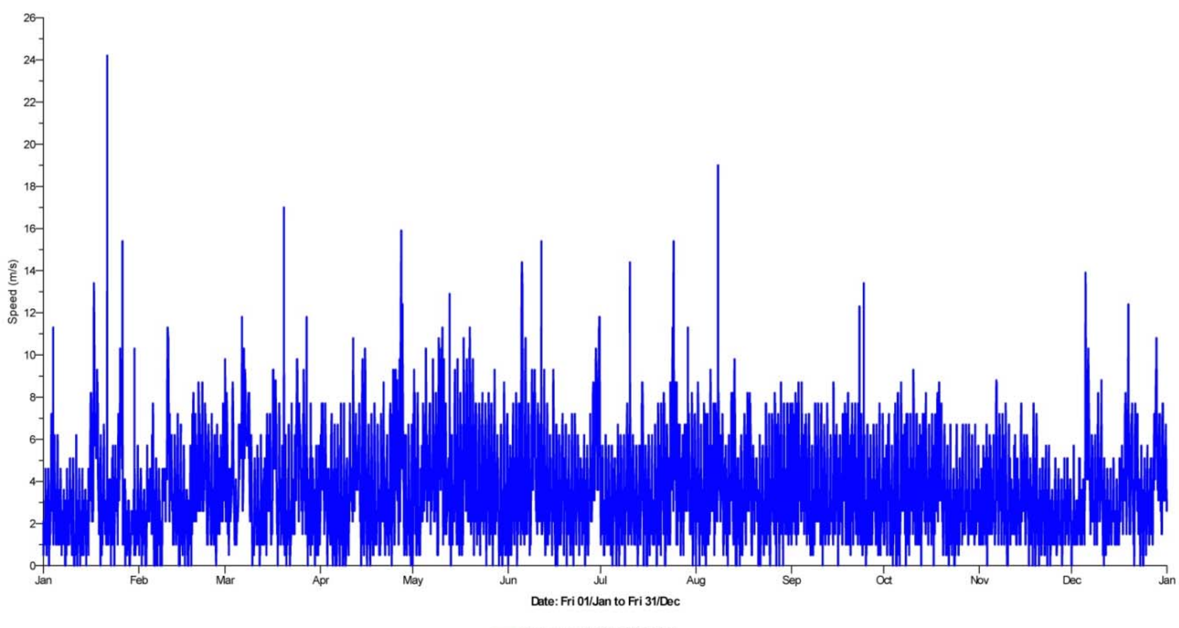


Figure 2.60 Abu Dhabi Annual Wind Speeds (IES-VE Database)

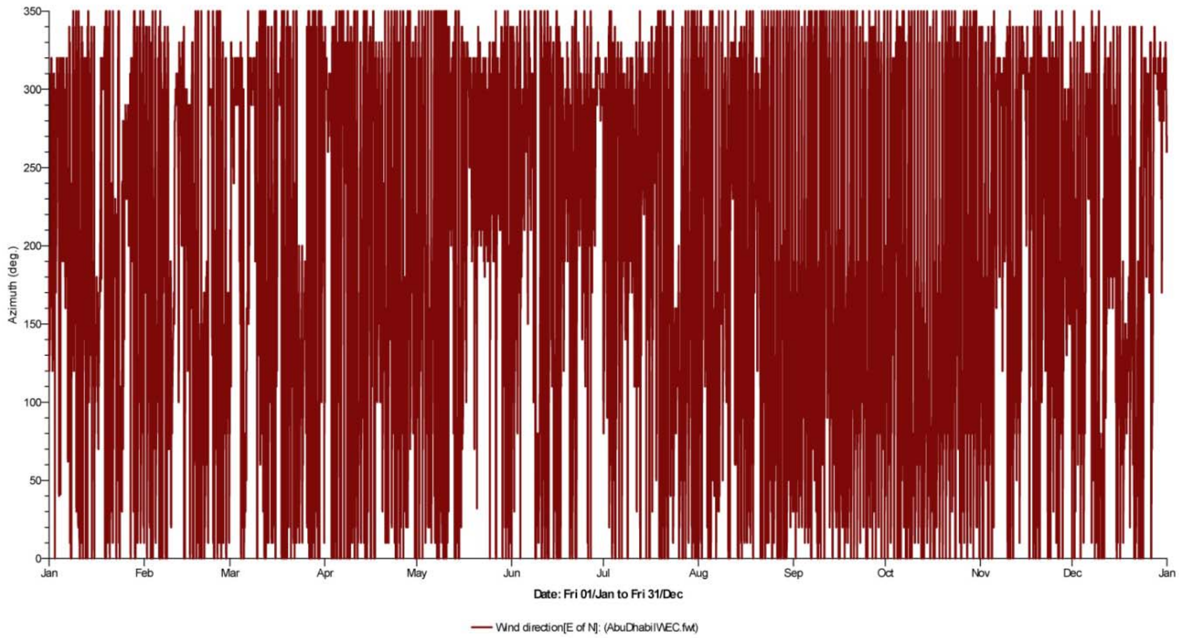


Figure 2.61 Abu Dhabi Annual Wind Directions (IES-VE Database)

2.8 AIMS & OBJECTIVES

The research aims to compare benefits in terms of overall building energy use that can be expected from adopting two alternative façade technologies. In order to make the study more focused, office buildings are taken as the only building typology under consideration, as they are "the largest energy consumers in the buildings sector" (McCarthy 1997). An assessment will be made of the energy benefits that might arise from installing EC glazing or BIPV instead of conventional glass across the vertical façade. The energy benefit of EC glazing will be quantified in terms of its capability to reduce the total energy consumption (from electrical lighting plus building system like HVAC) on an annual basis through providing controlled day-lit environment when compared to standard glazing with blinds. In the case of the BIPV, the study will estimate energy balance through the energy consumed for lighting and HVAC, PV energy that can be generated on site, and the resulting energy equilibrium on daily, monthly, and annual basis. An economic analysis will be conducted to evaluate the financial viability of the proposed designs.

The objective of the research is to recognize the benefits of each system according to various parameters. These can include façade orientation, concerned area of façade that the system is applied on, varying weather conditions (i.e. clear sky, overcast, etc), and possibly further exploration of these parameter in different geographical location to compare with Abu Dhabi.

The research will comprise of two parts, technical and economical, and answer the following to meet its objective.

1. What is the expected advantage that might be expected from each technology particularly in terms of energy reductions?

2. What is the effect of façade orientation on the predicted energy reductions?
3. What is the predicted energy benefit if the technology was applied across more than one façade?
4. How much does the local climate impact the effectiveness of each technology?
5. What can be done to make the study comparative to this region particularly in the UAE?
6. Which technology is more cost competitive and feasible to deploy? (Economic Analysis: Initial Investment vs. Savings)

CHAPTER 3: RESEARCH METHODOLOGY

3.1 RESEARCH PARAMETERS

The previous chapter looked at how alternative facades can optimize control over sun and shade to help save energy, improve the economic efficiency of the building and create a more pleasant, healthier place to live and work. The evaluation in this study shall consider very closely the advantages and disadvantages of introducing of each system on the building facade.

It is imperative to use a common measuring system in order to compare the potential energy benefit from the two technologies. Accordingly, a basic office room model will be created to form the benchmark for comparison. Through the manipulation of certain variables, the efficiency of each system from various configurations will be analyzed. The energy benefits of both EC glazing and BIPV will be based primarily on energy consumption values.

The following are the main variables that will be tested and will define the final simulation results:

Orientation

The study will examine the effect of orientation on the energy benefit by studying the four façades. This will enable the research to make a distinction about which orientation is most suitable for each technology.

Office Timings

It is vital that the research accurately depicts the building's occupancy timing. The typical office timing will be considered from 8am to 6pm, and on a five-day working week starting from Sunday through Thursday. This means that the electrical lighting demand will only be modeled during this period. Although this will limit the energy potential efficiency of EC glazing to the hours of operation, this does not affect the PV total output. The electrical output from the PV will be independent of the working hours, and instead based on total annual hours of irradiation for that particular location. Thus, by manipulating the office timings, the research aims to find whether the outcomes will be differently favored for either system.

Light sensors

The software allows only one sensor in each room. This sensor will be used to measure available daylight in each room and is coupled with the luminaires to provide artificial lighting to achieve adequate light levels at working plane. The light sensor in the room will be tested in three different positions, the front near the window, the middle and back of the room.

Blind Characteristics

This study will use Venetian blinds, the shading device commonly used in offices, for the base case model. The daylight illuminance will be the control variable for the operation of the blind, which will be either fully open or closed. The percentage of the blind's visual transparency and the percentage of diffused direct light transmission will be manipulated. The results of these configurations will determine which is the most optimum for energy efficiency.

Glass Shading Coefficient (SC)

The total solar heat transmission is dependent on the SC. Consequently, variations in the SC will impact the levels of day light and influence the need for artificial lighting. Further, this affects the total cooling load for the space. Therefore, the performance of the facade in each system will be dependent on the glass SC. The EC glazing is a dynamic version of the SC.

BIPV module

The type of BIPV selected will affect the total electricity production (higher output from Monocrystalline cells), the amount of light that is transmitted through the glass (higher transmission for thin films), and ultimately the electrical light energy demand and cooling load. For example, by specifying the number of PV cells to be used and the spacing between each cell, it is possible to control the amount of generated electricity as well as the ambient light entering the room. The selection and configuration will be based on a simulation study which will be explored later in chapter four.

The next Chapter will give a detailed description of the office models along with various arrangements of the above parameters.

3.2 REVIEW OF PREVIOUS RESEARCH METHODOLOGIES

This section discusses the research methodology of other academics that are related to this research topic. The analysis reviews the reason behind the selection of each methodology. This will form as a guide toward the selection of the appropriate option for this study in the next section.

Observational research (Field Monitoring)

Mallick et al. (2005) conducted an outdoor experiment between a non-concentrating and an asymmetric compound parabolic photovoltaic concentrator (ACPPVC) to analyze the difference between each system. Figure 3.1 shows the equipment diagram for characterizing the systems performance. The recording of data was very fast which involved measuring short circuit current, open circuit voltage, instantaneous current and voltage for each system, wind speed, solar radiation and different temperatures. Further, in order to prevent any unwanted shadow on the cells, the thermocouples were attached near the edge of the cells. The research concluded that the electrical conversion efficiency of non-concentrating cells is still higher than ACPPVC.

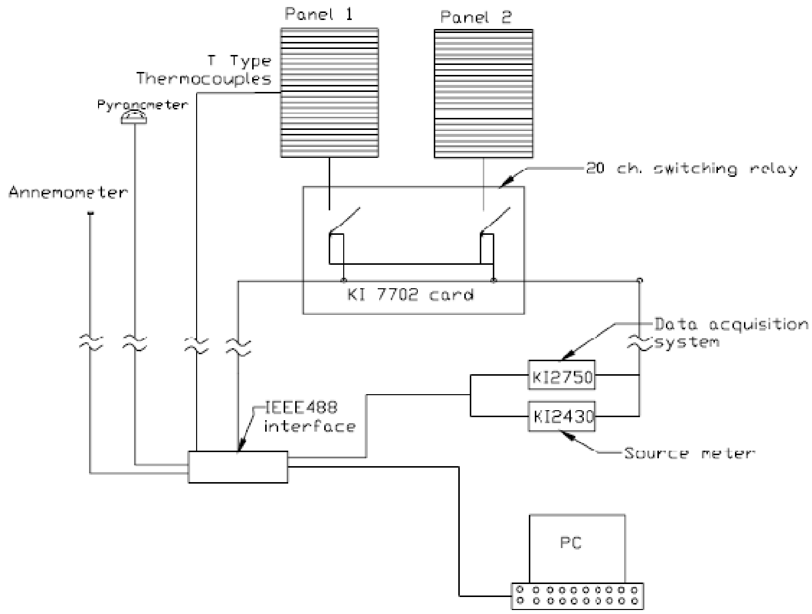


Figure 3.1 Block diagram of equipment used for characterizing PV systems (Mallick et al., 2005)

Yalcintas and Kaya (2009) analyzed various case studies in Hawaii to show that building-equipment retrofitting can be practical and necessary for increasing the buildings' energy efficiency. The study compares benefit from retrofitting and installing PVs by assessing their return on investment. Their research observes energy savings in buildings where actual energy conservation retrofit is implemented. Further, a hypothetical situation was assumed where power produced by installation of PV panels is compared to energy saved by the retrofitting. A cost comparison is then made between each scenario. Table 3.1 shows the comparison of energy consumption before and after building-equipment retrofits for the four Cases. These results show that, even after considering renewable energy tax returns, equipment retrofitting is approximately 50% or more cost-effective than using PV systems.

Table 3.1 Energy savings and cost of retrofitting and installing PV systems* (Yalcintas and Kaya, 2009)

	Energy usage before retrofit (kW)	Energy usage after retrofit (kW)	Energy saving (kW)	Energy saving (%)	Retrofit cost ($)	PV cost without federal and state incentives ($)	Payback period for retrofitting (Years)	Payback period after deducting federal and state incentives (years)
Case study 1	539	388	151	28	1,125,000	7,250,000	4.3	17.3
Case study 2	44	17	27	61	340,000	1,300,000	7.2	9.6
Case study 3	152	96	56	37	420,000	2,690,000	4.3	14
Case study 4	145	70	75	51	90,000	2,020,000	<1	20

*Calculations are based on a $10 perWatt installation cost of PV and $0.20 per kW of electricity, which are the average costs in Honolulu, Hawaii in 2006 through 2008.

One of the most obvious flaws of this approach is that it is specific to a particular region. For example, in the case of Hawaii, it might be less viable to install PVs due to cheap electricity charges, however, it other regions with higher rates, this would be a more suitable alternative. Further, an assumption is made that increasing efficiency will reduce the energy intensity index, or energy consumption per GDP. However, it fails to consider whether people would actually change behavior trends as a result; i.e. a person knowing that their lighting fixture is operating more efficiently might leave it on when otherwise they would have turned it off realizing how much it would cost them. Another disadvantage of this method is that it ignores scenarios for new buildings that already have efficient technologies installed. Hence, this claim can only benefit cases that compare older buildings.

Experimental studies

Piccolo (2009) carried out an experimental test for evaluation of EC windows in relation to solar control in buildings. The study used a test-cell consisting of small area of EC double-glazing unit (EC-DGU). As seen in Fig. 3.2, all the walls except the one holding the glazing have been protected with clear panels. Figure 3.3 illustrates how the test cell is equipped with multiple sensors for monitoring various microclimatic parameters influencing heat transfer with surrounding external environment. Data was collected for 2 months during the summer on the roof of a building under completely clear sky conditions for two main orientations. The collected data was tested against numerical analysis to evaluate the EC-DGU performance in summer cooling load reduction.

Figure 3.2 Test-cell on roof (Piccolo, 2009)

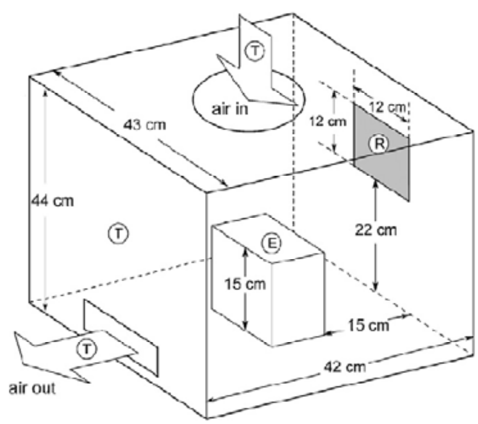


Figure 3.3 Schematic of the test-cell showing sensor locations (Piccolo, 2009)

Chaar and Lamont (2009) investigated climatic conditions in the UAE for implementing PV technology following an experimental approach. They conducted studies over a period of three years in five different locations in the Emirate of Abu Dhabi shown in Table 3.2. They collected hourly, daily, and monthly GHI, and used statistic methods for evaluating the computed GHI during summer period. Furthermore, the annual clearness index were calculated and tabulated to investigate the frequency of cloudy days.

Table 3.2 Geographical locations of the test sites in Abu Dhabi (Chaar and Lamont, 2009)

Site	Latitude North			Longitude East			Altitude
	Degree	Minutes	Seconds	Degree	Minutes	Seconds	Meters
Al Aradh	23	54	10.8	55	29	56.7	178
Madinat Zayed	23	33	39.6	53	42	32.4	137
Sir Bani Yas	24	19	19.2	52	33	43.2	7
Al Raha	24	25	11.0	54	36	46.1	7
Al Mirfa	24	7	19.2	53	26	34.8	6

The studies done by Jardine et al. (2001), and Lee et al. (2006) also used experimental approach to identify the energy benefits of BIPV on the building façade and advantages of using EC glazing respectively.

Simulation studies

Nabil and Mardaljevic (2008) used computer simulation methodology to assess the potential energy benefits of façade photovoltaics and EC glazing in non-domestic buildings. The performance evaluation is based on full year's hourly meteorogical data in fourteen climatic locations. The effectiveness of each system is tested on four different façade orientations. For the EC glazing the energy benefit is measured according to the displaced electric lighting usage against standard glazing with blinds, whilst for the façade PV this is based on the total electrical output from the PV array. The authors worked on a 7-day-occupancy period for the office models. Table 3.3 lists the summary of the evaluation settings of their methodology. This is meant to be used as a comparison tool for understanding which technology offers the most energy benefit given a particular combination of locale and glazing orientation.

Table 3.3 Summary of the evaluation settings

Setting	Blinds/EC operation	Electric lighting	Electric energy use	Energy benefit
Basecase	Lower when E>2000 lux	On/off to 500 lux	Q_B	–
EC	Maintain 2000 lux	Dimming to 500 lux	Q_{EC}	Q_B–Q_{EC}
FPV	–	–	–	Q_{FPV}

Jonsson and Roos (2009) used simulation to evaluate the heating and cooling need of the building in different climatic conditions. They investigated four control mechanisms using EC glazing in combination with other solar glazing. Figure 3.4 shows the schematic of the various window combinations. The objective of their study was to investigate the methods and compare strategies, and not to evaluate the performance of actual products. Instead of performing a complete building simulation, they used a simplified technique based on idea of balance temperature. The window simulation tool Winsel calculates the window's energy contribution to the building, thus eliminating the need to perform calculation for the building's total consumption.

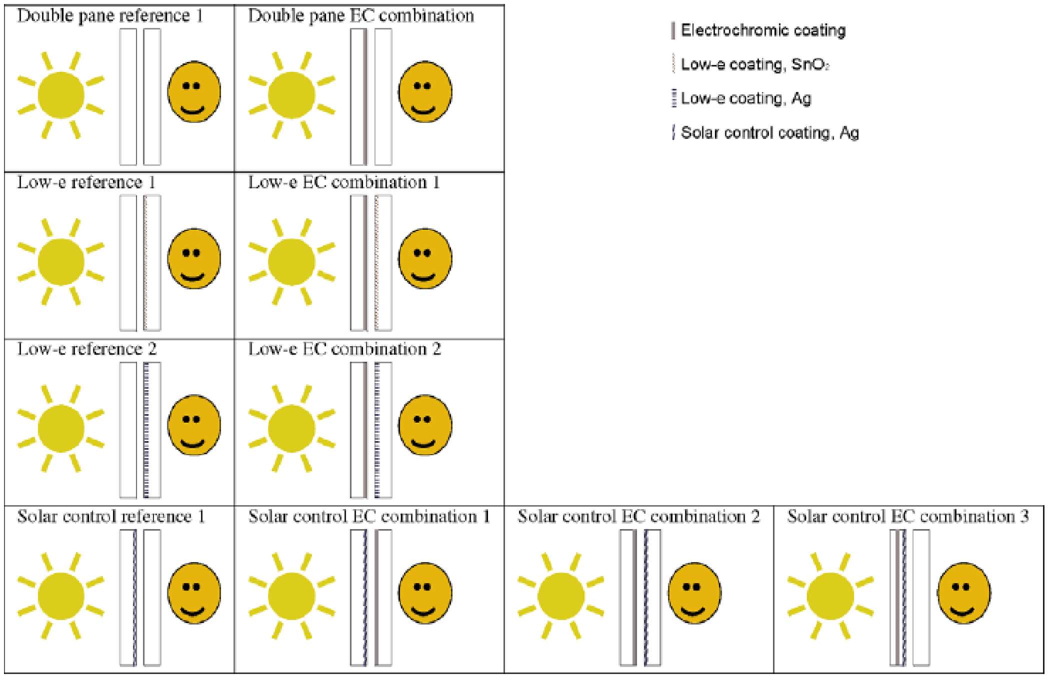


Figure 3.4 Window configurations used in the investigation (Jonsson and Roos, 2009)

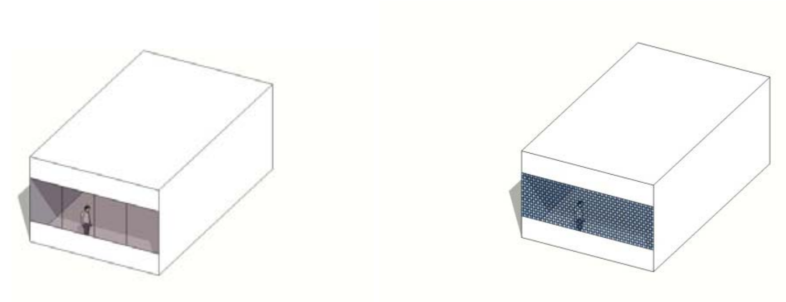
The research works completed by Maurus et al. (2003), Gugliermetti et al. (2004), James et al. (2008), and Fernandes et al. (2006) all used simulation methodology in order to evaluate different aspects of EC glazing and BIPV.

3.3 CHOOSING AN APPROPRIATE RESEARCH METHOD

The following are brief outlines of the four different research methods applicable to the question. The description of each of these methodologies will form the reasonable criteria in choosing an appropriate research method.

Experimental

In experimental or laboratory approach, tests can be carried out at a smaller scale to demonstrate the benefits of each system. The experiment can be conducted by using prototype side-lit office-like rooms, with 50% glazing ratio. Although country location is not as important, as both rooms will be in the same laboratory field environment, the windows must however be facing the south side, where majority of insulation occurs. In the first room seen in Fig. 3.5a, EC glazing is installed over the area where vision glass is typically placed. This is coupled with a dimming light control mechanism that is required to provide steady “work plane illuminance” and control direct sunlight (ASHRAE, 2000). In the other room, seen in Fig. 3.5b, semi-transparent PVs are integrated and replace conventional glazing.



a b

Figure 3.5 EC glazing replacing conventional glass (a); BIPV cells within the vision glass (b)

Comparing the results through this method allows for the benefits of each system to be directly visible and quantifiable. For example, in the former, the reduction in electrical demand can be summarized as a cost saving in a building's total energy use. Similarly, the amount of electricity produced from the array of PV over the façade can determine how much less electricity is needed from the grid to light the room, hence lower utility bill.

At the same time, thermal and optical properties can be measured to test the occupant's comfort level. For example, the temperature of the room can be measured during the day's average peak temperature period, to see which system would provide the more comfortable working environment. In addition, monitoring of lux levels can show whether the user would require blinds when glare causes discomfort. However, in order for this factor to be more justifiable, the room's window orientation must be towards the west. It is worth mentioning that for most such cases, EC glazing fails to offer full protection and requires "additional shading devices" (Piccolo et al., 2009). This research approach can look at both quantitative (overall cost savings) and qualitative (human comfort) results.

<u>Modeling</u>

In computer modeling, an energy simulation program can be used to analyze the energy benefits that may result from replacing conventional glass with EC glazing or photovoltaic panels across the entire opaque (spandrel glass) portion. For EC glazing the energy benefit is calculated on the basis of reduced electric lighting usage against standard glazing with blinds. As for PV panels it is equal to produced electrical output.

A benchmark can be a typical perimeter office module of 6m x 4m area with 50% glazing area. Similar to the laboratory approach, in one model, the solid areas of the façade would be covered with PV cells while in the other normal vision glass can be replaced with EC glazing. The software can evaluate the performance of each system based on location by using a prototype office building in both cooling and heating dominated locations, and summarize which is more suited for a particular climate. Even more, the program can determine the optimum orientation for maximum energy benefits by testing the different façades. The properties of each system in the model need to be based on actual measured data of industry developed prototypes. This data needs to be collected prior to start of modeling.

Field Monitoring

A field study can be carried out over a longer period of time, minimum one year, to measure the performance of the two systems in existing buildings. A longer duration ensures a more consistent data average due to fluctuations in weather conditions. Two buildings that are in same geographical location are typically chosen to observe data more precisely. They must also have similar built environments, because urban settings tend to have elevated temperatures in comparison to rural sites known as "Urban Heat Island effect" (Golden et al., 2007). In addition, the effect of any external elements must be taken into consideration such as trees and adjacent buildings that might cast shadow on the façade at certain times of the day.

It is important that the façade being analyzed has the same orientation for both systems. The preferred elevation to study is the south, as it has the maximum sun exposure. Also, the area being studied must be relatively equal for both. That is to say, that even if two building have the same number of floors (for example 10), if building one has EC glazing over the entire façade of its 10 floors, as in Fig.3.6a, but building two has PV built into the façade of only 3 levels, seen in Fig. 3.6b, the data must be collected and analyzed for the same 3 levels for both in order to compare the efficiency and benefits of each system. At the same time however, collecting data of all levels for building one, and using an average efficiency of the system multiplied by three levels can help to minimize any estimated error or uncertainty during the information gathering process.

a b

Figure 3.6 EC glazing utilized over all the floors (a); BIPV cells only on the top three levels (b)

Historical or literature-review

This approach covers issues that have been looked at by other researches of similar topic. By examining a number of case studies, the energy efficiency of each system can be deduced from the success or failure of each projects' goals. Table 3.3 below might suggest the selection criteria for case studies to be undertaken. Once again, it is important to note that although comparison can be made for the efficiency of either system for different regions, considering typical geographical location will enhance the investigated data's accuracy.

Thus, two cases can be selected for each system in hot and cold regions, as is shown for case studies one through four in Table 3.4. Further, because each country might have different regulation and incentive for integration of these two systems, the results can be further scrutinized if cities in same country are analyzed, as is shown for case study five through eight. The results of this research approach should indicate which system is a better alternative in a particular region.

Table 3.4 Selection of case studies according to regions

Case Study #	Electrochromic Glazing		Building Integrated Photovoltaics	
	Hot Region	Cold Region	Hot Region	Cold Region
1	Abu Dhabi, UAE	-------------------	Miami, USA	-------------------
2	-------------------	London, UK	-------------------	Toronto, Canada
3	Miami, USA	-------------------	Abu Dhabi, UAE	-------------------
4	-------------------	Toronto, Canada	-------------------	London, UK
5	Abu Dhabi, UAE	-------------------	Abu Dhabi, UAE	-------------------
6	-------------------	London, UK	-------------------	London, UK
7	Miami, USA	-------------------	Miami, USA	-------------------
8	-------------------	Toronto, Canada	-------------------	Toronto, Canada

3.4 RESEARCH DESIGN AND METHODOLOGY

Based on the findings of other research methods, and the limitations associated with each, the modeling approach was deemed most appropriate in this study. However, this approach is complimented with literature-review that has been covered in Chapter two of this paper. The review of these previous studies has enabled a broader knowledge when it comes to application of BIPV and EC glazing worldwide, and the extent to which there are gaps in applying them to UAE. Following are comparisons and contrasts between the four research methodologies that will support this methodology selection for this topic.

In laboratory testing, the process is very time-consuming as the test environment has to be built as a prototype. This is much easier in modeling method, where everything is simulated in a 3D environment and can usually be done in a matter of hours. Thus, the speed of modeling production is much quicker in simulation. Further, the cost of conducting laboratory testing is much higher than computer analysis, mainly because it will require more resources. As a result, most laboratory tests can only identify benefits associated to a small prototype space, where as a modeling approach can give the same results for an entire building. Also, with phenomenal advances in analysis methods and computational power, the software tools can simulate a life-like digital built environment. Therefore, rather than relying on outdoor conditions to dictate when it is suitable to conduct the test, it is easy to control parameters and flexibility of the software allowing for increased opportunity to get comprehensive results via simulation instead of laboratory.

In the field measurement technique, one of the disadvantages is that the person who is collecting information might be influencing the data because of his/her presence in the environment. Another drawback is that the research will be limited to whatever building is available to study. If the research is targeting residential buildings that can minimize energy cost by using integrated PVs, and only commercial buildings are available, then it makes the research more difficult. One more downside is that the accessibility to a building could be limited due to reasons such as timing restrictions. Even if the observer has been given access, it might be very time consuming to travel to the site to collect data several times a day. Where as in simulation, all the external elements are under the control of the experimenter; using on-site monitoring can prove difficult when faced with the difficulty of factors that will affect the study. For example, the shading of adjacent buildings on the façade can reduce the system efficiency of PV. Similarly the reflection of the sun from nearby buildings can cause glare that will cause discomfort for the building user despite the installed EC glazing.

When only using the literature-review approach, the researcher is limited by the existing material previously done by others. In many case studies, it is complicated to find the data from a particular system that fits other locations. As a result, choosing a desired geographical location is not always easy. Further, the case studies process is a review and interpretation of old data that might be outdated. In the case of BIPV and EC glazing, because these two are competitors in the market, there are always advances in the new technologies and thus relying on old data could lead to inaccurate results. More importantly, even if the data is correct, the assumption that a previous researcher has made might not be deemed accurate enough to follow. That is to say, each researcher has personal beliefs and opinions that will ultimately alter the research to usually benefit the outcome of their study.

Altogether, it is easier to control the research parameters in simulation than the other methods. The software can be managed to reflect the construction parameters and test the correlation of various variables such as tilt angle of PV on the façade, shading coefficient of the EC glazing and the interior lighting levels, weather conditions, geographic location (latitude), façade orientation, effect of adjacent building, and thermal comfort levels, on performance of the system. The conductor can set the boundaries that define the level of detail that the research is aiming for.

3.5 CHOOSING A SIMULATION SOFTWARE

An advanced computer software program will be used to run the analysis. There is a variety of programs that offer such capabilities, some of which are EnergyPlus©, Autodesk Ecotect Analysis© and Integrated Environmental Solutions or IES©. Figure 3.7 shows the structure of EnergyPlus which makes integrated (simultaneous) simulation and underlying concept. Accurate space temperature predictions allow energy efficient system engineering, evaluation of system and plant size, and occupant comfort and health (Crawley et al., 2000).

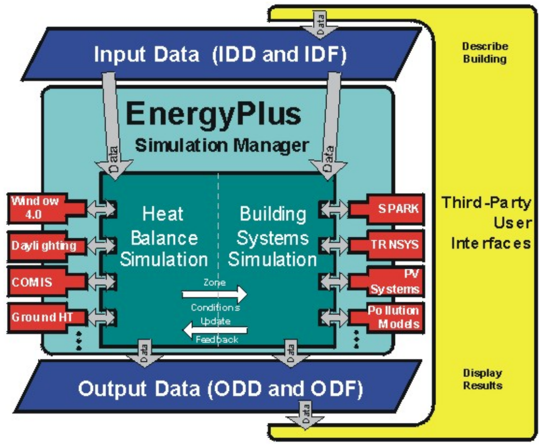


Figure 3.7 Overall EnergyPlus program structure (Crawley et al., 2000)

There are several important criteria in choosing the correct software tool for this study. The following are a pre-requisite that were deemed necessary by the author in a computer program to be capable of handling this study:

- Ability to model BIPV and mimic characteristic of EC glazing
- Available third-party user interface and plug-in particularly Google SketchUp
- User-friendly graphic interface
- Easy to follow user guide for a person with architectural background
- Reliable with validation certificates
- Used by other scholars in similar research
- Comprehensive database of various building construction materials and
- Easy configuration of model operation profiles and schedules

The selection process also included consultation with other professionals and colleagues using various computer simulations. Furthermore, making the correct choice involved a review of other papers that compared some of the most recent building simulation tools. A study by Crawley et al. (2008) compared the twenty simulation programs under a number of functions and capabilities. From the analysis, IES-VE achieved the highest score as shown in Table 3.5, where X is the feature or capability available and in common use; P means feature or capability partially implemented; R means optional feature or capability for research use; and E means feature or capability requires domain expertise.

Table 3.5 Excerpt from Zone loads (11 of 21 rows) from Table no. 2 (Crawley et al., 2008)

	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	IDA ICE	IES ⟨VE⟩	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Interior surface convection																				
• Dependent on temperature	X	X					P		X		X	X	X		X	X	X	X		X
• Dependent on air flow	X						X		P		X		X		X			X		E
• Dependent on surface heat coefficient from CFD									E		E		X							
• User-defined coefficients (constants, equations or correlations)		X	X	X	X				X		E	R	X		X	X	X	X		X
Internal thermal mass	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Automatic design day calculations for sizing																				
• Dry bulb temperature	X	X	X	X	X	X	X	X	X	X		X	X	X	X	P		X	X	
• Dew point temperature or relative humidity			X	X		X	X		X	X		X	X	X				X	X	
• User-specified minimum and maximum			X	X		X	X		X	X		X	X	X	X			X	X	
• User-specified steady-state, steady-periodic or fully dynamic design conditions			X									X	X	X				X	X	X

Attia et al. (2009) carried out a research to assess building performance simulation tools used in daily Architectural design practices as "Architect friendly". The 249 respondents of the surveyed architects, designers, architect educators, and students ranked IES at first category amongst the ten programs seen in Fig. 3.8. The user friendly graphic interface and the "template driven approach" are the top strengths of the program (Attia et al., 2009).

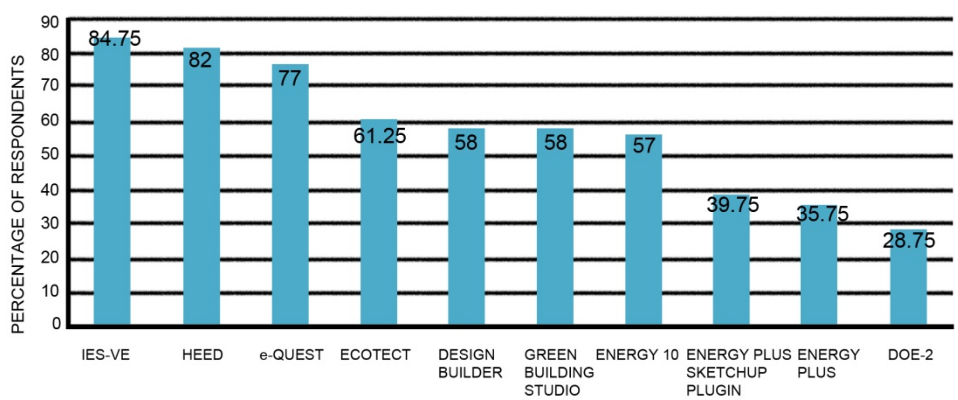


Figure 3.8 Ranking the ten simulation tools (Attia et al., 2009)

Based on this information, the author chose the software Integrated Environmental Solutions (IES) as the simulation instruments in this study. One of the most important criteria in the case of IES was its availability as a plug-in into other architectural 3D software used by author, mainly Google SketchUp. This meant that importing architectural models into the energy simulation environment is much simpler and less time-consuming.

3.6 INTEGRATED ENVIRONMENTAL SOLUTIONS-VIRTUAL ENVIRONMENT (IES-VE)

<u>Software description</u>

The unique suite of integrated building performance analysis tools enables design teams to undertake advanced analysis right from the start. High quality information is available from the earliest stages of design, so that the project team can work effectively to develop creative solutions. The ripple effect of any design changes – from major modifications to fine tuning – can be assessed at the touch of a few buttons. Building Information Modeling is a significant move towards integrated design – but to strive towards carbon neutral and energy saving, it is imperative to integrate performance analysis right from the start. IES <Virtual Environment> does exactly that – ensuring that architectural elements and engineering systems work effectively together from concept stage onwards; optimizing the collaborative workflow and putting sustainability right at the center of the discussion. And with our range of links and plug-ins – including the direct link to Google SketchUp™ and Autodesk's® Revit® platform and the connection to Graphisoft® ArchiCAD® via gbXML - it really is achievable to take advantage of everything 3D design tools have to offer and raise the bar towards the true definition of sustainability (IES, 2010).

The software includes the following modules:

- Model Builder
  - ModelIT: Building modeler and importing already created geometries
  - CompLib: Allows creation of components which can be placed within the model

- Energy
  - Apache: Thermal calculation and simulation; assessment the feasibility and performance of renewable sources like wind, PV, CHP.
  - Apache HVAC: HVAC system simulation
  - MacroFlo: Multi-zone air movement

- Solar
  - Suncast: Solar shading analysis

- Lighting
  - FlucsDL: Daylighting analysis
  - FlucsPro: Electric and daylighting design and analysis
  - LightPro: Luminaire database and layout tool
  - RadianceIES: Daylighting and electric lighting simulation

- Cost and Value
  - CostPlan: Capital cost analysis
  - Lifecycle: Life-cycle analysis
  - Deft: Value engineering analysis

- Egress
  - LiSi: Lift design and simulation
  - Simulex: Occupant movement and evacuation

- Mechanical
  - IdusPro: Duct sizing
  - PiscesPro: Heating/chilled water pipe sizing

- CFD
  - MircoFlo: CFD simulation system

The author attended several training sessions by IES representatives in order to become familiar with the component. It was advised that due to the high cost of the software's full license version, which is in the range of £3000-3500, a student license copy be purchased for 50£. Although, this copy is valid for only one year, this duration was adequate to run the necessary analysis and finish the study. The software was acquired on March 2010.

Software validity and reliability

One of the most important aspects of a building energy simulation program is its validation. Table 3.6 lists simulation programs in terms of their validation (Crawley et al., 2005). The software has been approved and validated by the following bodies:

- CIBSE TM33 (Macdonald et al., 2004)
- IEA Task 12
  - Envelope BESTEST (Judkoff and Neymark, 1995a; also ANSI/ASHRAE Standard 140, 2001)
  - Empirical (Lomas et al., 1994)

Table 3.6 Summary of simulation validation (Crawley et. Al, 2005)

Table 13 Validation	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
IEA ECBCS Annex 1[239]											X									X
IEA ECBCS Annex 4[240]											X									X
IEA SHC Task 8[241]											X						X			X
IEA ECBCS Annex 10[242]											X									X
IEA SHC Task 12																				
▪ Envelope BESTEST[243]	X		X	X	P		P	X[244]	X[245]		X	X[246]	X	X	X	X[247]	X	X	X[248]	X
▪ Empirical[249]		X[250]	X		P		P				X						X	X		X
IEA SHC Task 22																				
▪ HVAC BESTEST Volume 1[251]				X					X[252]	X	X[253]			X					X[248]	X
▪ HVAC BESTEST Volume 2[254]				X					X		X			X					X	X
▪ Furnace BESTEST[255]									X		X									
▪ RADTEST[256]				X							X			X						X
IEA ECBCS Annex 41 Moisture																X[257]				
HERS BESTEST[258]	X			X	P								X				X			
ASHRAE 1052-RP[259]	X			X					X											
BEPAC Conduction Tests[260]									X		X									
BRE/EDF validation project[261]											X									
PASSYS project[262]											X									
CIBSE TM33[263]					P						X				X[264]			X		
ISO 13791[265]					P						X							X		
Other						X[266]														

More information about the software and its validity can be obtained from IES website www.iesve.com.

Furthermore, in order to ensure the validity of the model in the current study, the author consulted IES support team for the verification of the model throughout the modeling process and a final inspection at the end. Also, the base case model described in next chapter was tested against another software. With the help of a mechanical engineer at KEO International Consultants, the same model was built using HAP 4.5. The results of the test comparisons and validation are presented in Chapter four.

CHAPTER 4: THE SIMULATION MODELS

4.1 MODEL DESCRIPTION

The basic model established for this simulation study represents the common construction practice in the Emirate of Abu Dhabi. The space configuration as well as the type of materials incorporated into the model is frequently found in UAE building construction. At the same time, some of the design parameters considered for the prototype are the outcome of the literature review. For example, when it comes to BIPV, the benefit is directly related to the available area on the façade for the system to be installed. However, using façade dimension does not work for the EC glazing, because the benefit is characterized by reduction in lighting loads. Instead, it is the system's ability to properly modulate lighting levels that determines the energy benefits. For instance, if the office depth is shallow, then the work area which daylight can act to reduce artificial light is also small. This means that the energy benefits would be less. However, a sufficient office depth of around 6m presents a reasonable light penetration into the office space (Nabil and Mardaljevic, 2008). The following are the basic description of the office module and its parameters.

4.1.1 Office Module

A simulation model was developed which represents a perimeter private office room situated in Abu Dhabi. The space modeled, shown in Fig. 4.1, has a rectangular shape of 4m (width), 6m (depth), and 3m (height). There is a plenum of 1m height, which brings the total floor to floor height to 4m. The façade is a typical curtain wall construction, with a flush window size of 4m width and 3m height consisting of double-glazing unit. Hence, the façade ratio of glazing to solid (or window to wall ratio – WWR) will be 75% vision glass and 25% solid. There are two workstations, one near the window, and other at the back. The height and location of these tables will define the two areas where sensors will be placed. The façade is also modeled with interior roller blinds. The blinds were either fully up or fully lowered over the whole window. Figures 4.2 and 4.3 show the setting out of the proposed office module.

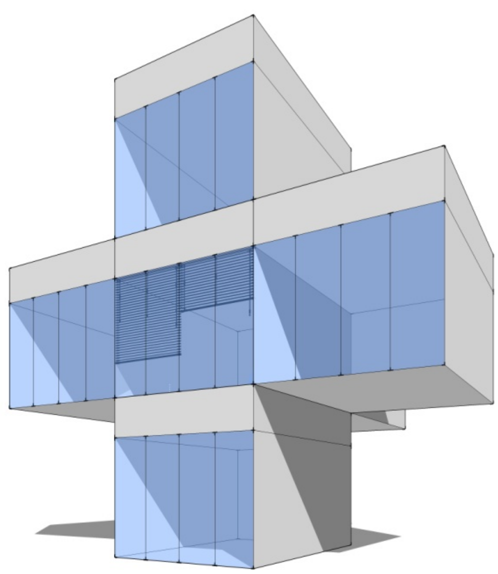


Figure 4.1 Axonometric of the simulation model

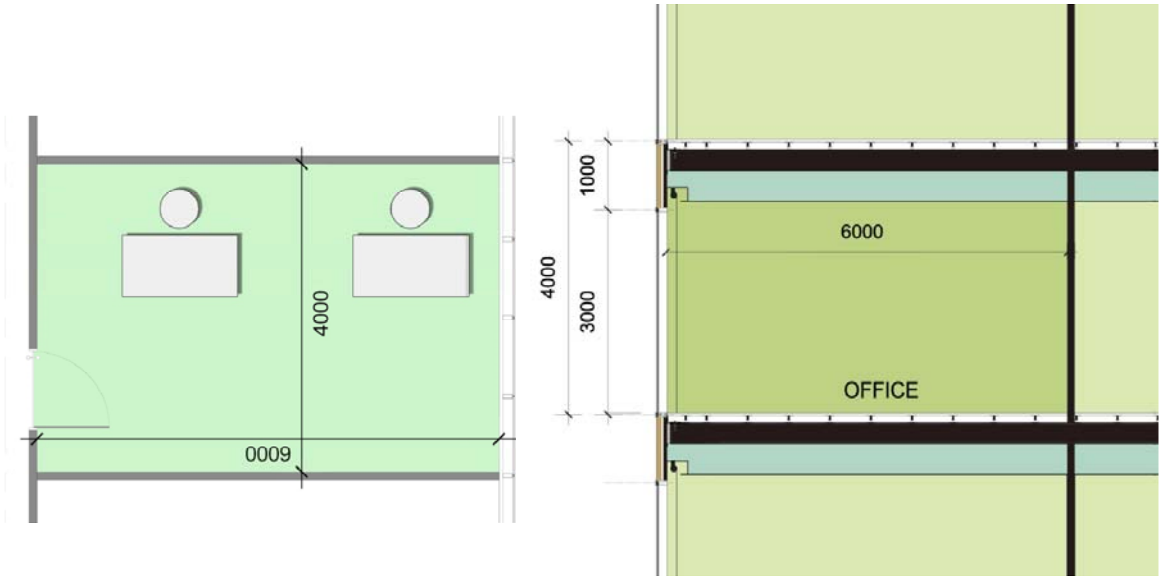


Figure 4.2 Floor Plan (left) and section (right) of the simulation model

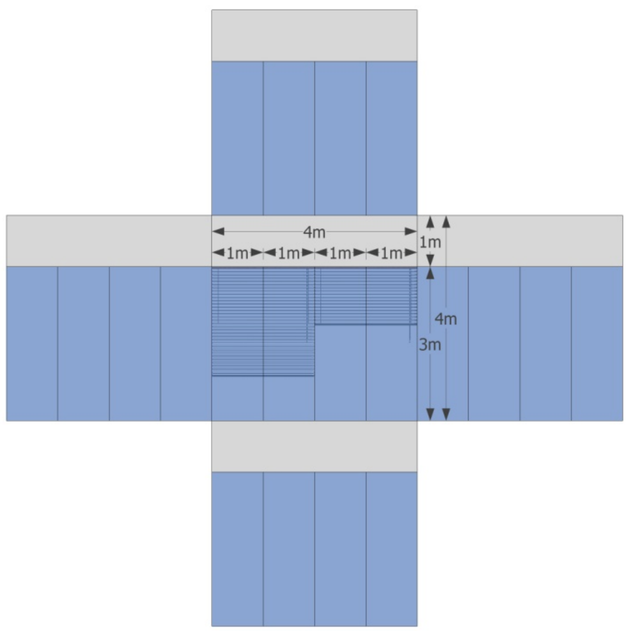


Figure 4.3 Elevation of the simulation model

4.1.2 Module Finishes

The space that is modeled uses building materials and furniture that is typically found in an office environment in Abu Dhabi. The software's Construction Database allows easy editing and management of all construction types such as walls, ceilings, and windows. It is very important to define the right properties in order to get the best results from the thermal model. Table 4.1 shows the list of the materials finishes from IES-VE that are selected for the model.

Table 4.1 Simulation model construction materials

	Material	**Thickness (cm)**	**Conductivity (W/m.K)**	**Density (kg/m^3)**	**Category**	**ASHRAE U-Value**
External walls	Limestone	10	1.5	2180	Stone	0.3458
	Cavity	1.2	-	-	-	
	Polyurethane Board	5.85	0.025	20	Insulation	
	Concrete Block (heavy weight)	10	1.63	2300	Concretes	
	Plaster (Lightweight)	1.5	0.16	600	Plaster	
Internal partitions	Gypsum Plaster Board	2.5	0.16	950	Plaster	1.366
	Cavity	10	-	-	-	
	Gypsum Plaster Board	2.5	0.16	950	Plaster	
Internal Ceiling / Floors	Synthetic carpet	1	0.06	160	Carpets	0.8191
	Aluminum deck	4	160	2800	Metals	
	Cavity (Raised Floor)	10	-	-	-	
	Screed	5	0.41	1200	Screeds & Render	
	Cast Concrete (Dense)	25	1.4	2100	Concretes	
	Cavity (Ceiling)	54	-	-	-	
	Ceiling Tiles	1	0.056	380	Tiles	
Doors	Pine (20% Moist)	4	0.14	419	Timber	2.2967

	Material	**Thickness (cm)**	**Transmittance**	**Outside Reflectance**	**Inside Reflectance**	**ASHRAE Net U-Value**
External glazing	Pilkington Activ Suncool	0.6	0.23	0.39	0.1	2.06
	Cavity	0.12	-	-	-	
	Clear Float	0.6	0.78	0.09	0.1	
	Glass total shading coefficient = 0.27; SHGC (center-pane) = 0.23					

	Material	**Thickness (mm)**	**Solar Transmittance**	**Solar Absorptance**	**Shading Coefficient[1]**	**Short-Wave Radiant Fraction[2]**
Roller Blinds	Verosol 816 Fabric[3]	0.23	0.29	0.27	0.5249	0.5525
	Fabric Color is light grey					

Notes:
1- Blind Shading Coefficient = (0.87 x Solar Absorptance) + Solar Transmittance (IES User Guide 2010)
2- SWRF = Solar Transmittance/Shading Coefficient; this is the proportion of the room heat gain associated with the blind that pass through it as short wave radiation (IES User Guide 2010)
3- Refer to Appendix C for full manufacture's specifications

4.1.3 HVAC and lighting assumptions

The occupancy ratio of the room is assumed to be at 10m2/person. This allows for 2 work stations with two computers of 300W each and two adults with Maximum Sensible Gain 90W/person. The heating profile of the room is assumed to be always off, and the cooling is always on with the simulation cooling set point maintained at 24˚C. The room infiltration is at a maximum flow of 0.25 Air Change per Hours (ACH) typical of Abu Dhabi office and still more efficient than the 0.35 minimum local standards because of lower cooling loads. In the literature review, studies for the basic need of an office space have identified key issues for determining the success of a workplace in achieving goals of productivity and comfort for the users. For example, in the UK the space should have natural ventilation and allow manual component operation for users. Such interactions can achieve high satisfaction levels inside the workplace (Bahaj et al., 2008). However, It should be noted here that the possibility to reduce cooling needs through extra ventilation such as opening windows during times when outdoor temperatures is lower than indoors is not considered in this study.

The design value for the light levels for office work is set at 500 lux at the work plane following recommendation of the CIE, Guide on interior lighting (Gugliermetti and Bisegna, 2005). The position of the light sensors will be at 2m and 4m distance from the window edge shown in Figs. 4.4 and 4.5 respectively. These will be placed at the height of 0.85m, which is the working plane of both office tables. The simulation will test the change in sensor location and its impact on the efficiency of the two systems. The type of lights will be fluorescent lamps, although they are not as efficient as LED, they are more commonly used in offices. The sensor is linked to these fluorescent luminaires which are ceiling level at 3m high. The installed power density of the luminaires is $3W/m^2/100lux$. The lights will be assumed turned on whenever the natural light levels are below 500lux. Similarly, whenever the work plane illuminance exceeds 500lux, they are turned off. In the base office module, no light dimming will be considered as this is the norm in a typical office. However, each luminaire is considered to have independent control depending on the lighting requirement.

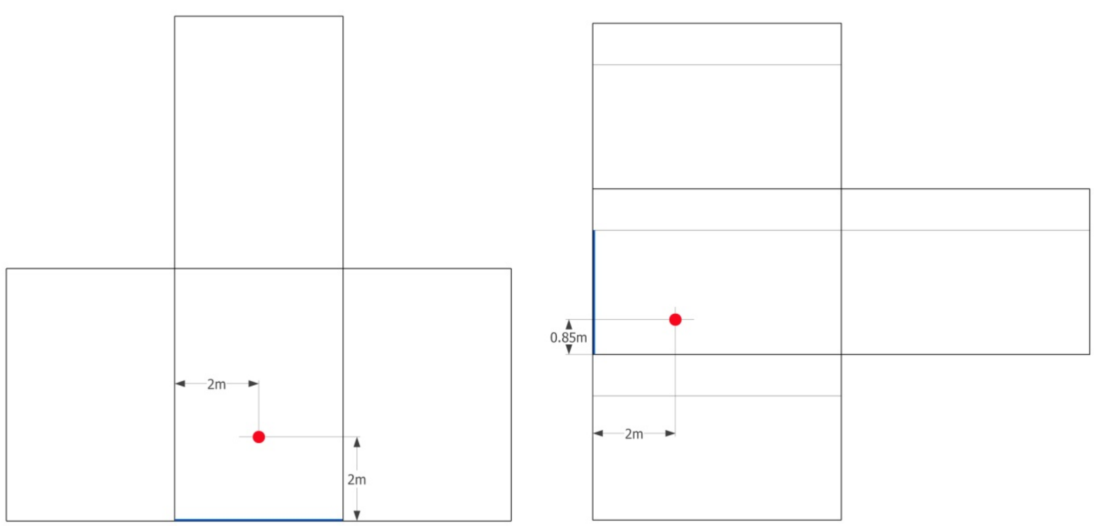


Figure 4.4 Plan (left) and side elevation (right) of lighting sensor at 2m from window

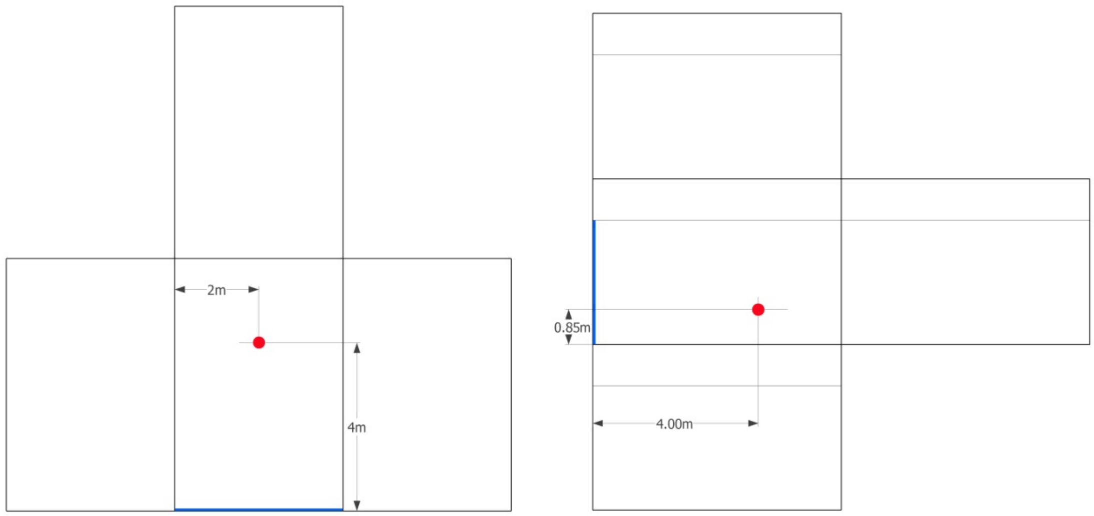


Figure 4.5 Plan (left) and side elevation (right) of lighting sensor at 4m from window

The U-value and shading coefficient effect the glazing's light transmission and hence the amount of daylight permitted into the space. The glazing U-value is fixed at 2.06 W.k/m2 while shading coefficient will be set at two values of 0.27 and 0.6 depending on the case configuration described later.

4.1.4 Electrochromic glazing control strategy

The benefits of EC glazing were discussed in Chapter two where such energy savings can be predicted using sophisticated software. In Fig. 4.6 the dots represent various static solar control glazing products commonly used today. However, they are only suitable for a given set of environmental conditions, because of their fixed solar heat gain coefficient (SHGC) and level of visible light transmission (VT). The arrow across the chart indicates the dynamic range of the SageGlass window product, which is one of leading manufacturers of EC glazing. Therefore, through a simulation program that maintains a static U-value but dynamically adjusts the SHGC and VT, EC glazing can be associated to such benefits as the reduction in air-conditioning loads.

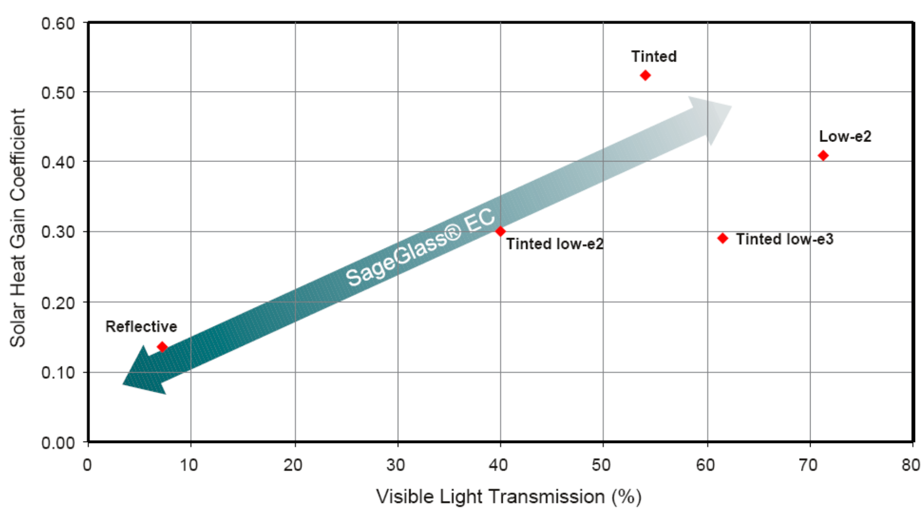


Figure 4.6 Relation between SHGC and VT (SageGlass, 2010)

The purpose of this study is to find out the energy performance of EC against other technologies. However, the software does not have the capability of dynamically changing the glazing properties, based on fluctuations in illuminance levels. Instead the performance of EC glazing, as it switches from bleached (high transmission state) to colored (darkened to a highly tinted state), will be examined by manually testing various tinting conditions on an hourly basis. Based on available technology, it is assumed that the range of visible transmittance in the model could vary between 3.5% and 62% as seen in Table 4.2. Thus, the other values in-between the maximum and minimum are interpolated as shown in Table 4.3. This will be further elaborated in the description of the various simulation case configurations.

Table 4.2 EC glazing specifications (SageGlass, 2010)

PRODUCT			TRANSMITTANCE				REFLECTANCE			U-FACTOR		SHGC	LSG*	STC**
Color	Inboard lite	Tint State	Visible	Solar	UV	KDF	VIS in	VIS out	Solar	Winter	Summer			
Classic™	Tempered/HS 6mm clear	clear	62%	40%	5.6%	18%	15%	21%	20%	0.29	0.28	0.48	6.9	35
		tinted	3.5%	1.5%	0.8%	2.2%	10%	6%	10%	0.29	0.28	0.09		

*LSG: Light to Solar Gain ratio for SageGlass IGU calculated as Tvis (clear)/SHGC (tinted) Modelled using Windows 5.2
**STC: Sound transmission class 90% argon filled units; 1/2" air gap

Table 4.3 Range of EC glazing properties for simulation

Glazing ID #	Tint State	Transmittance		Reflectance		SHGC	Shading Coefficient
		Visible (T_{vis})	Solar	Inside	Outside		
ECG 1	Clear	62%	40%	15%	21%	0.48	0.5517
ECG 2	15% Tinted	50%	36%	14%	18%	0.41	0.4716
ECG 3	30% Tinted	40%	32%	13%	15%	0.34	0.3915
ECG 4	45% Tinted	30%	20%	12%	12%	0.27	0.3105
ECG 5	60% Tinted	20%	10%	11%	10%	0.21	0.2419
ECG 6	75% Tinted	10%	5%	10%	8%	0.15	0.1728
ECG 7	90% Tinted	3.5%	1.5%	10%	6%	0.09	0.1041

4.1.5 BIPV model selection strategy

The literature review in Chapter two showed the advantages associated with various types of PV cells. Nabil and Mardaljevic (2008) argued that an "increase floor pitch" is one of the limiting factors of deployment of PV on façade. However, they did not consider semitransparent BIPV modules can be considered without the expense of larger opaque façade area. This trend is now becoming more popular, making BIPV a suitable candidate for harvesting solar energy. Part of this study is to explore some of these different technologies to compare their benefits against each other. An annual simulation will identify the best type based on total light energy, total electricity, total displaced electricity, and the total energy balance. The models are different types of PV cells that are integrated in various ways within the facade of a room with similar configuration as the base office module. The type of PV cell used, its nominal efficiency, and its available area on facade will have a direct influence on electrical output and hence its energy balance. The software can quantify the total annual electrical output from the PV arrays based on the measured area on the facade. Table 4.4 lists some of the other input variable required to run the simulation.

All of the ten cases will be tested for South facing window only as this receives the most solar radiation in Abu Dhabi. The outcome of this exercise will form a baseline of optimum BIPV model for assessment against the EC glazing and the base case model. Table 4.5 shows the matrix of different scenarios that will be tested for this reason. The control strategy of these models will be further elaborated in the description of the various simulation case configurations. The schematic diagrams in Figs. 4.8-4.17 show the physical characteristics of these models. It is worth mentioning that mono-crystalline cells are opaque. In fact what is meant the by semi-transparent is through the addition of spaces between the cells. In the case of model case #1, seen in Fig. 4.8, two modules of 2m x 3m are used side by side on the façade. This module has an array of 12 x 19 cells of 125mm x 125mm each. The spacing of 30mm between each cell thus creates a 43% transparency effect. Figure 4.7 shows the technical specification of the product from the supplier.

Table 4.4 Characteristic of PV modules used in the study

PV array type	Nominal Efficiency	Nominal Operating Cell Temperature (NOCT)	Reference Irradiance for NOCT (W/m2)	Temperature Coefficient for Nominal Efficiency	Degradation Factor (Percentage)	Shading factor	Electrical conversion efficiency	Manufacturer
Mono-crystalline	14.5%	45 ˚C	800	-0.45%/˚C	1%	1[1]	80%[2]	Suntech[3]
Thin Film (CIS)	11%	47 ˚C	800	-0.36%/˚C	1%	1[1]	80%[4]	RHC[3]

Notes:
1- The effect of shading that might be caused by adjacent buildings, trees, etc., is not considered for simplicity
2- Based on a 25 year power output warranty
3- Refer to Appendix C for the manufacturer data sheet
4- Based on a 25 year power output warranty

Table 4.5 Matrix of BIPV simulation cases

Case #	PV Properties			Building Model Properties	
	Type of cell	Efficiency[1]	Transparency	Façade Integration	Available area (m^2)
1	Mono-crystalline	17%	Semi	Checkered	7.125
2			Opaque	Horizontal Bands	6
3				Vertical Bands	6
4				Replaces Spandrel[2]	4
5			Combination	Checkered with Spandrel	11.125
6	Thin Film (CIS)	13%	Semi	Uniform 10%	10.8
7				Uniform 25%	9
8				Uniform 50%	6
9			Opaque	Replaces Spandrel[2]	4
10			Combination	Uniform 50% with Spandrel	10

Notes:
1-Effieciency corresponds to 1000W/m2, and 25˚C (STC)
2-The models that utilize PV only across the spandrel area of façade will use blinds for solar protection

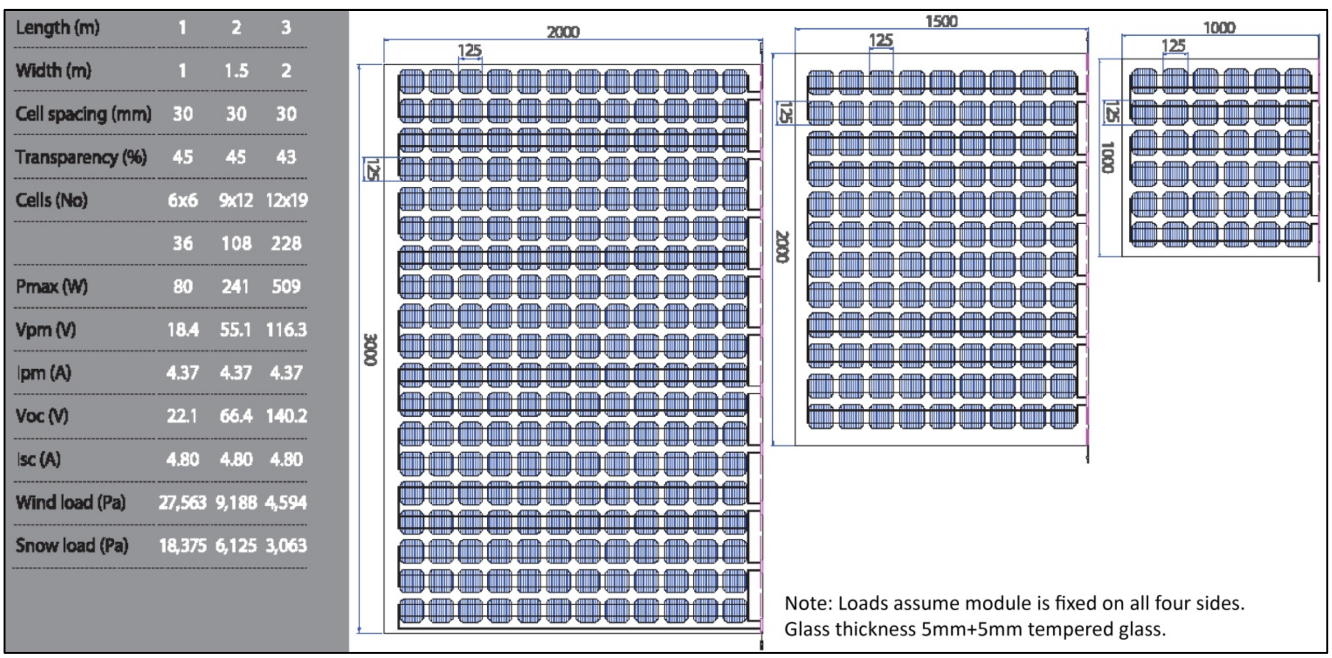
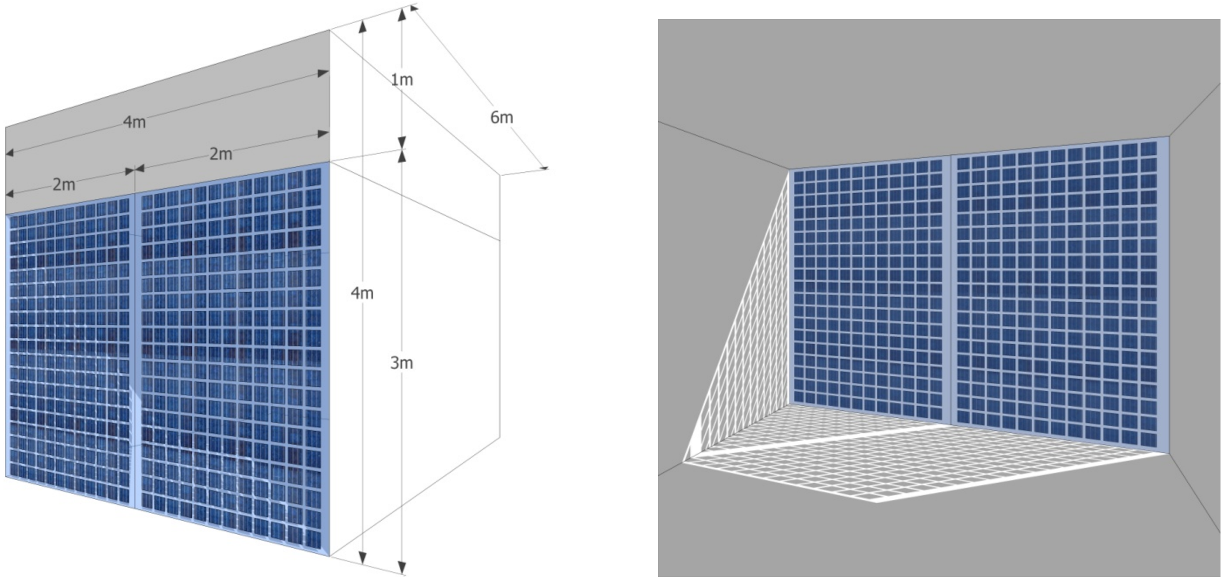


Figure 4.7 Technical specifications of semi-transparent mono-crystalline PV cells (Suntech, 2010)



a b

Figure 4.8 BIPV case 1: checkered semi-transparent mono-crystalline PV cells; axonometric (a), interior (b)

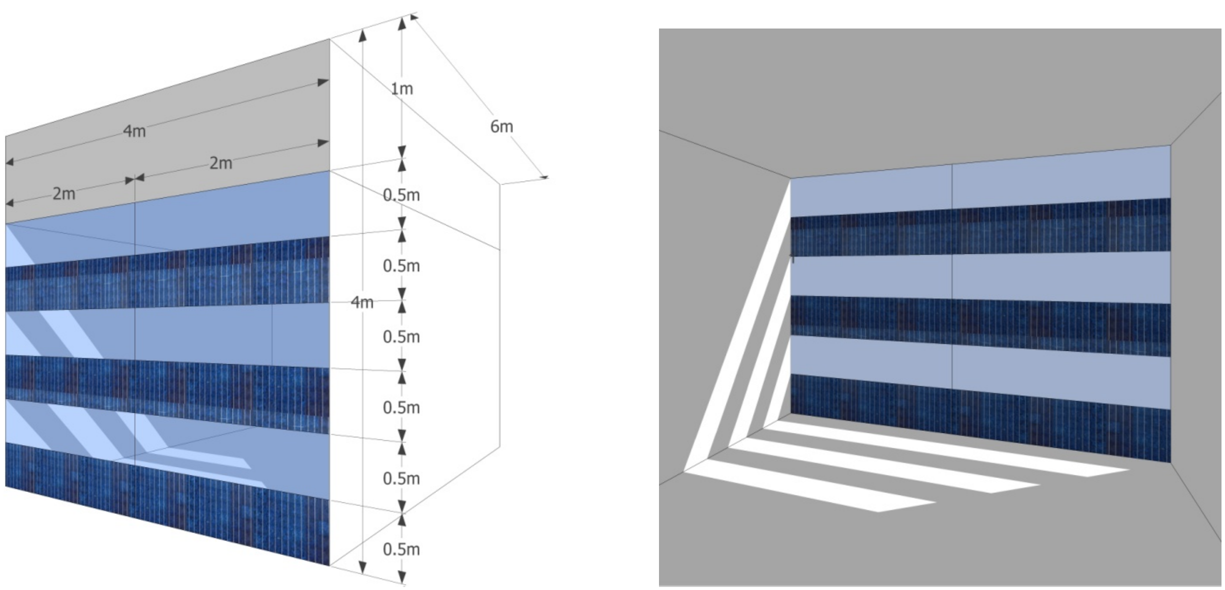


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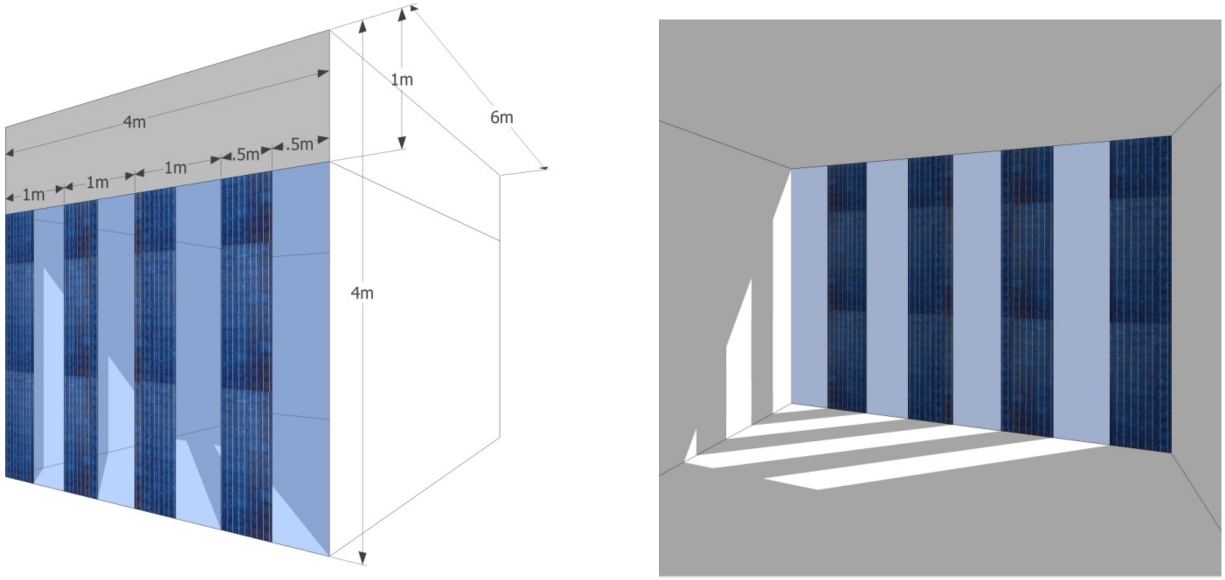
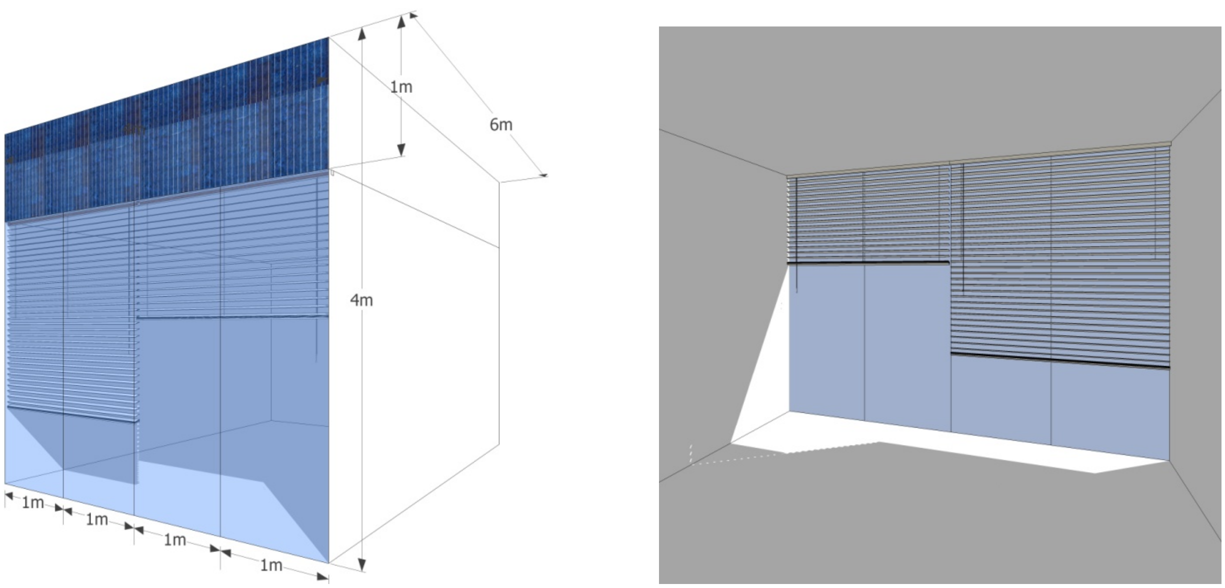
Figure 4.9 BIPV case 2: horizontal opaque mono-crystalline PV cells; axonometric (a), interior (b)



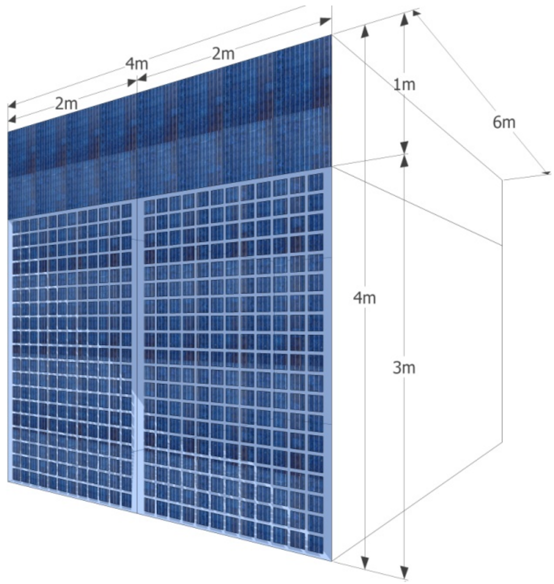
a b

Figure 4.10 BIPV case 3: vertical opaque mono-crystalline PV cells; axonometric (a), interior (b)



a b

Figure 4.11 BIPV case 4: with blinds and horizontal opaque mono-crystalline PV cells replace spandrel panel; axonometric (a), interior (b)



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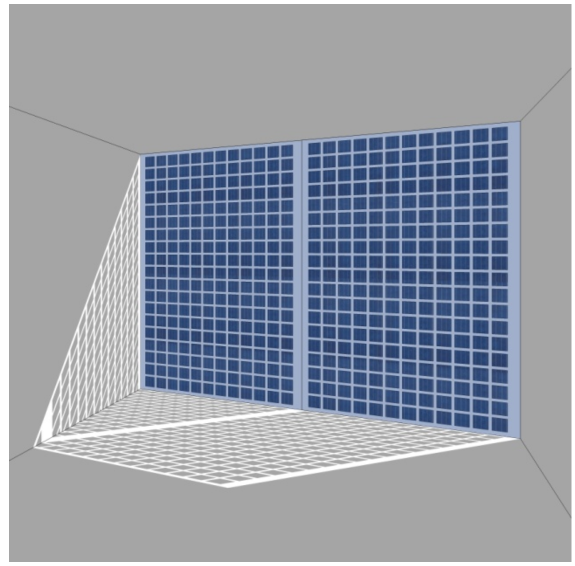
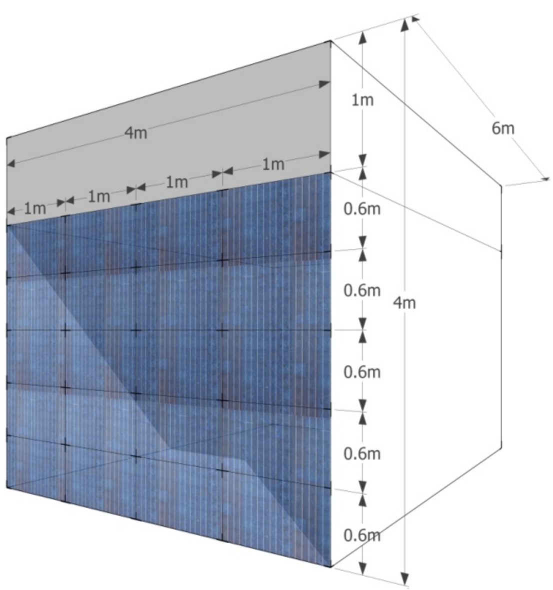


b

Figure 4.12 BIPV case 5: checkered semitransparent over vision glass and horizontal opaque mono-crystalline PV cells replace spandrel panel; axonometric (a), interior (b)



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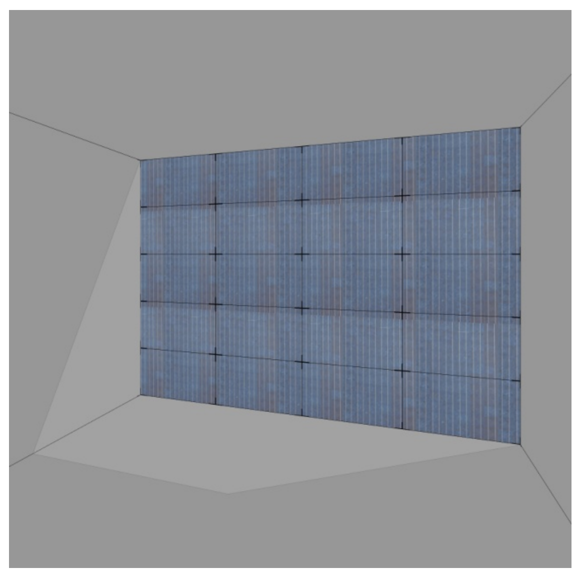
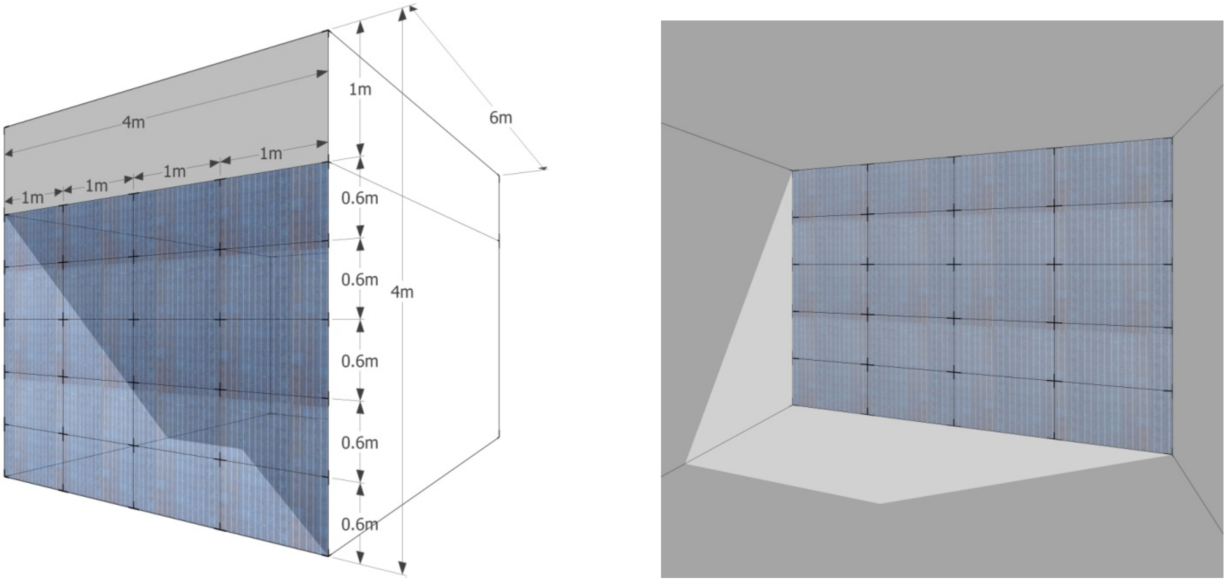


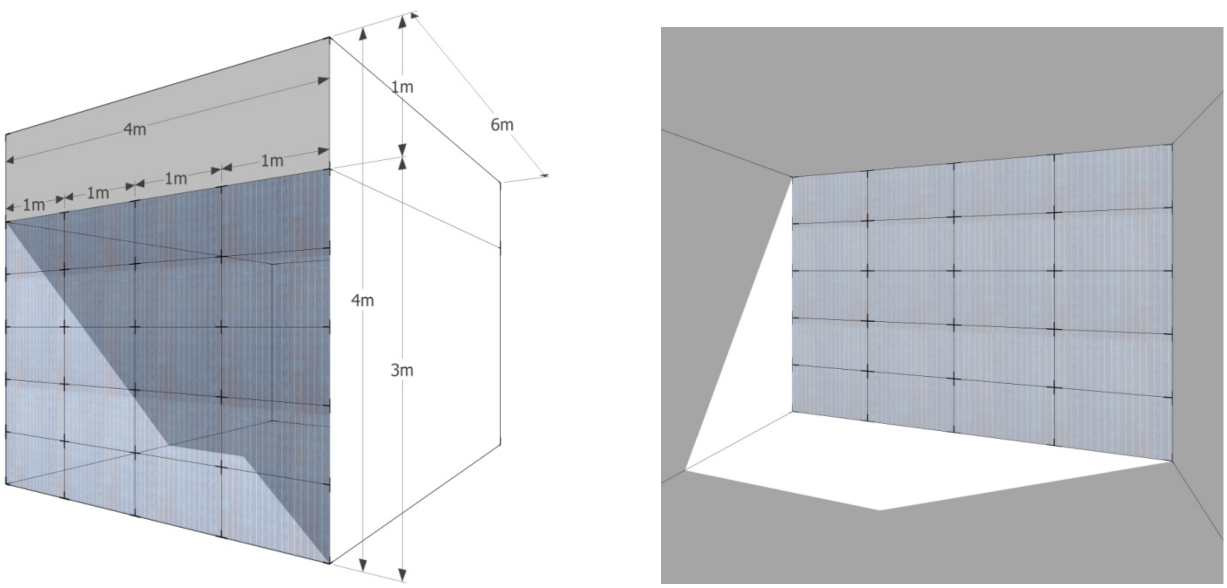
b

Figure 4.13 BIPV case 6: standard CIS PV cells with 10% uniform transparency; axonometric (a), interior (b)



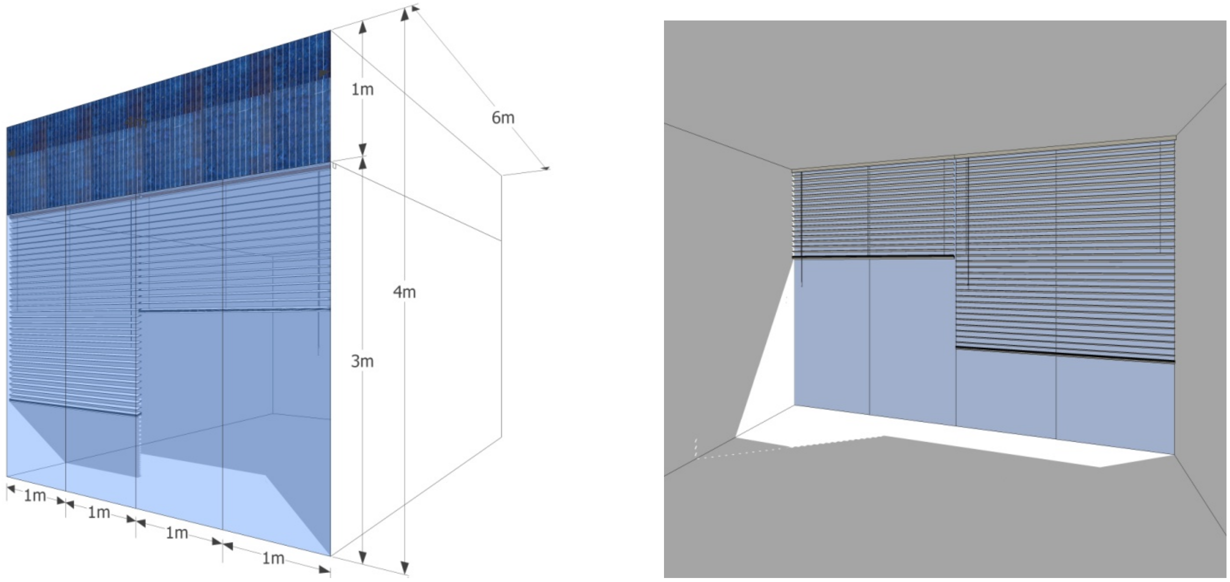
a b

Figure 4.14 BIPV case 7: standard CIS PV cells with 25% uniform transparency; axonometric (a), interior (b)



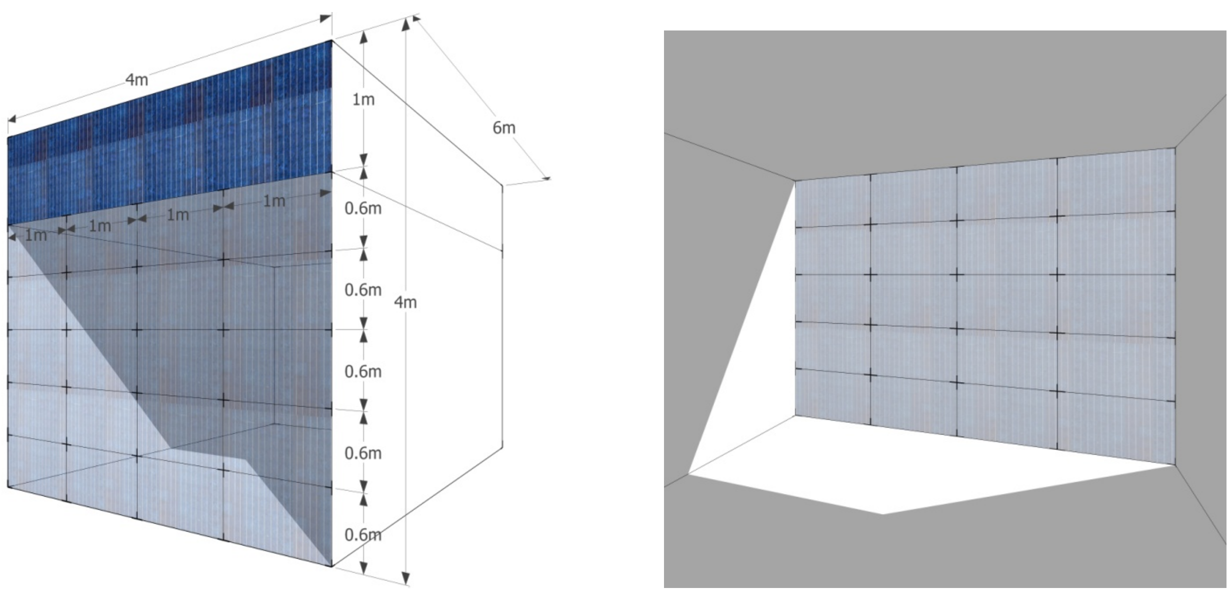
a b

Figure 4.15 BIPV case 8: standard CIS PV cells with 50% uniform transparency; axonometric (a), interior (b)



a b

Figure 4.16 BIPV case 9: with blinds and standard CIS PV cells with 0% transparency replace spandrel glass; axonometric (a), interior (b)



a b

Figure 4.17 BIPV case 10: standard CIS PV cells with 50% uniform transparency replace standard glazing and standard CIS PV cells with 0% transparency replace spandrel glass; axonometric (a), interior (b)

The results of this assessment will be discussed in the next Chapter.

4.1.6 Weather Data

One of the features of IES-VE is APLocate, which is the weather and site location editor for the programs CIBSE Heat Loss & Heat Gains (ApacheCalc), ASHRAE Heat Balance Method (ApacheLoads), ApacheSim, SunCast and Radiance. It is possible to choose a location from an extensive database and guidance is given on defining weather data for various locations. APlocate utilises site data that contains values for latitude, longitude and height above sea level of a wide range of sites throughout the world drawn from standard tables published by CIBSE and ASHRAE. For this study, the weather data that represents the prevailing local climate of Abu Dhabi is chosen. Each weather file has hourly values of: dry-bulb and wet-bulb temperature, direct normal and horizontal diffuse solar radiation, solar altitude and azimuth, wind speed and direction, cloud cover and atmospheric pressure. It is advisable to edit project specific data as soon as the information becomes available. However, if project data is unknown at the beginning of using the Virtual Environment, it may be created it at a later date.

4.1.7 Orientation and Time

All cases are tested for the four different orientations, East, South, West, and North. The program is designed to show the Sun's path across the sky on any date as viewed from any position in the earth's surface. The factors which determine the apparent path are the latitude and longitude of the observer and the date and time of the observation. The Sun's position is expressed in degrees of azimuth and degrees of altitude. The path is displayed over a period which can be selected by the user. Figure 4.18 shows the annual sun path diagram for Abu Dhabi, where the solstices or the equinoxes that occur are also displayed during this period. The simulation timing for this study will be on an annual basis. However for daily comparisons of the selected cases, the study uses four design days as representation of the whole year. The selected dates are June 21, March 21, September 21, and December 23, shown in Figs. 4.19 to 4.22. The criteria for selection of these dates are:

- Solstices and equinox occur during this period or very close to these dates
- Dates do not fall on weekends when office is not in operation
- Minimum cloud cover in the sky as this negatively impacts the performance of BIPV and EC glazing

Although all of these criteria were met for the design dates, in December overcast skies dominated the whole month. However, the selected design date has one of the least amounts of cloud cover during this month.

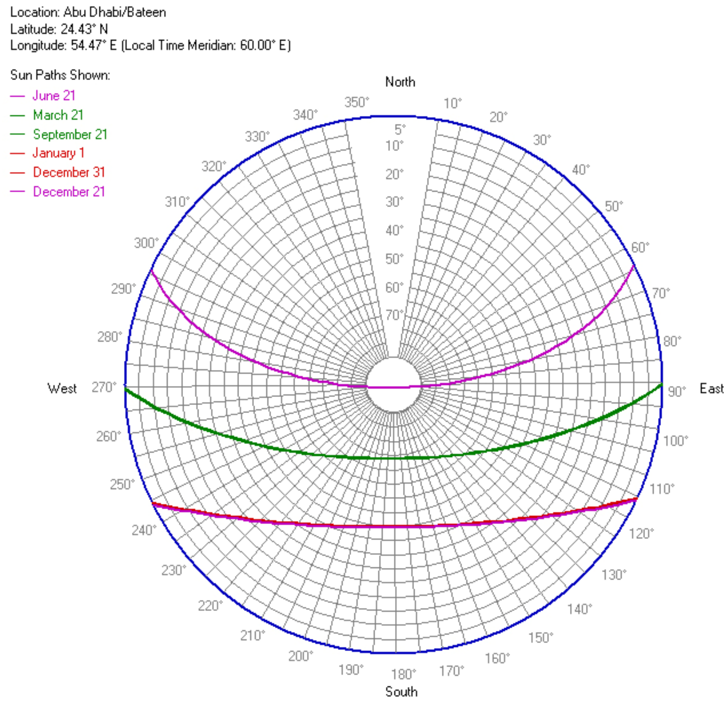


Figure 4.18 Sun Path diagram for Abu Dhabi (IES Database)

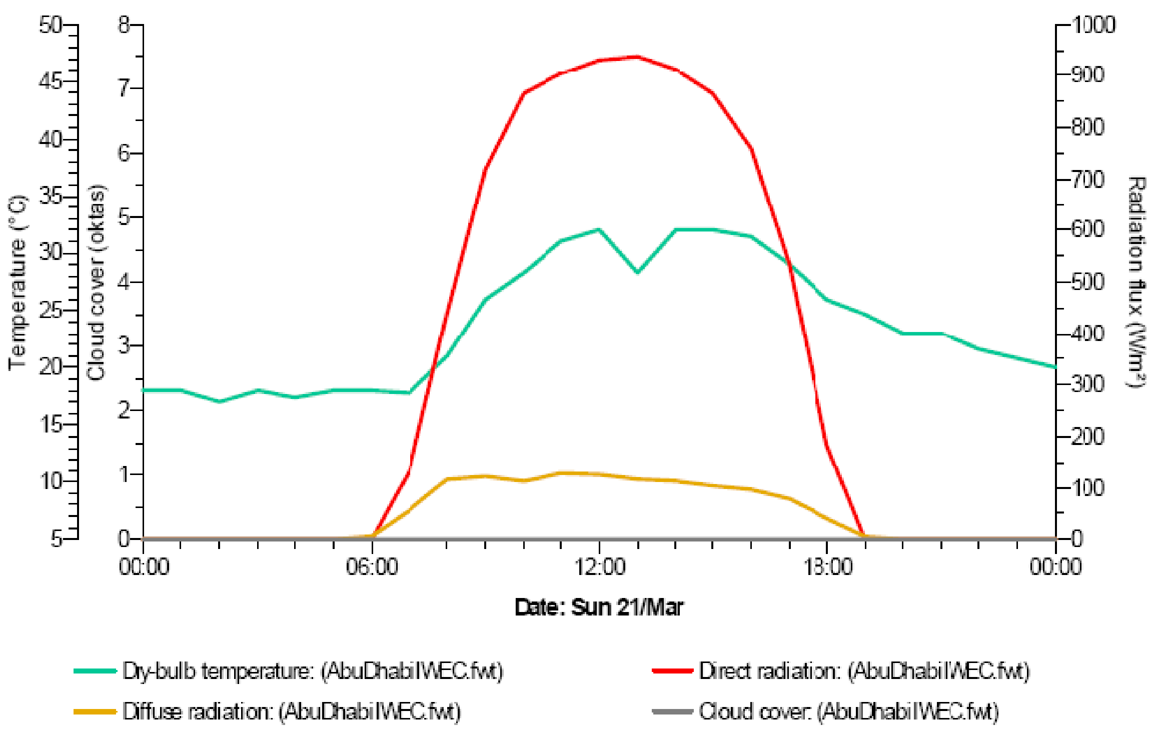


Figure 4.19 March 21 Weather Data of Abu Dhabi (IES-VE Weather Database)

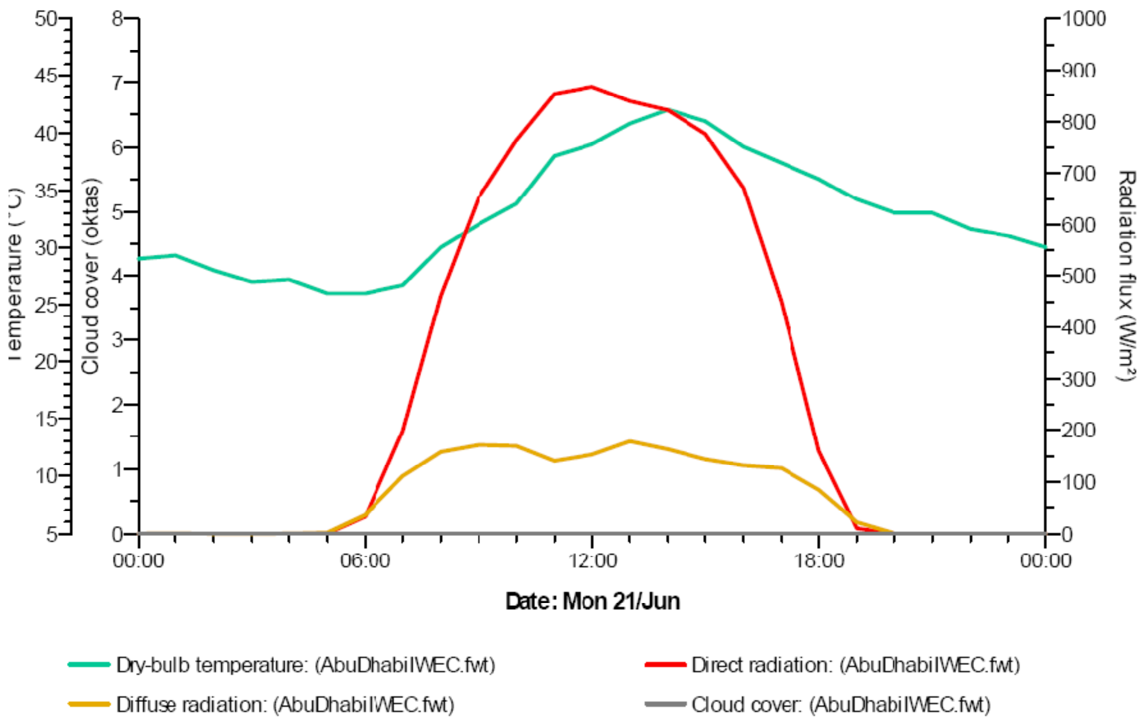


Figure 4.20 June 21 Weather Data of Abu Dhabi (IES-VE Weather Database)

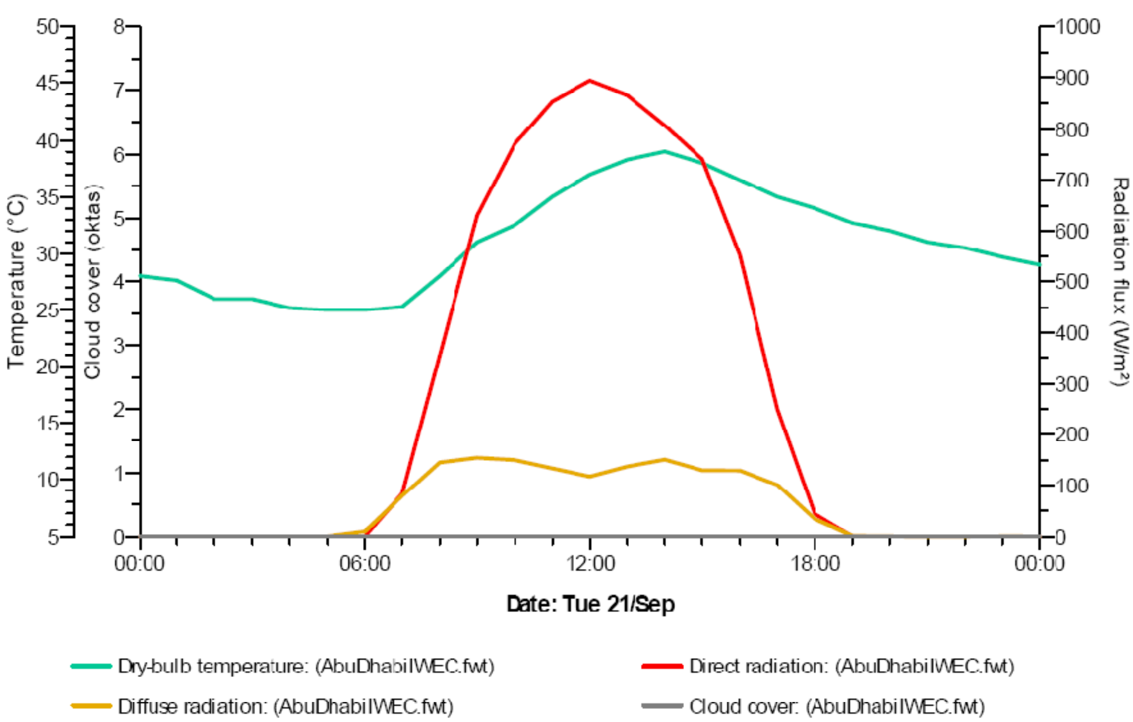


Figure 4.21 September 21 Weather Data of Abu Dhabi (IES-VE Weather Database)

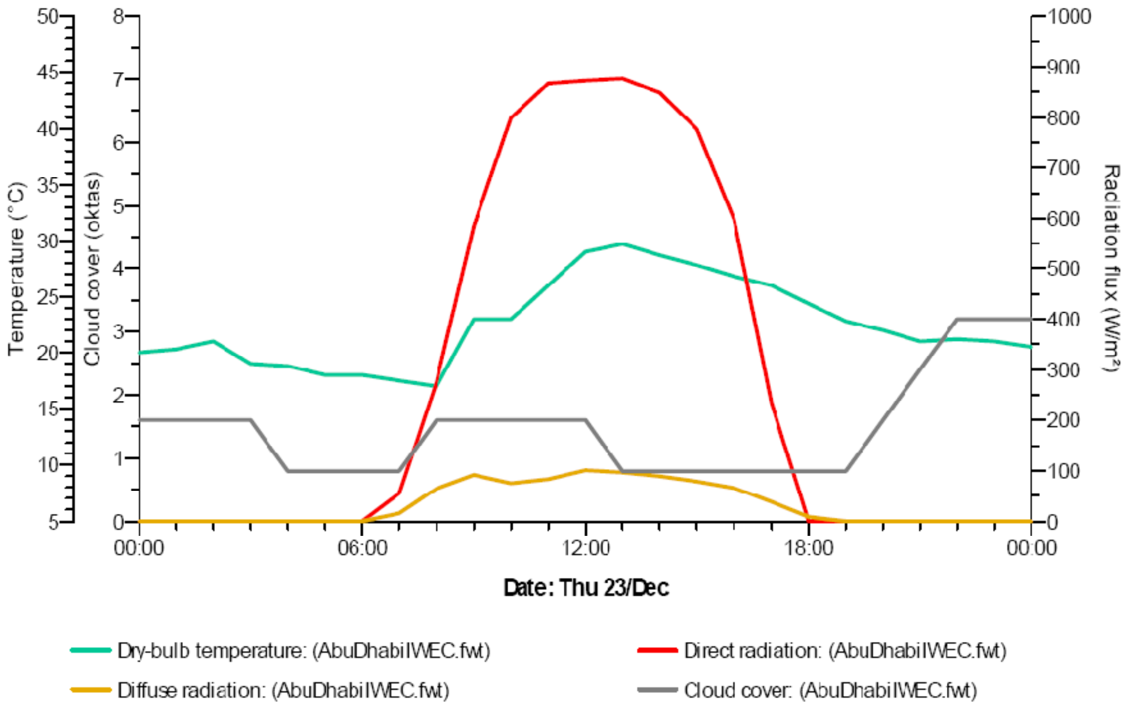


Figure 4.22 December 23 Weather Data of Abu Dhabi (IES-VE Weather Database)

4.1.8 Operation Profiles

Various profiles can be assigned using the Apache Profile Database in IES-VE. These are usually used for manipulation of different parameters that affect the lighting and HVAC systems. They are created from daily, weekly and annual profiles. This study will use profiles based on the normal operational modes found common in offices in Abu Dhabi. The standard office timings are set from 8am to 6pm on weekdays, and closed on weekends (Friday and Saturday).

Daily Profiles

The first daily profile, named Daily Blind Profile, activates the blinds. This is based on a deterministic behavioral model, as most occupants tend to respond to certain daylight changes to avoid glare and heat. Thus, whenever the illuminance levels in the office module (e1) go above the trigger set value of 2000lux, the blinds close, fully covering the window. This profile which follows the formula, gt(e1(1)2000,200), is appropriate for controlling solar heat gain as a function of available daylight. It adjusts the direct and diffused solar radiation as a function of available illuminance on the working plane, and helps to illuminate glare. The value of the profile, which is linear, falls from zero at illuminance below 2000 lux to 1 at illuminance above 2000lux, subject to a proportional bandwidth of 200lux. This bandwidth helps to reduce the number of times that this profile is activated in case of frequent changes in daylight levels.

The second daily profile, named Daily Auto Light Profile, activates the artificial lights. This is also based on illuminance levels of e1 that trigger the lights to be switched on below set value of 500lux. This profile is useful for controlling lighting gain as a function of working plane illuminance levels and follows this formula, lt(e1,500,0). The profile value falls from 1 at zero illuminance to 0 at 500lux illuminance. This profile follows the operational timings and will automatically switch lights off during non working hours regardless of illuminance levels.

The third daily profile, named Daily Light Dim Profile, triggers the dimming sensor when the illuminance levels of e1 are below 500lux. Similar to the previous profile, this profile which follows a new formula, lt(e1,350, 300), is also suitable for controlling lighting gain as a function of daylight illuminance on the working plane. The difference here is that the profile will modulate the artificial lights (lighting gain) in conjunction with the natural light levels achieved at the sensor location. The profile is set to maintain this balance at a constant level of 500lux illuminance on the working plane. The profile works by modulating a dimmer switch preset to an illuminance level of 350lux. This value is then subject to a proportional bandwidth of 150lux. This means that the profile will turn the lights (lighting gain) off when the room sensor measures daylight illuminance levels above 500lux and will alternatively turn them fully on when it measures daylight levels below 200 lux. The profile will then modulate the lighting levels (lighting gain) proportionately between these upper lower set points. For example, if the room sensor measures an illuminance of 350lux the light (light gain) would be at 50%. Similarly, if the daylight illuminance is 200lux or lower, the artificial lights would be at 100%.

The fourth daily profile, named Daily Operational Profile, activates the artificial lighting and HVAC system from 7am to 7pm and turns them off otherwise. This extra hour is assigned to help keep the room cool and because in most offices without automated lighting, the lights are switched on before the employees arrive. Figure 4.23 shows the graph of this profile.

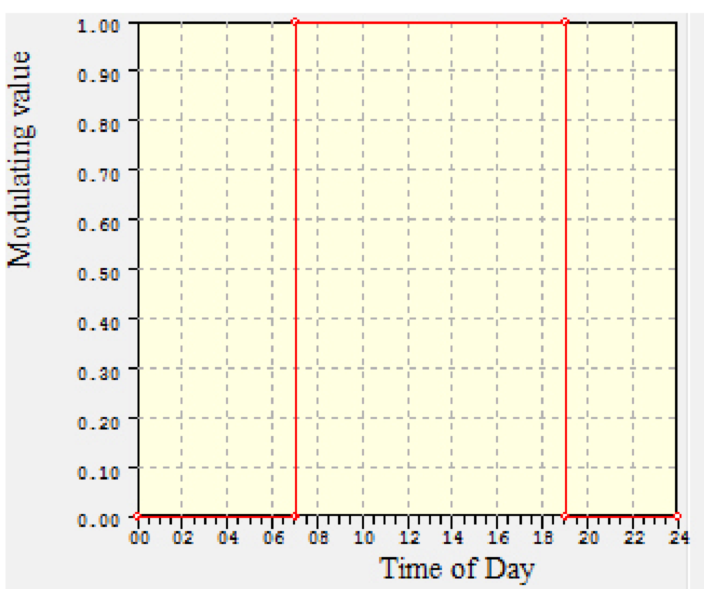


Figure 4.23 Daily Operation Profile (IES-VE Apache Profile Database)

Weekly Profiles

The weekly profiles are created from the daily profiles. The first weekly profile uses the Daily Blind Profile throughout the week and is always on during weekend. This means the blinds will remain closed on weekends. This profile is called Weekly Blind Profile seen in Fig. 4.24.

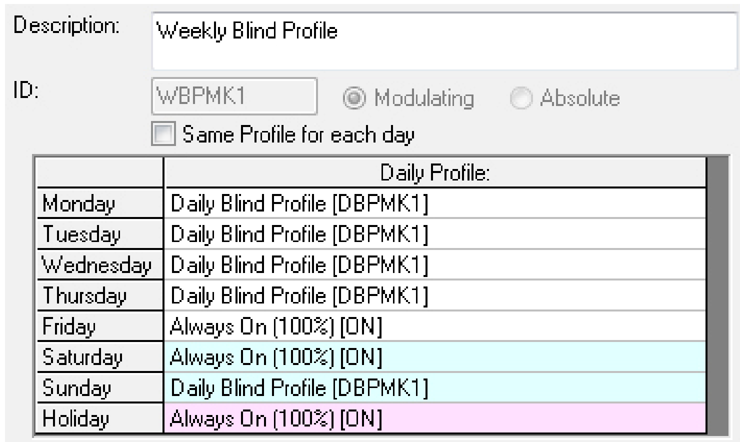


Figure 4.24 Weekly Blind Profile (IES-VE Building Template Manager)

The second weekly profile uses Daily Auto Light Profile throughout the week and is always off during the weekend. This means that during the weekend, the lights will always be turned off. This profile is called Weekly Auto Light Profile. The third weekly profile uses Daily Light Dim Profile throughout the week and is off continuously during the weekend. This means that during the weekend, the lights will remain switched off. This profile is called Weekly Light Dim Profile. The fourth weekly profile corresponds to the office operations on weekdays. This profile, named Weekly Operation Profile, follows the Daily Operation Profile for weekdays and keeps the HVAC and lighting system turned off during weekends, as shown in Fig. 4.25.

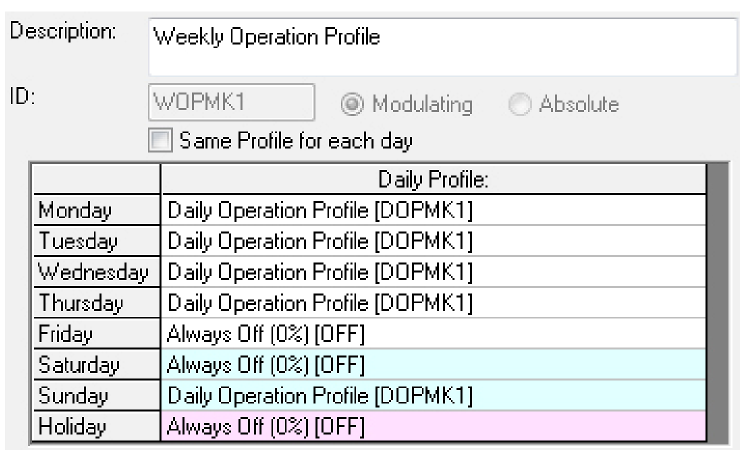


Figure 4.25 Weekly Operation Profile (IES-VE Building Template Manager)

Annual profiles

There are no annual profiles created because this will have a minimal effect on the overall results. The weekly profiles are used to simulate the whole year. Ultimately, the four design days will be the focus of the analysis.

4.2 SIMULATION CASE CONFIGURATIONS

The energy efficiency of EC glazing and BIPV has been assessed by studying various situations. The difference between the cases is made possible by changing the following variables:

- Daylight control
- Orientation
- Shading Coefficient (Solar Transmittance)
- Visible Light Transmittance
- Blind operation
- Sensor location

The simulation models have been categorized to make a comparative analysis. First they are divided into four groups based on orientation, south, east, west, and north. The simulations are run for a full year based on the daily and weekly profiles created. However, as previously mentioned, the assessment will be made by comparing only the selected design dates. Table 4.6 shows the matrix of the simulation cases.

Table 4.6 Simulation case matrix

	Sensor @ 2m					Sensor @ 4m		
	Shading Coefficient 0.27		Shading Coefficient 0.60		EC Glazing Model	Shading Coefficient 0.27		EC Glazing Model
	Base case Model	BIPV Model	Base case Model	BIPV Model		Base case Model	BIPV Model	
Group 1: South Façade								
March	x	x	x	x	x	x	x	x
June	x	x	x	x	x	x	x	x
September	x	x	x	x	x	x	x	x
December	x	x	x	x	x	x	x	x
Group 2: East Façade								
March	x	x			x			
June	x	x			x			
September	x	x			x			
December	x	x			x			
Group 3: West Façade								
March	x	x			x			
June	x	x			x			
September	x	x			x			
December	x	x			x			
Group 4: North Façade								
March	x	x			x			
June	x	x			x			
September	x	x			x			
December	x	x			x			

The following section describes the various simulations based on the matrix seen in Table 4.6.

4.2.1 Model #1: Base case

A base-case situation will provide the common ground from which the energy benefits of both the EC glazing and BIPV can be established. This model will use the standard characteristics of the module described for an Abu Dhabi office building. In this situation, there will be lights with on and off switch that can provide normal working conditions up to 500 lux. These lights will only be linked to an automated sensor that will switch them off beyond illuminance levels of 500lux. Thus, the model will use Automated Weekly Lighting Profile. This model uses roller blinds for daylight control which will follow the Weekly Blind Profile. The operation of blinds would be triggered by automatic sensors determining daylight levels going above 2000lux, thus giving protection from glare. And whenever illuminance levels are below this value, the blinds would be retracted. Although this automated control does not match accurate human behavior, it will primarily be used as a comparison benchmark. This comfort limit is used by Mardaljevic and Nabil (2005) in creation of a new daylight design paradigm entitled "useful daylight illuminance."

4.2.2 Model #2: BIPV case

The second model represents the PV cell integrated into the façade. An appropriate PV integration technique and selection of product is critical for optimum energy performance comparison to the two other cases. Section 4.1.5 described a strategy for selection of the most energy efficient BIPV configuration. All of the cases used automatic lighting control coupled with dimming linked to a sensor located at 2m away from window edge. Figure 4.26 shows the model which gave the best results in terms of overall energy consumption and occupant comfort amongst the ten cases. The explanation behind this selection is given in the beginning of the next Chapter. Hence, this model will be chosen for comparison against the base case and the EC glazing and configured as shown in Fig. 4.27.

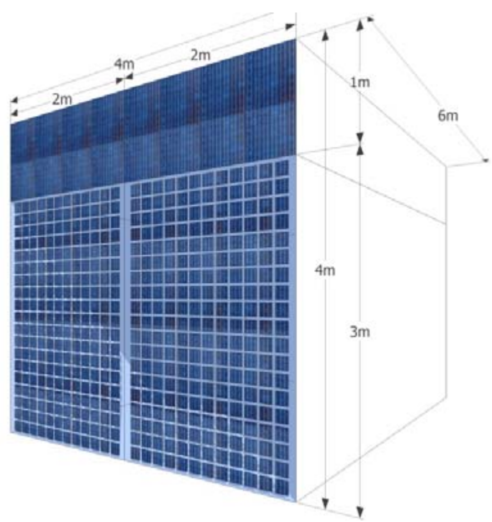


Figure 4.26 BIPV case 5 combines semitransparent and opaque mono-crystalline PV cells on facade

Furthermore, in this model, the system is assumed to be connected to a grid. Therefore, any additional power produced during the day beyond the needed capacity, can be fed back into the grid with the meter running in reverse. However, the fact that grid-connectivity is not available in the UAE, other strategies must be considered.

For example, an energy storage strategy is an option for power produced at times when it cannot be utilized, especially in the weekends. In addition, because PV arrays tend to heat up, especially in the hot regions, in order to simplify the model, an assumption is made about their cooling mechanism. This is considered to be a passive system, whereby the heat is simply dissipated back into ambient air.

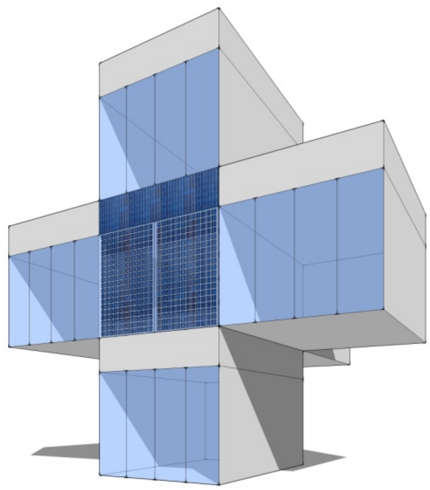


Figure 4.27 Model #3: Conventional façade replaced by BIPV

4.2.3 Model #3: EC glazing case

For the third model, the standard glazing will be replaced by EC glazing shown in Fig. 4.28. Previous researches have shown that the best energy performance is achieved by daylight control switching of EC, mostly because of the "large electric lightning load reduction from day-lighting" (Sullivan et al., 1997). The lighting mechanism will be similar to the base-case, where dimming control will be used to maintain a constant lighting condition of 500lux levels from natural light with artificial lights acting as supplementary. In this scenario, the EC glazing will be considered in full tint mode during non working hours and weekends. The objective of this model is to evaluate the contribution of dynamic glazing and dimming control in the overall energy consumption.

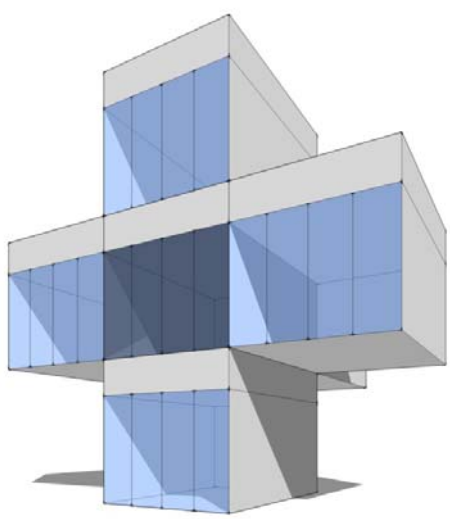


Figure 4.28 Model #2: Conventional glass replaced by EC glazing

4.4 MODELLING PROCESS

The following describe the different modeling stages that were carried out for this study.

- Creating the models: The models were created from ModelIT which is IES-VE model building component. Only the BIPV case with the checkered patterns (Refer to Chapter 4, Fig. 4.8) was built in Google SketchUp and then imported into IES.

- Defining model parameters: APLocate, Building Template Manager, and Construction Database are used to define the location and weather data, room parameters, and construction materials respectively.

- Lighting sensor: The lighting sensor will be placed at distance of 2m and 4m from the window at centerline of the office module using the Radiance lighting simulation component. This will create a model.ill file using the "Apache" button which is used in the ApacheSim Radiance link.

- Project profiles: The various daily and weekly profiles, described in section 4.1.8, are set up suing the Profiles Database (APpro). The lighting luminaires as well as the blinds are linked to these different profiles.

- Solar analysis: SunCast component is used for performing solar shading analysis and solar insolation for the obstructions, windows and openings. Whenever there is a change in orientation, or the obstruction objects are changed, this analysis needs to be repeated. In ApacheSim, there is a link from the SunCast calculation, which is required prior to running the simulations.

- Simulations: ApacheSim (Dynamic Simulation) is used to perform the simulations. The "Renewables" button is used to add the details of the BIPV panel configuration. The Radiance and SunCast link are optional for studying the changes in sensor profiles and shading elements. The Vista component is used for viewing the results of the ApacheSim.

4.5 MODEL VALIDATION

The software commonly used by mechanical engineers, HAP 4.5, which is a thermal simulation tool, was used to validate the results obtained from the base case model. The parameters of the base case model were given to a mechanical engineer from KEO (www.keoic.com). This model, as described earlier, had shading coefficient of 0.27, and with a constant cooling load set point of 24˚C. However, in this comparison, there will be no blinds used for simplicity and the operation will be on 24 hour basis. The cooling loads for peak hours of months of June and December were obtained in IES using the ASHRAE Loads calculation tool. These findings were compared to cooling loads obtained from HAP (see appendix D).

Figure 4.29 and 4.30 show the comparison of the results between the two simulation programs on an hourly basis. Further, Fig. 4.31 shows the total daily cooling loads for each simulation tool in the selected months. It can be seen that the loads follow the same trend. The small variation can be accounted due to minor difference in weather data files used by the two softwares. For instance, IES can take up to five decimal points, where as HAP cannot take more than two decimals. Another difference is the slight variations in the ambient temperatures used by both softwares. Altogether, the results show the author's proficiency in confidently using IES for conducting this research.

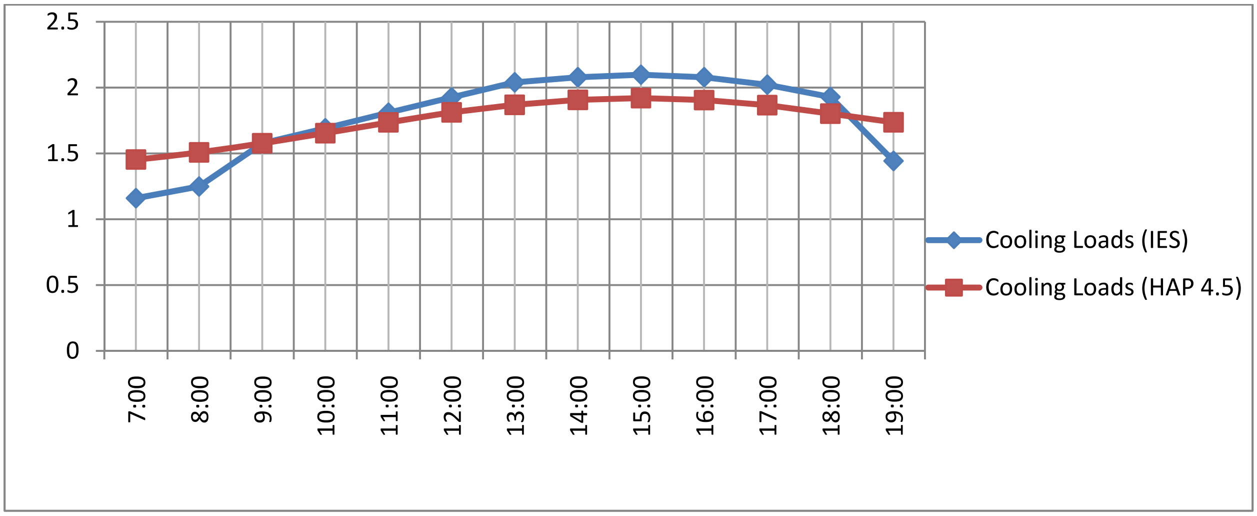


Figure 4.29 IES and HAP cooling loads in June

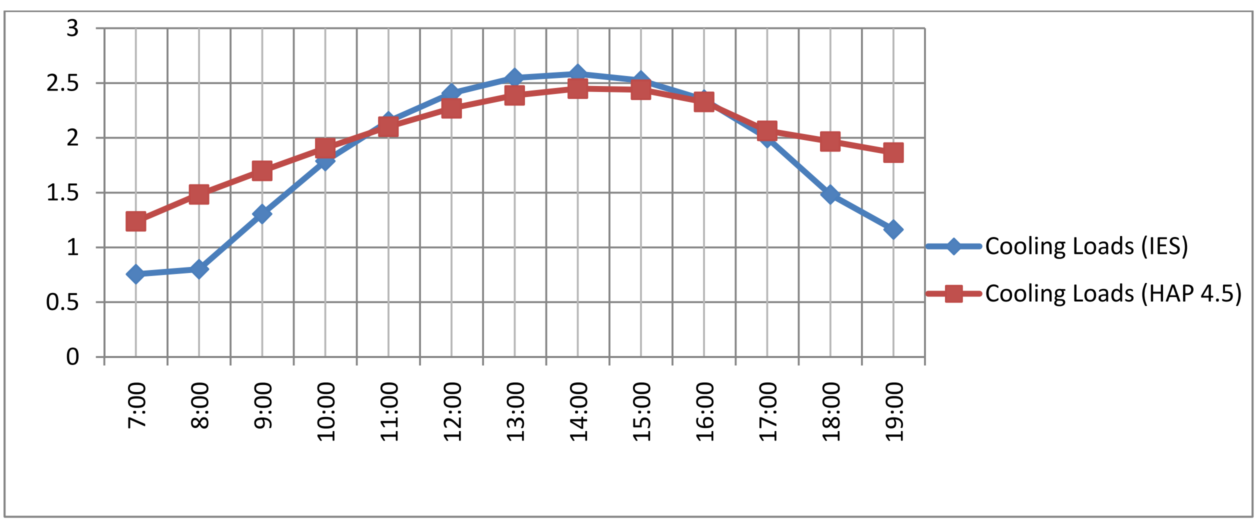


Figure 4.30 IES and HAP cooling loads in December

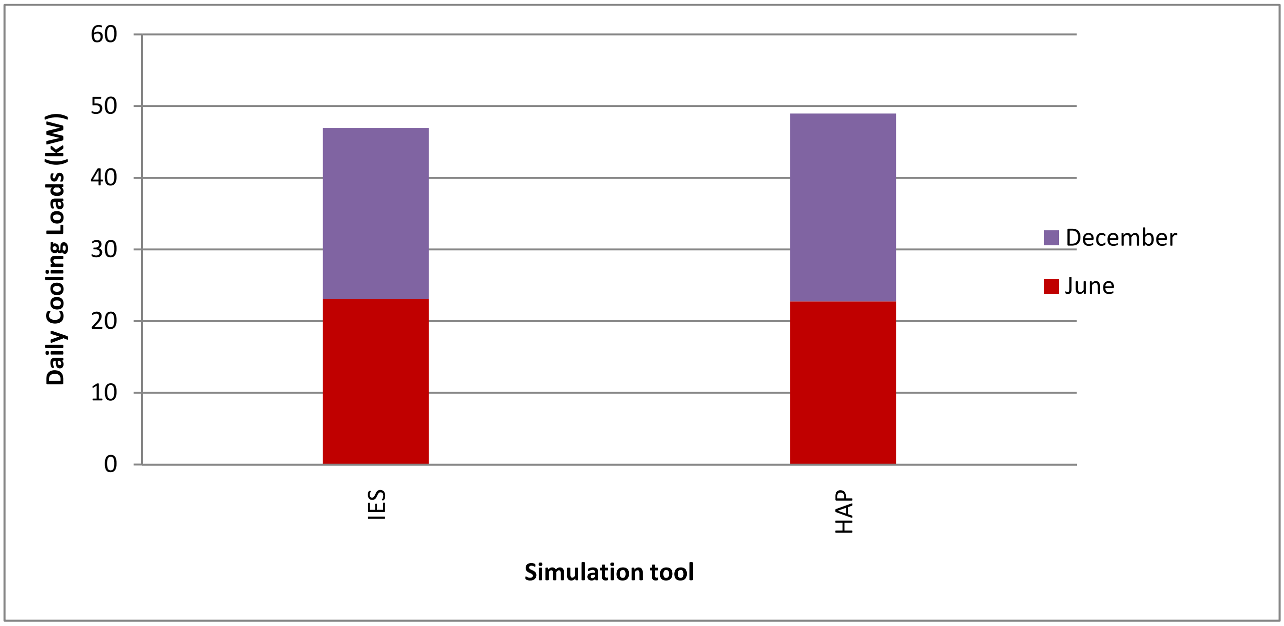


Figure 4.31 IES and HAP daily cooling loads in June and December

CHAPTER 5: SIMULATION RESULTS AND DISCUSSION

This Chapter presents the results from all the simulation of the configurations outlined in the previous Chapter. The first section will discuss the results from the ten BIPV test cases mentioned in chapter four. A discussion of these findings will form the reasoning of the selection process and the final model chosen for the comparison against the other two cases. Following this discussion, the proceeding sections are the results of simulations that are grouped according to the orientations, value of shading coefficient, and the position of the light sensor.

5.1 BIPV CONFIGURATIONS ASSESSMENT

As mentioned earlier in chapter four, the main purpose of this assessment is to select the optimum BIPV configuration to compare against the other two models. The results are from simulation runs on annual basis for a South facing façade with a lighting sensor in middle of the room. The four criteria which were considered in choosing the most optimum case study were energy used for artificial lights, power used to run HVAC and lights (total electricity), total grid displaced electricity (amount of PV power generated), and net energy consumption (HVAC + lights – PV power). All the models used the Weekly Auto Light profile and Weekly Operation profile described in chapter four.

5.1.1 Profile Review

An early investigation tests the behavior of the artificial light in relation to the daylight illuminance for the selected day in December. Recall that BIPV case no. 5 has semitransparent Monocrystalline cells embedded within the glazing, while the case no. 10 uses thin film cells. Undoubtedly, these two scenarios should have different lighting consumption behavior. As Fig. 5.1 shows, the former is consuming more artificial light energy shown with two peaks. It is evident that once the lux levels go beyond 500, the lights are turned off, and hence the lighting gain (yellow line) drops to zero. This is maintained until the lux levels in the room fall below 500 again which triggers the lights coming on and adds to energy use for cooling from lighting gain. This is evidence that the profiles are working correctly.

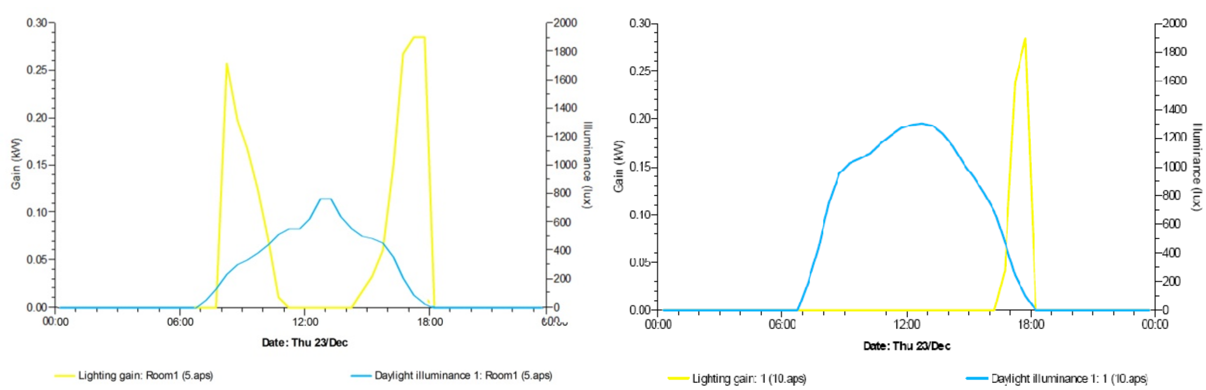


Figure 5.1 Lighting gain relative to daylight illuminance on December 23 for BIPV case no. 5 (left) and no. 10 (right)

5.1.2 Achieving energy efficiency

The summary of the overall results of the BIPV tests shown in Table 5.1 indicate that case no. 5 has the lowest total energy. At the same time, a closer observation reveals that this case did not have the lowest light energy consumption. This is mainly due to the majority of BIPV cells blocking natural light which increases the need for more artificial light. However, this value was offset with the high amount of PV power produced, and therefore, the total energy balance is still better compared to all other cases. It is important to mention that although the BIPV configurations all differ, the power output of some of the cases (no. 2 and 3) were identical as can be seen in Total Grid Displaced Electricity of Table 5.1. This is because the software calculates the PV power based on total area of PV cells. Thus, even though the façade configurations are different, the power output would be identical if both have identical area of BIPV. After comparing the total energy value of case no.2 and 3 with case no. 1, it is evident that the higher need for artificial lighting outweighs the electricity produced in the latter, and thus amongst there three cases, case no.3 is the most practical. Therefore, if this scenario also utilized PV cells across the spandrel area of the façade, it would undoubtedly have the best energy results. In fact, the repetition of the tests for this case shows the total energy value to come down to 2.351MWh. This scenario, although not previously considered in the BIPV selection strategy (section 4.1.5) is here named case no. 11 as seen in Table 5.1.

Table 5.1 Energy analysis of the BIPV cases compared to the Base case

Case #	Total Lights Energy (MWh)	Total electricity (MWh)	Total Grid Displaced Electricity (MWh)	Total Energy (MWh)	Ranking
Base case	0.3626	4.9571	0	4.9571	12
1	0.5672	3.6412	-0.7105	2.9307	8
2	0.4625	3.3745	-0.5983	2.7762	5
3	0.4435	3.3482	-0.5983	2.7498	4
4	0.1940	3.3265	-0.3989	2.9276	7
5	0.5672	3.6412	-1.1094	2.5318	2
6	0.7293	4.1504	-0.8263	3.3241	11
7	0.4830	3.7949	-0.6886	3.1063	10
8	0.1687	3.3405	-0.4591	2.8814	6
9	0.1940	3.3265	-0.3060	3.0204	9
10	0.1687	3.3405	0-.7651	2.5754	3
11	0.4435	3.3482	-0.9972	2.3510	1

It is important to consider that cases no. 8 and 10, which used thin film BIPV with highest level of transparency of 50%, gave the best results for light energy consumption. This is due to increased use of natural lighting which cuts on artificial light loads and reduced HVAC loads. Hence the total electricity for both these cases is better than case no. 5. Furthermore, the results of cases no. 4 and 9, which used conventional glazing with blinds, and only employed BIPV over the spandrel area of the façade, comes in second place in terms of light energy. Moreover, the use of blinds helps in HVAC load reduction and thus these two cases have the lowest total electricity value. However, due to small amount of power produced, the overall results do not fare well for both cases. The BIPV case with the highest light energy consumption and highest overall energy use is no. 6. This case utilizes thin film with only 10% visible light transmittance, which consequently increases the artificial light energy demand.

The overall results confirm that although case no. 10 has a much lower need for artificial lighting, case no. 11 outperforms the other configurations when it comes to total energy. However, it is important to consider that case no. 10 gives a better integration effect on the façade as the vision glass is not obstructed with checkered patterns and is more uniform giving a clear view to the outside.

5.1.3 Achieving comfort

Having so far examined the ten scenarios in terms of energy savings, it is imperative to understand that such an assessment might not be sufficient for selecting the best BIPV case. Other parameters must be analyzed to ensure adequate working conditions are met for the maximum comfort of the occupants. One of the important aspects is proper lighting conditions and glare protection. Glare is commonly caused by either the excessive luminance values in the field of view and or too high luminance contrasts. Windows can have a high luminance compared with other luminances in a room. This gives a strong contrast from inside to outside, potentially causing glare. The sun is the strongest luminance source, therefore, if this in the field of view then glare is inevitable (IES, 2010). Figure 5.2 shows the illuminance levels at working plane for the selected day in December under standard clear sky conditions for all the configurations. Case no. 6 shows the least amount of daylight penetration which coincides with Table 5.1 findings of having highest artificial light usage. In a similar fashion, cases no. 8 and 10 both have a large amount of daylight which matches the results shown in Table 5.1 with lowest amount of artificial light usage.

Moreover, cases no. 4 and 9 are also permitting a large quantity of natural light. In the case of the former, this is because PV cells are only used on the spandrel area of the façade, therefore, natural light is not blocked. While in the case of the latter, the high transmission value of thin film cells gives the natural light advantage.

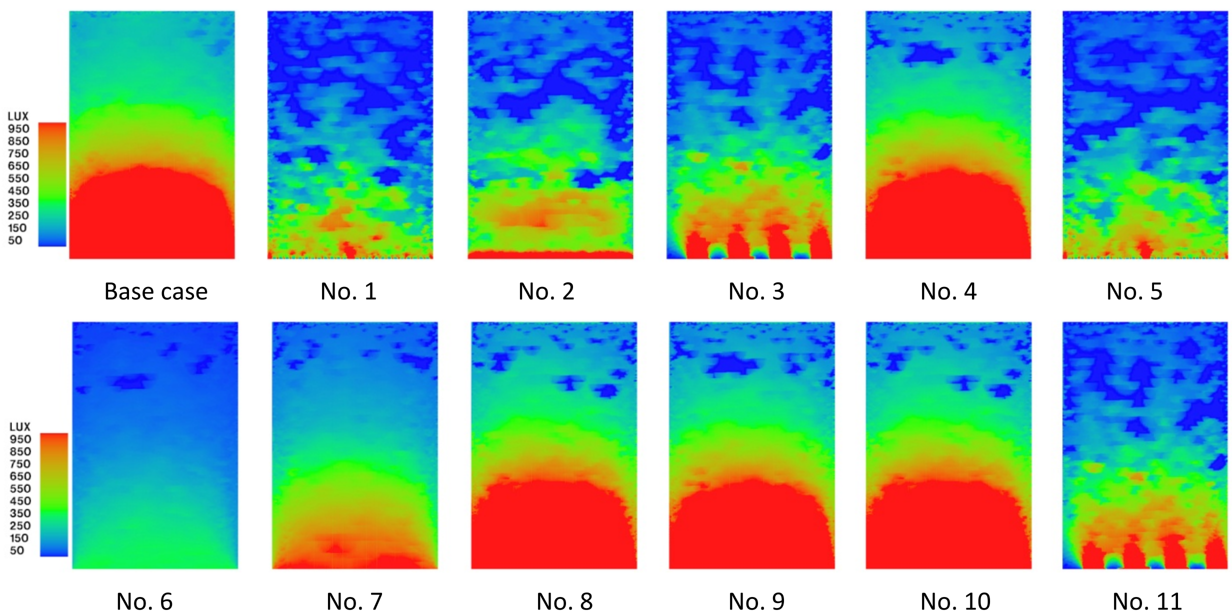


Figure 5.2 Working plane illuminance levels on December 23 at 12pm for BIPV cases and base case

The glare analysis for the ten configurations, seen in Fig. 5.3, shows that the BIPV cases with Monocrystalline cells (case no. 1 to 5) perform better than thin films in blocking unwanted high luminance levels. In cases no. 6 and 7, where the light transmission value is low, the thin film cells also block glare effectively. For both case no. 4 and 9, the high luminance would mean that the blinds would need to be used. Similar results were obtained for case no. 8 and 10 showing glare near the window edge. However, due to lack of blinds in these models, the occupant would be left with a discomforting experience.

Bearing in mind the important aspect of glare protection for occupant's comfort, the earlier comparison between case no. 11 and 10 in terms of energy savings and façade uniformity now turns in favor of the former. However, taking into account the glare analysis of case no. 11, this case would not fare as well as case no.5. Furthermore, this simple glare analysis was done for South facing window at noon. If it were repeated for a West facing façade at 4pm, the results would be even worse for case no. 11 with its large unprotected areas of glass. Therefore, through examinations of energy efficiency and human comfort, case no. 5, which had the third overall energy consumption value compared to the others will be chosen as the BIPV model for comparison against the EC glazing and the Base case. Figure 5.4 shows the glare values of this model at various time of the selected day in December.

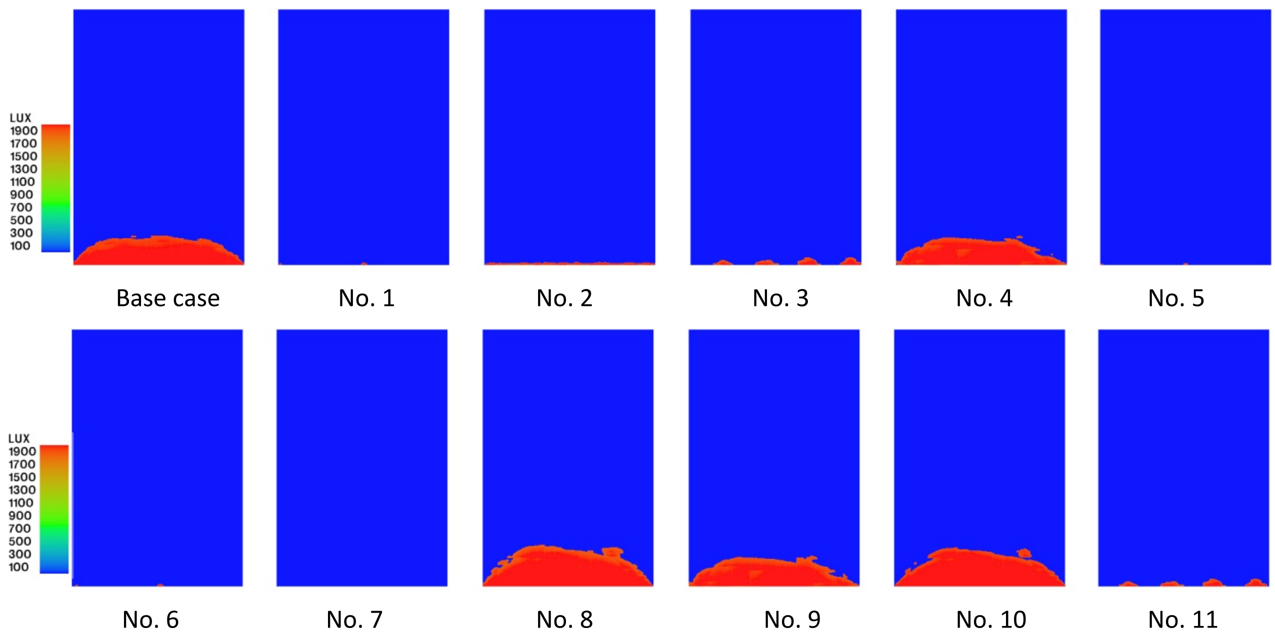


Figure 5.3 Working plane glare levels on December 23 at 12pm for ten BIPV cases and base case

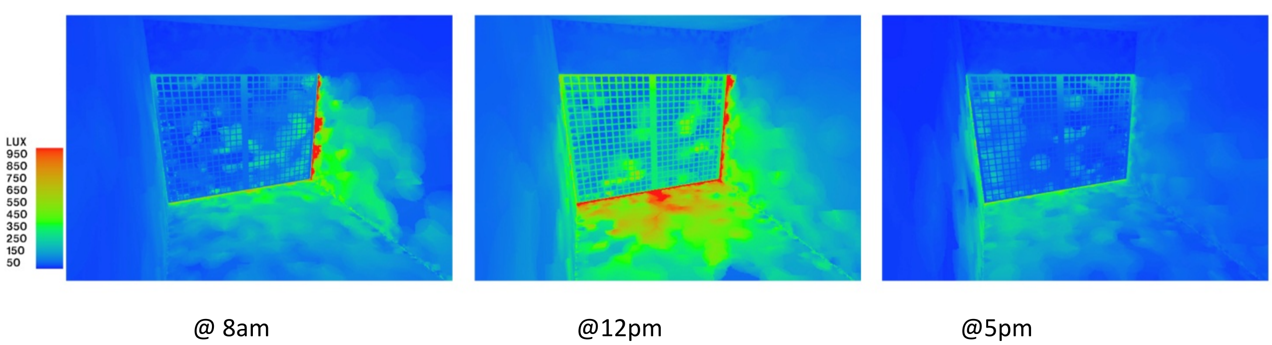


Figure 5.4 Case no. 5 South facing window illuminance levels on December 23 under clear skies

5.2 SOUTH FAÇADE ORIENTATION

5.2.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

March

The simulations of the selected day in March show completely different results for the EC glazing and the BIPV model. The former consumes slightly more energy (7.75%) compared to the base case model, whereas the latter has a significant reduction (30.7%) against the base case. One of the main advantages of the BIPV model is that even when the building is unoccupied the façade is producing electricity, and thus offsetting the total daily energy consumption, assuming there is a battery for storage or the BIPV is connected to the grid. Figure 5.5 shows the energy consumption of the various configurations in selected day in March.

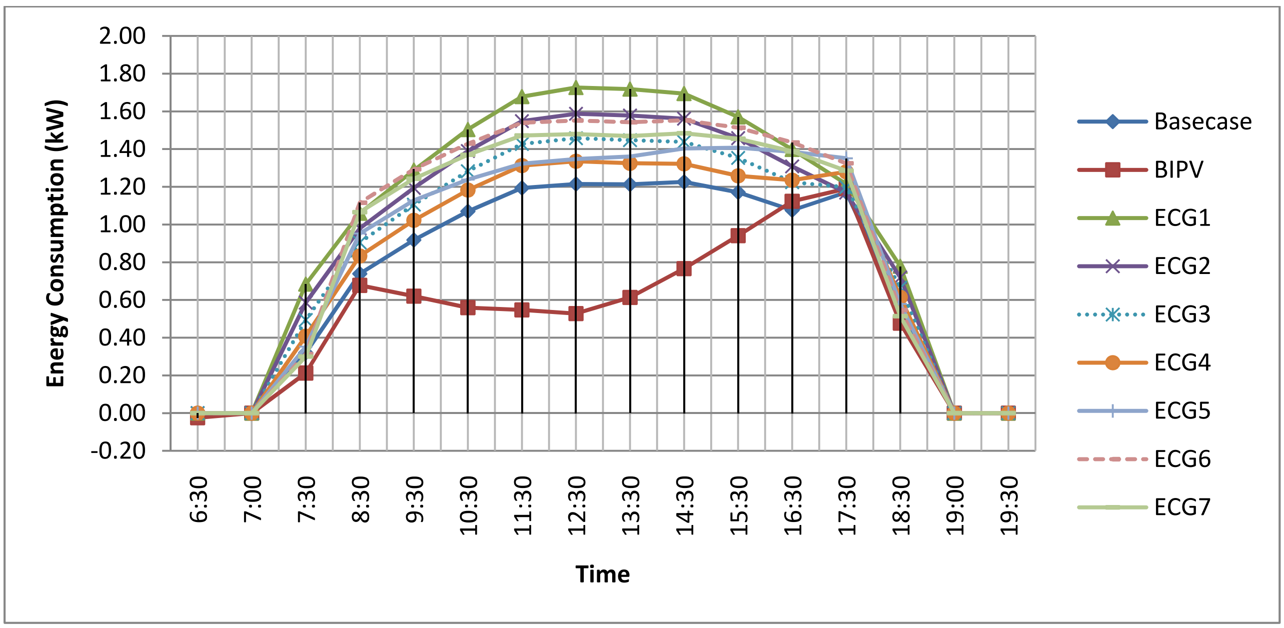


Figure 5.5 Hourly Energy Consumption for all configurations for South façade in March 21

The two main variables that affect the potential energy savings are the lighting energy and cooling loads. Figure 5.6 shows the lighting loads breakdown of each for all the configurations. The base case model with automated lights, no dimming and with blinds has one of the lowest loads. Not surprisingly, the EC glazing models with low tinting (ECG 1, 2, 3) have the lowest light energy consumptions amongst all the models. In the same way, the ECG model with the highest tinting value (ECG 7) requires the most amount of artificial light. Once again as seen previously in section 5.1, the integration of PV on the façade causes higher demand for lighting electricity. However, this is compensated by the electricity produced from the cells by a factor of two.

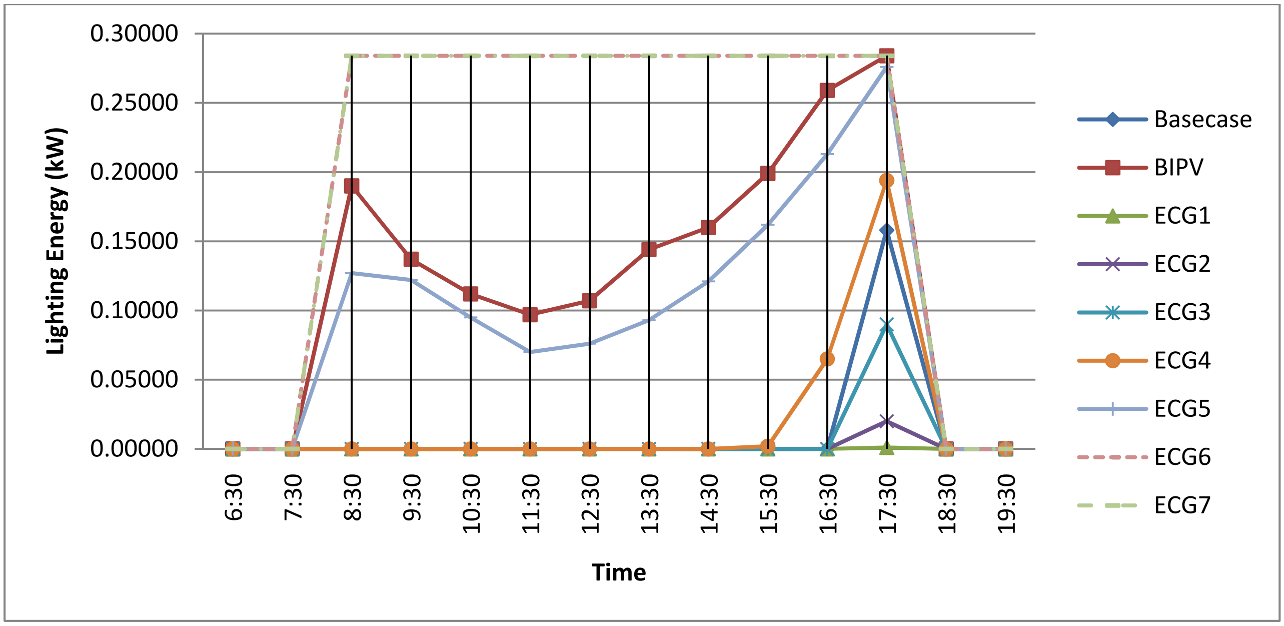


Figure 5.6 Total Lighting Energy for all configurations for South façade in March 21

Figure 5.7 shows the total system energy for all configurations. Since no heating requirement has been considered, the system energy is the total of Chiller energy, Chiller heat rejection fans/pumps energy and the system auxiliary energy (e.g. energy for FCU). In the case of the BIPV model, the electricity generated from the panels is displaced as well. The results indicate that the BIPV model has the lowest system energy amongst all cases.

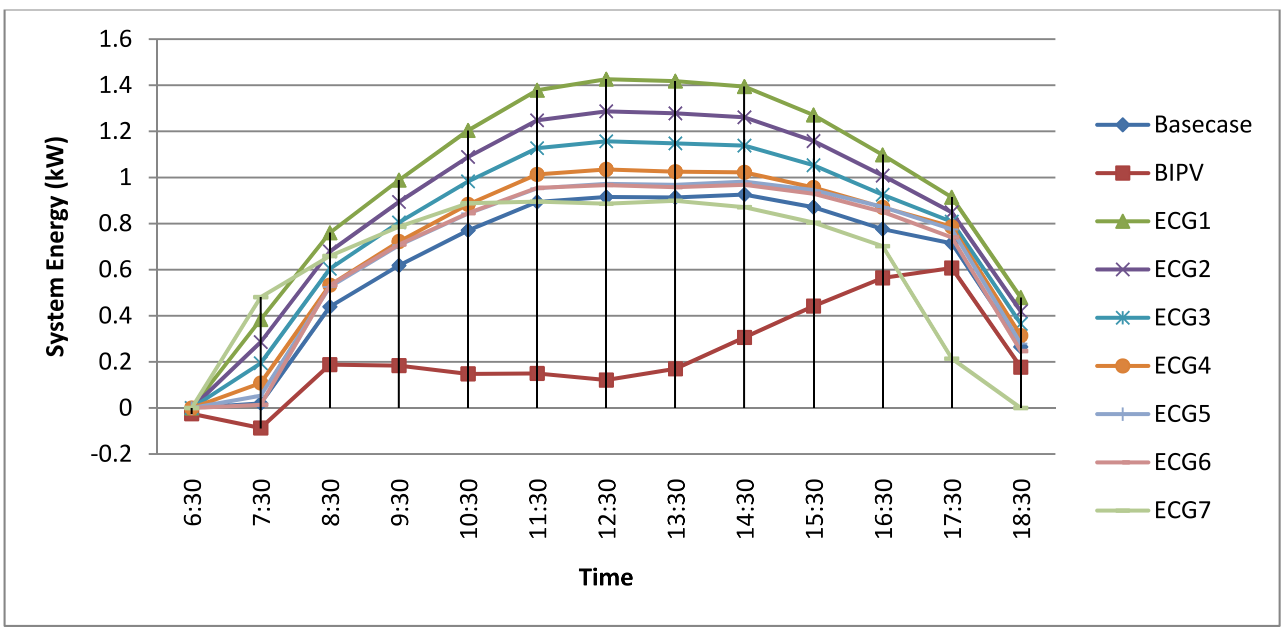


Figure 5.7 Total System Energy for all configurations for South façade in March 21

However, if the models were to be compared purely on the basis of cooling loads, without power generation, as seen in Fig. 5.8, the margins would be much less. Although the BIPV model still has the least cooling load, the EC glazing models with 90% tinting blocks a large amount of solar radiation and undoubtedly has the second lowest cooling load associated with it. Hence, the effect of high tinting has a positive effect on the reduction of cooling loads. The use of blinds for the base case model also produces very good results which are not far off from the best scenario.

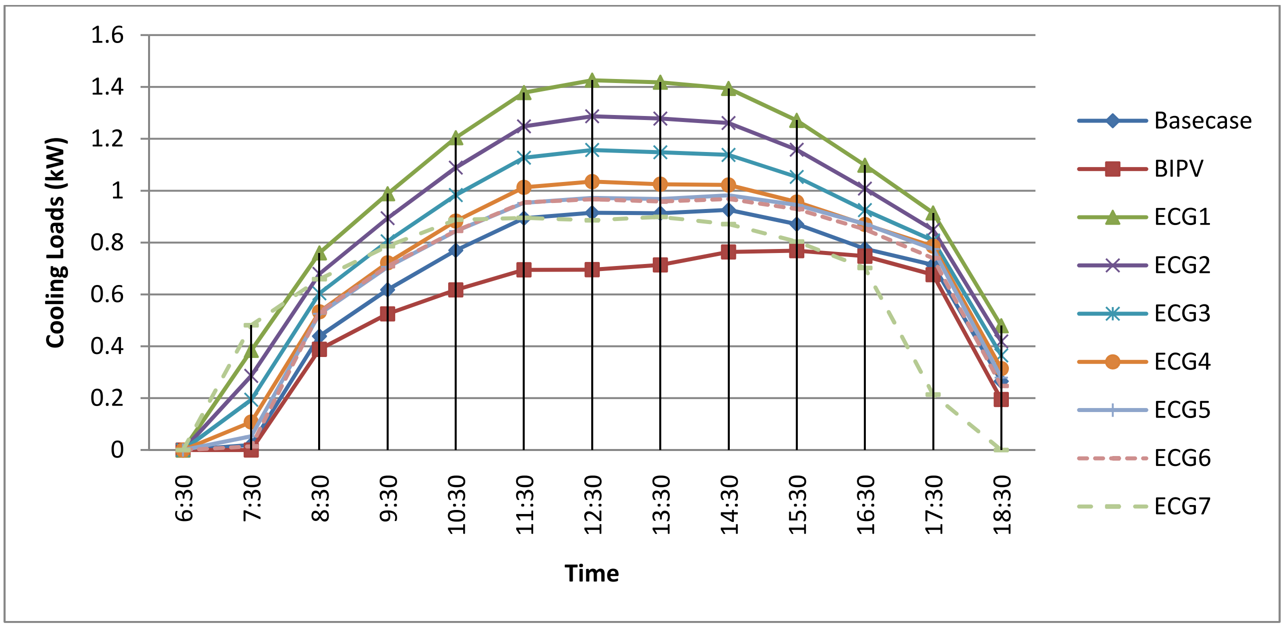


Figure 5.8 Total Cooling Loads for all configurations for South façade in March 21

In order to better evaluate the actual performance of EC glazing model, the seven tinting stages described earlier (refer Table 4.3), will be used to quantify with the optimum dynamic glazing energy consumption. Table 5.2 shows the values of least energy demand highlighted and used to calculate the EC glazing energy in comparison to the other two models. As expected, there is a requirement for dark tinting value in early morning and late afternoons due to high illuminance caused at sunrise and sunset. This is one of the benefits of the EC glazing in blocking glare at these times. During most of the day, a consistent tinting value for EC glazing is used to achieve optimum energy balance. As Fig. 5.9 shows, the optimum tinting percentage value for the EC glazing model is 45% which achieves a visible light transmittance (T_{vis}) of 30% (ECG 4). Thus with minimal fluctuations, it can be considered that an optimum fixed tinting for EC glazing would be 45% as this has the lowest energy consumption amongst the other models (13.12kW).

Table 5.2 Hourly energy consumption of all scenarios of South façade in March 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
March 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.02467	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	0.32000	0.21273	0.68391	0.58603	0.49415	0.40811	0.35256	0.31374	0.30000	33.52%	6.25%
	8:30	0.73900	0.67755	1.05991	0.97947	0.90422	0.83329	0.95197	1.11577	1.06558	8.32%	-12.76%
	9:30	0.91800	0.62020	1.28829	1.19367	1.10537	1.02238	1.12823	1.29302	1.24291	32.44%	-11.37%
	10:30	1.07000	0.55949	1.50384	1.38945	1.28271	1.18251	1.23856	1.42912	1.36989	47.71%	-28.03%
	11:30	1.19400	0.54757	1.67814	1.54821	1.42676	1.31263	1.32268	1.53941	1.47207	54.14%	-23.29%
	12:30	1.21500	0.52809	1.72631	1.58742	1.45750	1.33534	1.34726	1.55145	1.47939	56.54%	-21.76%
	13:30	1.21300	0.61322	1.71773	1.57806	1.44752	1.32489	1.36089	1.54219	1.46970	49.45%	-21.16%
	14:30	1.22600	0.76608	1.69391	1.56136	1.43780	1.32196	1.40330	1.55231	1.48368	37.51%	-21.02%
	15:30	1.17100	0.94086	1.57064	1.45809	1.35338	1.25822	1.40770	1.51350	1.45525	19.65%	-24.27%
	16:30	1.07600	1.12342	1.39789	1.30811	1.22462	1.23510	1.38552	1.43517	1.38790	-4.41%	-14.79%
	17:30	1.17100	1.19074	1.21500	1.16919	1.19787	1.27962	1.35134	1.32468	1.28572	-1.69%	-2.29%
	18:30	0.56500	0.47667	0.77859	0.71939	0.66490	0.61421	0.57874	0.54688	0.51409	15.63%	-17.68%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**11.87800**	**8.23195**	**16.31416**	**15.07845**	**13.99680**	**13.12826**	**13.82875**	**15.15724**	**14.52618**	**30.70%**	**-7.75%**
				Total (Optimal Dynamic Glazing)					**12.79912**			

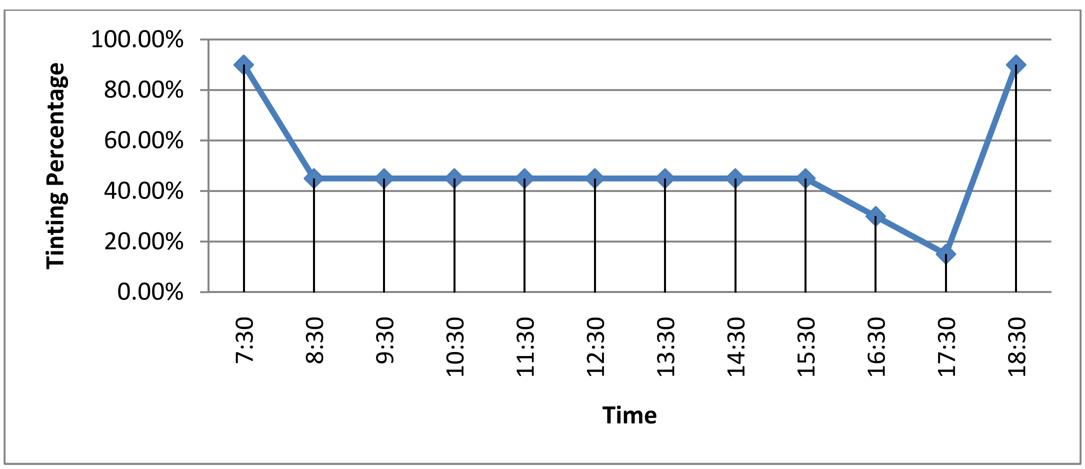


Figure 5.9 Optimum tinting percentage of EC glazing in March 21

Figure 5.10 shows the energy consumption of the base case, BIPV, and optimal dynamic glazing configurations. While the BIPV model has the least energy consumption, the EC glazing is slightly worse than the base case model using blinds. The BIPV model begins to show improvements in comparison to the other two models right after the first few hours in the morning by taking advantage of its power generating mechanism. The electricity production reaches its best peak at mid day and declines to its least around 5:30pm when the three cases become very similar.

Thus the results confirm that with the given parameters, EC glazing model is less beneficial than the base case model and does not come close to the BIPV case. This means that an EC window capable of dynamic tinting with ranges from 3.5% to 90% will consume more energy than a base case scenario with only blinds.

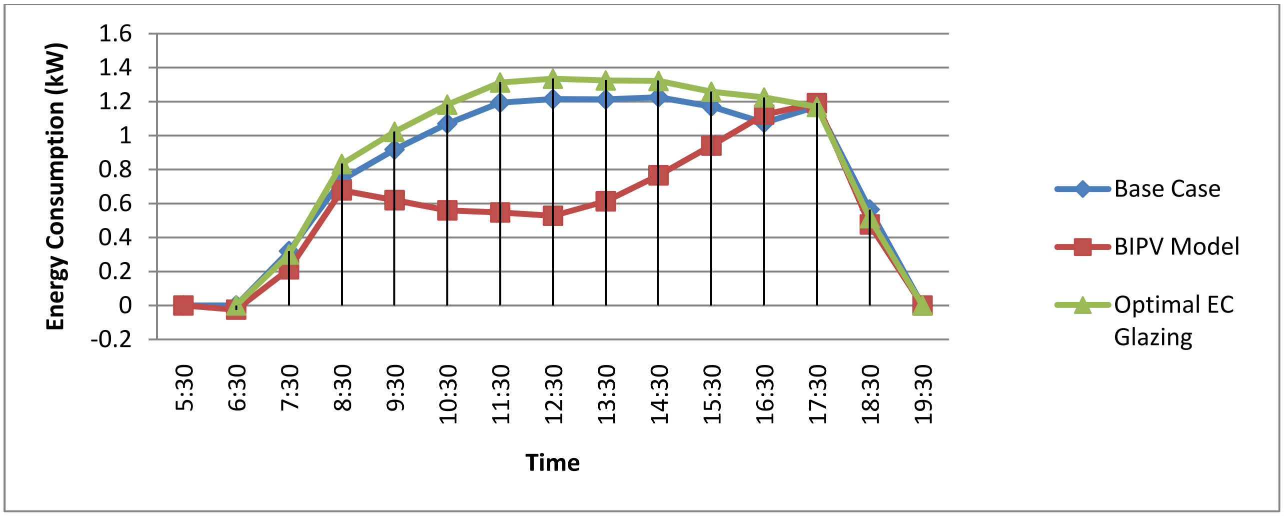


Figure 5.10 Hourly Energy Consumption for all configurations for South façade in March 21

<u>June</u>

The simulations for the selected day in June indicate an improvement in the EC glazing model which now consumes slightly less energy (3.5%) than the base case model. The BIPV model is now less energy efficient (2.49%) than the base case. The EC glazing model begins to show improvement over the base case in the middle portion of the day, seen in Figure 5.11. This implies that its shading coefficient is more suited than the base case for the selected day in blocking solar gain. Figure 5.12 shows a shift in the ECG optimum tinting percentage from March. The lower value suggests less solar gain penetration and hence higher chance of visibility to outside, as visible transmission has increased from 30% to 50%. Once again the consistency of high tinting at early morning and late afternoon compared to March confirms the functional behavior of the EC glazing in blocking glare during these periods. Table 5.3 shows the total energy consumptions for all the configurations in June.

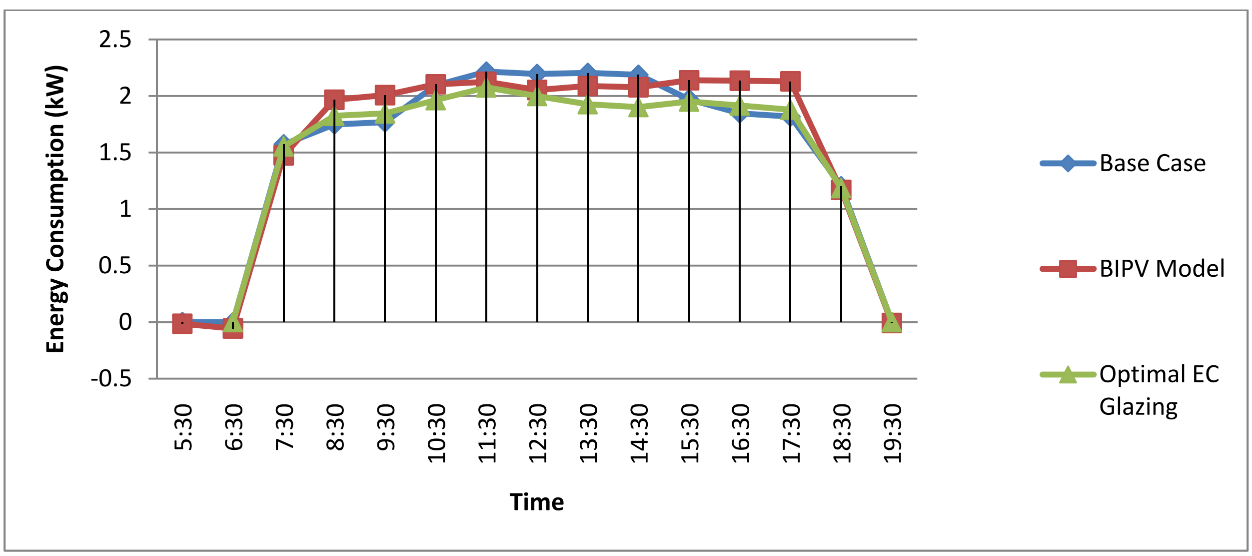


Figure 5.11 Hourly Energy Consumption for all configurations for South façade in June 21

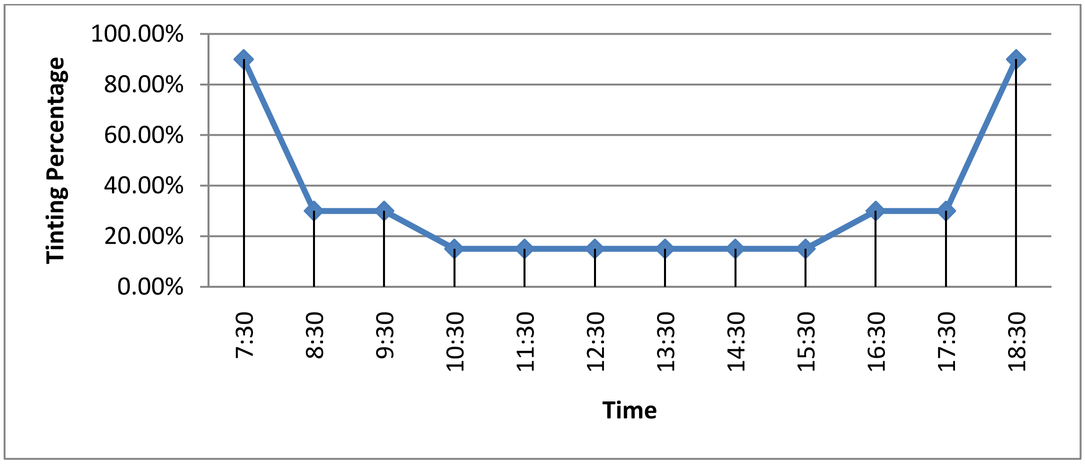


Figure 5.12 Optimum tinting percentage of EC glazing in June 21

Table 5.3 Hourly energy consumption of all scenarios of South façade in June 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
June 21, 2010	5:30	0.00000	-0.01442	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.05659	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.57200	1.47513	1.74026	1.70085	1.66457	1.63192	1.60721	1.57939	1.55398	6.16%	1.15%
	8:30	1.74900	1.96674	1.89191	1.85700	1.82455	1.83338	2.02833	2.13839	2.11593	-12.45%	-4.82%
	9:30	1.76800	2.00756	1.91503	1.87866	1.84575	1.95430	2.11664	2.16020	2.13685	-13.55%	-10.54%
	10:30	2.09400	2.10326	1.96468	1.96370	2.03202	2.14447	2.23306	2.21166	2.18853	-0.44%	-4.51%
	11:30	2.21600	2.12507	1.97397	2.07571	2.15416	2.23402	2.24048	2.21510	2.19211	4.10%	1.08%
	12:30	2.19500	2.05356	1.95682	1.99987	2.09292	2.17984	2.21566	2.18759	2.16241	6.44%	1.48%
	13:30	2.20400	2.08807	1.95541	1.92764	2.03768	2.14286	2.21959	2.19221	2.16715	5.26%	1.67%
	14:30	2.18700	2.07693	1.93931	1.90207	2.00348	2.11646	2.20751	2.18080	2.15617	5.03%	1.41%
	15:30	1.97000	2.13886	1.98734	1.95116	2.00734	2.13332	2.25456	2.23544	2.21151	-8.57%	-12.26%
	16:30	1.84700	2.13563	1.96931	1.93535	1.91514	2.04585	2.19957	2.22817	2.20570	-15.63%	-10.77%
	17:30	1.81800	2.12946	1.92757	1.89742	1.87910	2.00880	2.16925	2.20386	2.18388	-17.13%	-3.36%
	18:30	1.20200	1.16976	1.29060	1.26618	1.24513	1.22907	1.21786	1.20165	1.18534	2.68%	-3.59%
	19:30	0.00000	-0.00791	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**22.82200**	**23.39111**	**22.51221**	**22.35561**	**22.70184**	**23.65429**	**24.70972**	**24.73446**	**24.45956**	**-2.49%**	**3.50%**
				Total (Optimal Dynamic Glazing)					**22.02401**			

September

Figure 5.13 shows the simulation results which indicated that the BIPV model is the most energy saving potential amongst all models. For the selected day, the BIPV model shows energy reductions (12.15%) compared to the base case, and the EC glazing model has slightly higher energy consumption (2.82%) against the base case scenario. Figure 5.14 shows that the trend for the optimum tinting percentage is very similar to March, with the same results obtained thus far for glare prevention through high tinting during dusk and dawn. Table 5.4 shows the hourly energy consumptions for all the configurations for the design day in September.

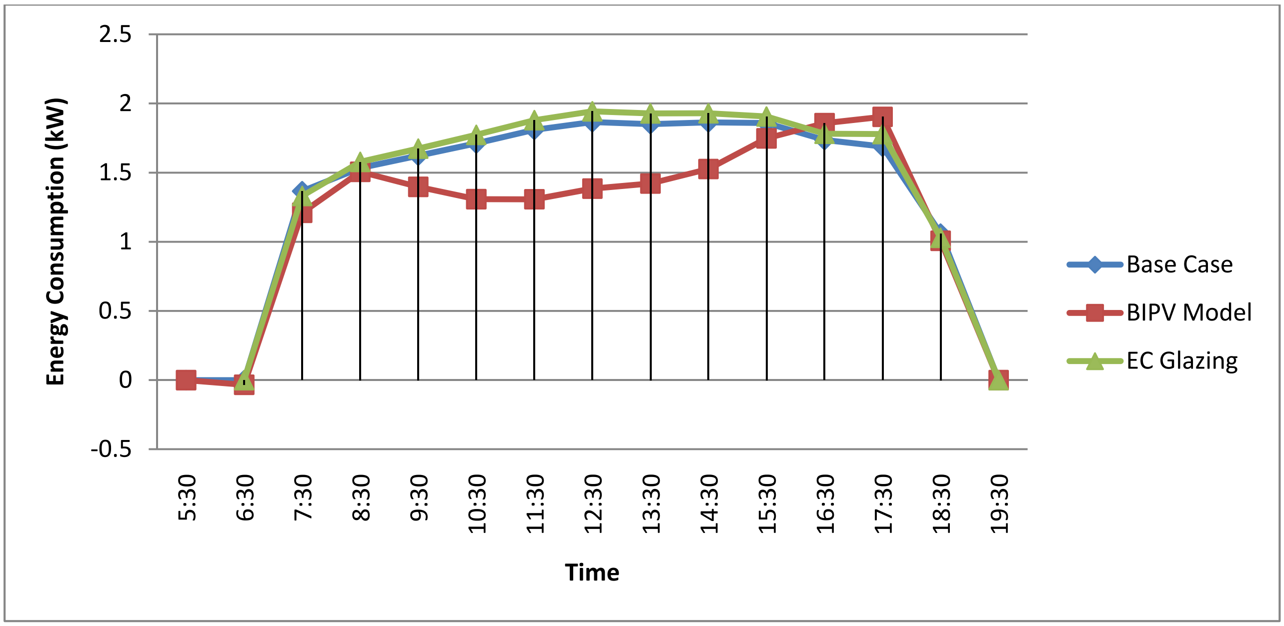


Figure 5.13 Hourly Energy Consumption for all configurations for South façade in September 21

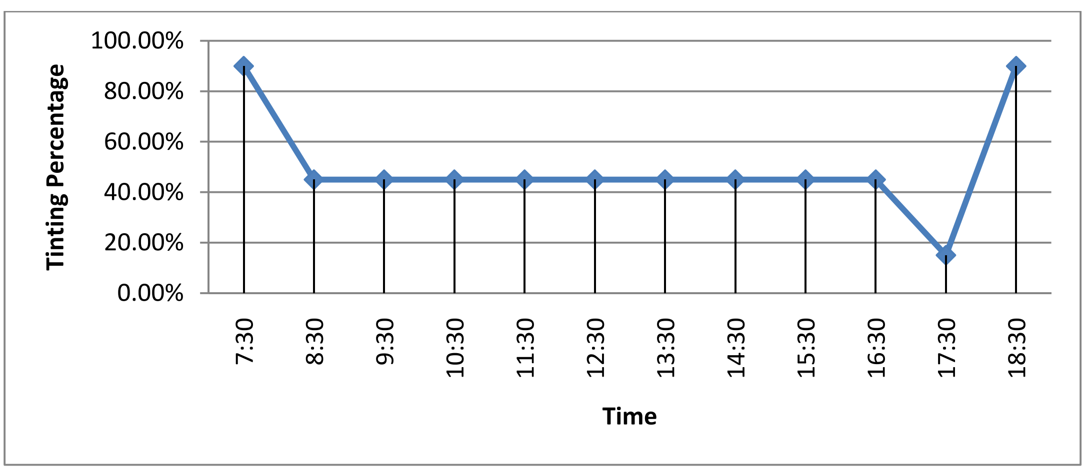


Figure 5.14 Optimum tinting percentage of EC glazing in September 21

Table 5.4 Hourly energy consumption of all scenarios of South façade in September 21

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase BIPV	Savings Over Basecase ECG (Dynamic)
September 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.03370	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.36636	1.20937	1.56218	1.50982	1.46100	1.41523	1.38541	1.35984	1.33104	11.49%	2.58%
	8:30	1.53343	1.50542	1.72310	1.67109	1.62275	1.57745	1.67313	1.90936	1.88141	1.83%	-2.87%
	9:30	1.62289	1.39722	1.87212	1.80120	1.73543	1.67399	1.78358	1.98728	1.95050	13.91%	-3.15%
	10:30	1.71159	1.30833	2.02773	1.93665	1.85203	1.77297	1.90609	2.06109	2.01465	23.56%	-17.71%
	11:30	1.80902	1.30739	2.17520	2.06965	1.97135	1.87934	2.04265	2.14850	2.09463	27.73%	-15.79%
	12:30	1.86513	1.38461	2.25326	2.14283	2.03986	1.94337	2.09679	2.20587	2.14977	25.76%	-15.26%
	13:30	1.85096	1.42086	2.22854	2.12135	2.02144	1.92786	2.03989	2.19542	2.14120	23.24%	-15.68%
	14:30	1.86354	1.52610	2.20022	2.10319	2.01298	1.92864	2.05707	2.21151	2.16250	18.11%	-16.04%
	15:30	1.85828	1.74726	2.12909	2.04906	1.97485	1.90551	2.07230	2.21214	2.17089	5.97%	-16.82%
	16:30	1.73598	1.85709	1.94390	1.88181	1.82414	1.78085	1.97130	2.10028	2.06717	-6.98%	-2.58%
	17:30	1.68813	1.90329	1.79905	1.77844	1.80284	1.88436	1.98341	1.99601	1.96973	-12.75%	-6.80%
	18:30	1.06012	1.00724	1.18905	1.15121	1.11657	1.08437	1.06612	1.05002	1.02911	4.99%	-5.32%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**19.96543**	**17.54048**	**23.10344**	**22.21630**	**21.43524**	**20.77394**	**22.07774**	**23.43732**	**22.96260**	**12.15%**	**-2.82%**
				Total (Optimal Dynamic Glazing)					**20.52857**			

<u>December</u>

Figure 5.15 shows that the EC glazing model has the least favorable results for the selected day in December. The BIPV model shows its highest energy savings (73.84%) with several instances where power produced is slightly higher than consumed hence the negative values. On the other hand, the EC glazing model ranks the lowest in all the design days so far and requires more energy (10.92%) than the base case. The optimum tinting percentage, seen in Fig. 5.16 has changed significantly from the previous simulations. Because the sun is at its lowest, therefore, the EC glazing requires higher percentage of time to be in dark tint mode in order to reduce solar gain. Figure 5.17 shows the illuminance levels and the lighting gain for design day in December and June. It is evident that with the higher natural light levels in winter, the lighting gain is considerably lower than in the summer. Table 5.5 shows the hourly energy consumptions for all the configurations for the design day in December.

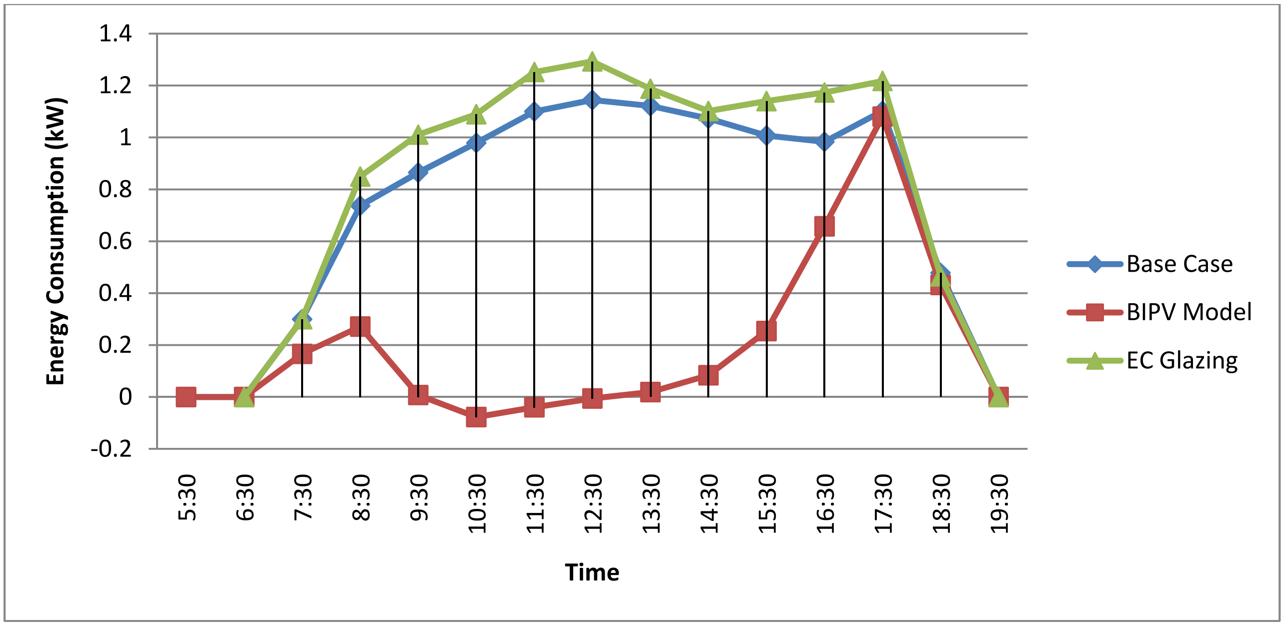


Figure 5.15 Hourly Energy Consumption for all configurations for South façade in December 23

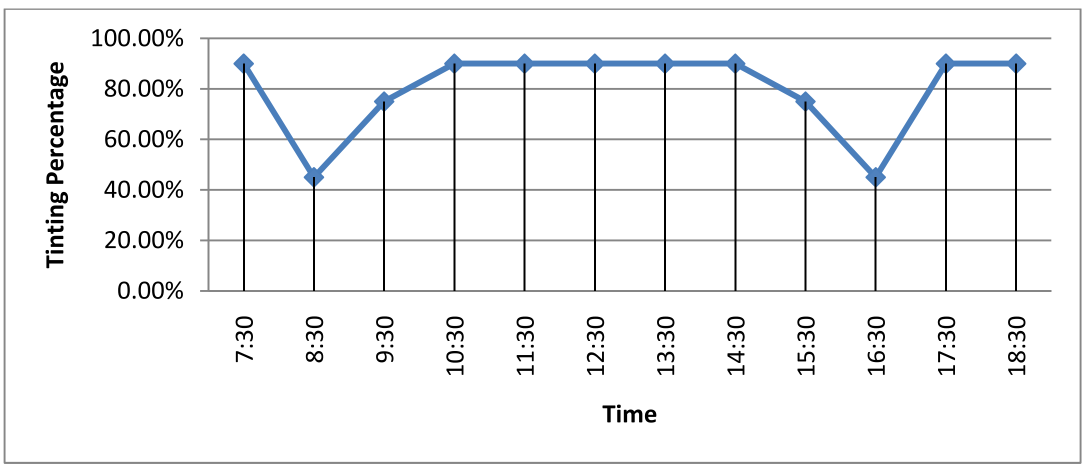


Figure 5.16 Optimum tinting percentage of EC glazing in December 23

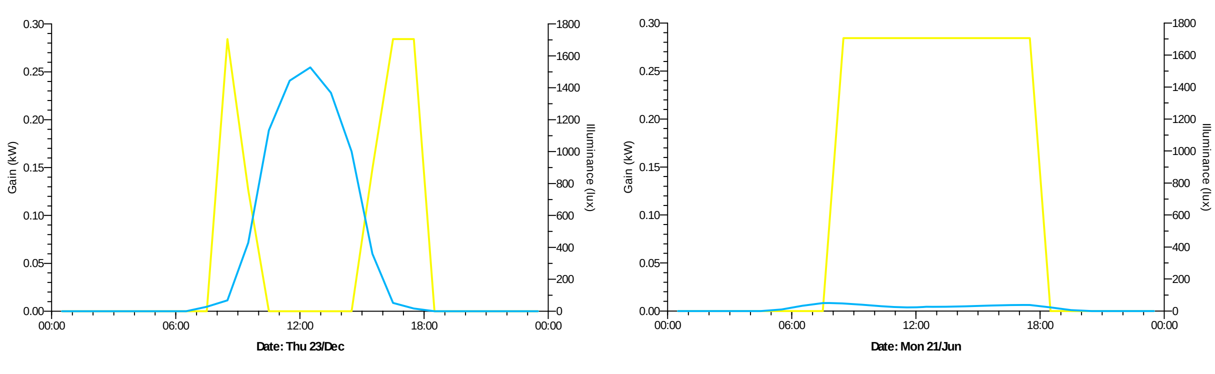


Figure 5.17 EC glazing model lighting gain and daylight illuminance for December 23 (left) and June 21 (right)

Table 5.5 Hourly energy consumption of all scenarios of South façade in December 23

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
December 23, 2010	5:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	6:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	7:30	0.3000	0.1662	0.4759	0.4248	0.3803	0.3437	0.3210	0.3050	0.3000	44.59%	0.00%
	8:30	0.7370	0.2714	1.0306	0.9680	0.9078	0.8493	0.8703	1.1194	1.1053	63.17%	-15.25%
	9:30	0.8650	0.0076	1.4231	1.3222	1.2251	1.1312	1.0557	1.0107	1.1035	99.13%	-30.78%
	10:30	0.9788	-0.0774	1.7546	1.6215	1.4931	1.3684	1.2673	1.1681	1.0894	107.91%	-11.30%
	11:30	1.1000	-0.0397	2.0298	1.8759	1.7269	1.5817	1.4634	1.3461	1.2519	103.61%	-13.81%
	12:30	1.1444	-0.0057	2.1537	1.9839	1.8194	1.6589	1.5281	1.3989	1.2928	100.50%	-12.97%
	13:30	1.1212	0.0189	2.1157	1.9315	1.7535	1.5802	1.4399	1.3041	1.1876	98.32%	-5.92%
	14:30	1.0726	0.0836	1.9911	1.8129	1.6413	1.4748	1.3407	1.2125	1.1016	92.20%	-2.71%
	15:30	1.0074	0.2540	1.7802	1.6237	1.4735	1.3285	1.2125	1.1400	1.2107	74.78%	-20.18%
	16:30	0.9834	0.6575	1.4852	1.3672	1.2544	1.1731	1.2271	1.3680	1.3039	33.15%	-19.28%
	17:30	1.1017	1.0804	1.3736	1.3247	1.3419	1.3319	1.3125	1.2627	1.2173	1.93%	-21.81%
	18:30	0.4783	0.4317	0.7551	0.6958	0.6394	0.5845	0.5412	0.5015	0.4653	9.73%	-33.68%
	19:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	20:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	Total	**10.8895**	**2.8485**	**18.3685**	**16.9520**	**15.6566**	**14.4061**	**13.5797**	**13.1369**	**12.6292**	**73.84%**	**-10.92%**
				Total (Optimal Dynamic Glazing)					**12.0788**			

Summary

A summary of the year round energy savings contribution from all configurations for the south façade with sensor located at 2m and glass shading coefficient of 0.27 is seen in Fig. 5.18. The results show that in all the configurations, the BIPV model proves more energy efficient than the EG glazing. It is interesting to note that in none of the scenarios, does the EC glazing model remain in its bleached form (clear tint), as this configuration results in the lowest percentage of savings (-22.49% i.e. increases the energy consumption). Also, the only time that EC glazing was more energy efficient than the base case was during the summer solstice (refer Table 5.3). Therefore, it is assumed that for the given parameters, the EC glazing model works best in summer. The use of blinds proves to be more effective overall than EC glazing as none of the EC glazing models reduced the energy demand. However, given the optimum combined results (dynamic EC glazing model), the results come very close to the base case energy consumption (-2.86%). It can then be argued that because the EC glazing provides better viewing connection to the outside than the use of blinds, this is not a bad compromise.

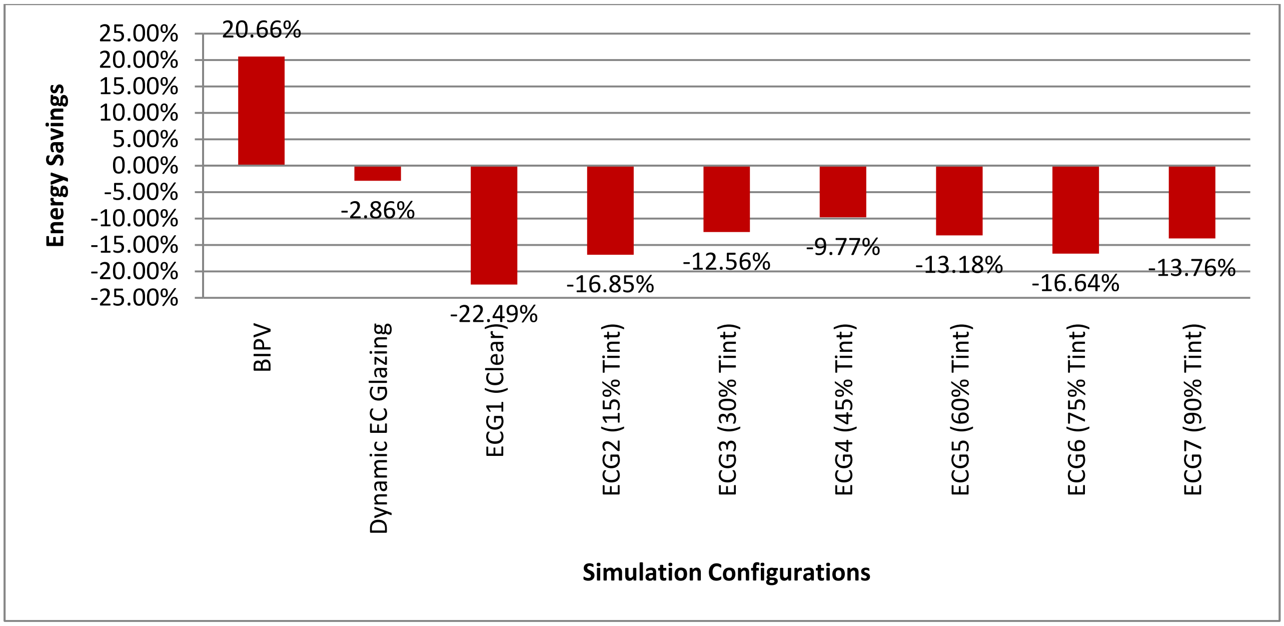


Figure 5.18 Total annual energy savings for the South façade

Figure 5.19 shows the grid displaced electricity (power produced) for the various design days of the South façade of the BIPV model given 11.12m^2 area of PV cells. For all cases, the peak electrical generation occurs at noon, when solar insolation is usually at its maximum. It is evident that for this orientation, the summer days are generally more efficient than winter for PV power output. However, analyzing the annual total system energy for the BIPV model in Fig. 5.20 illustrates that despite the higher displaced electricity in summer, the best energy consumption values occur during winter. This is most likely due to higher HVAC requirement during summer months. It is interesting to observe that the electrical production in the design days for months of March and September are not similar as would be expected, the former being slightly better.

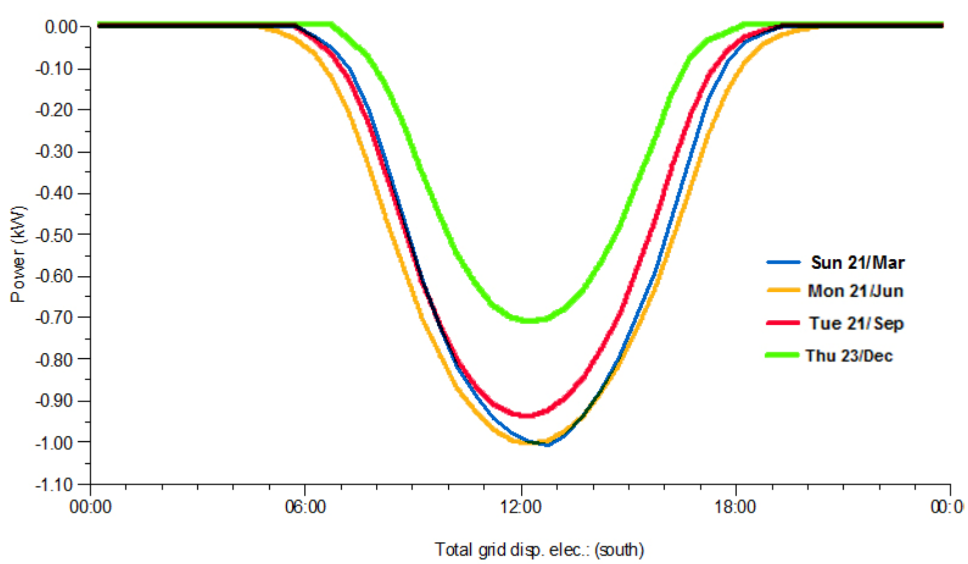


Figure 5.19 Power production of the BIPV model in the four design days for the South façade

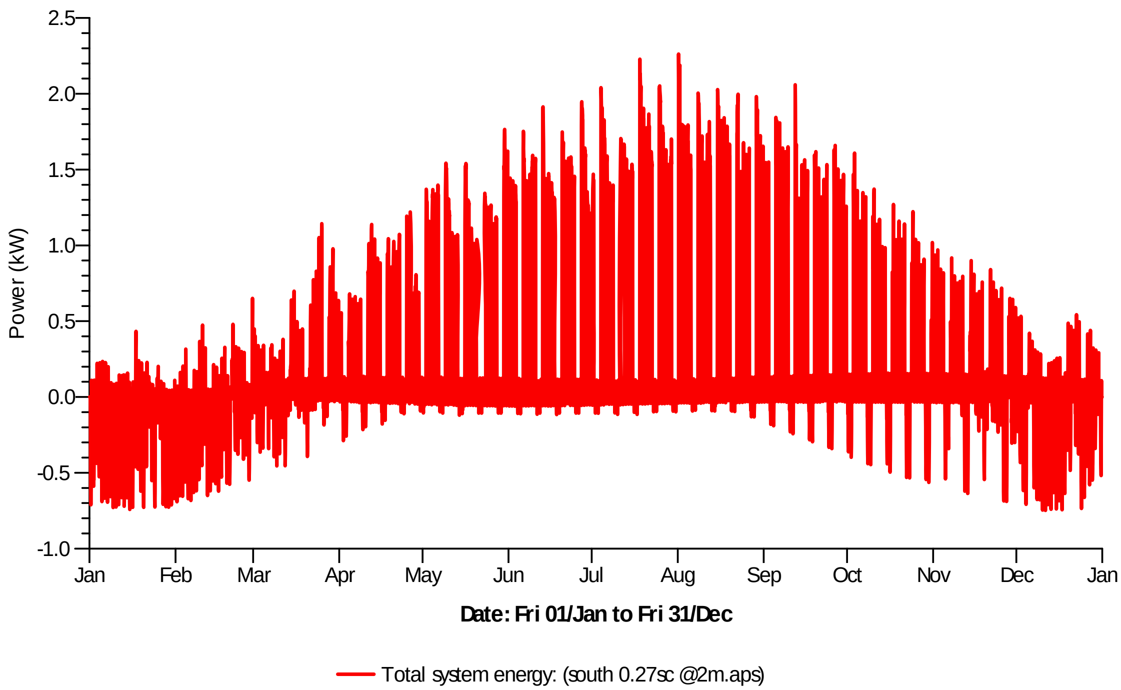


Figure 5.20 Annual BIPV model total system energy for the South façade with glass shading coefficient of 0.27

5.2.2 Lighting sensor @2m and Glass Shading Coefficient 0.6

The objective of these simulations is to check the benefit of changing the shading coefficient in the base case and BIPV model as the EC glazing model already has a varied shading coefficient range. Figure 5.21 shows the hourly energy consumption for the three cases during March 21 design day. The results prove that an increase in shading coefficient increases energy consumption in base case however reduces it in the BIPV model. One explanation could be that since the façade of the BIPV model already acts as a good solar shade, due to the opaque PV cells blocking solar gain, therefore, using a glass with higher shading coefficient allows the natural light to penetrate and hence lower the artificial lighting demand. Thus, when shading coefficient is higher in BIPV model, the energy consumption will be lower. For the base case model, the high shading coefficient requires more frequent need of the blinds for solar protection. When it comes to the EC glazing model, there is now an energy savings (18.82%) compared to the base case for the design day in March. Table 5.6 shows the hourly energy consumption of all configurations for one of the design days. The results of other design days can be found in Appendix A.1.

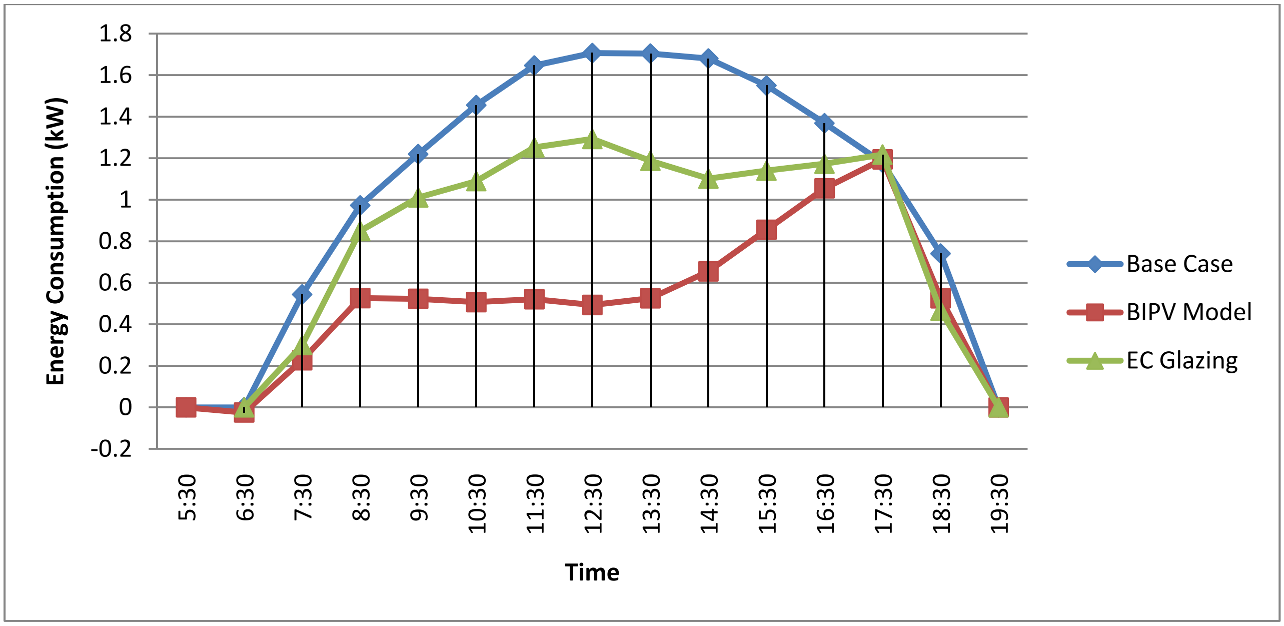


Figure 5.21 Hourly Energy Consumption for all configurations for South façade in March 21 with glass of 0.6 shading coefficient and lighting sensor @ 2m

A summary of the energy savings contribution from all configurations for the south façade with sensor located at 2m and glass shading coefficient of 0.6 is seen in Fig. 5.22. The results show that the energy savings of the BIPV model improved by over 15% compared with the lower shading coefficient of 0.27, and is now almost 35% more efficient than the base case. More importantly, the dynamic EC glazing now shows significant improvement in energy savings over the base case (11.17%). Therefore, replacing the conventional glazing (0.6 shading coefficient) of a south orientated façade with EC glazing will improve the energy efficiency, however, replacing it with BIPV will be even more energy saving.

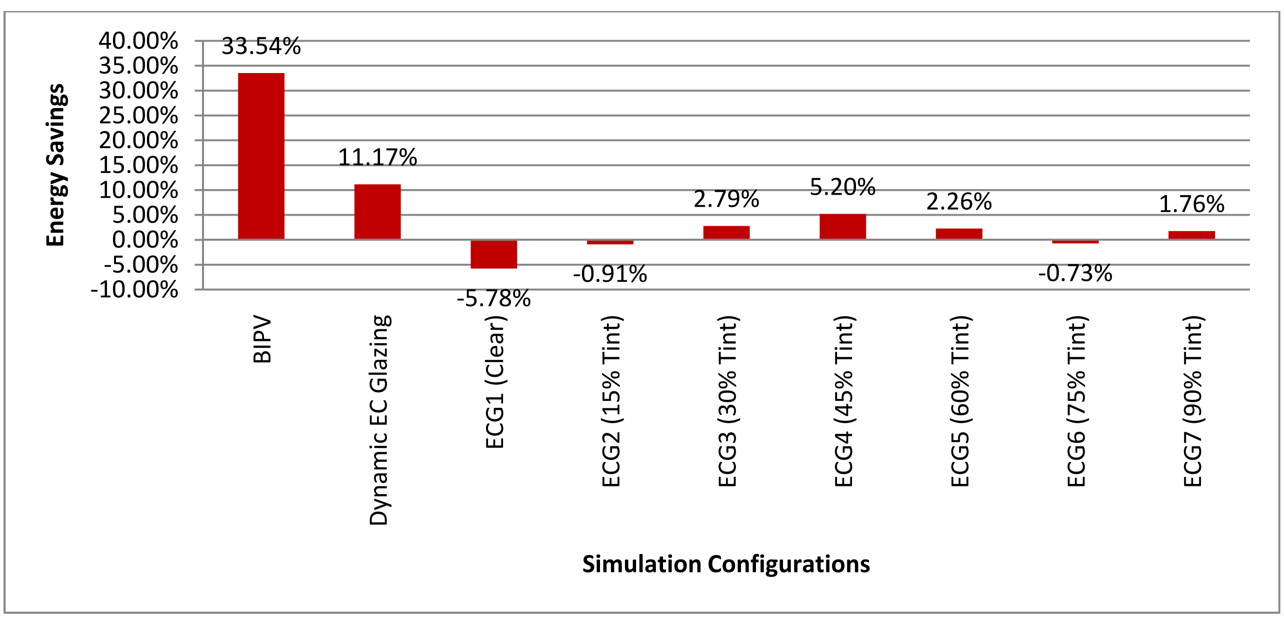


Figure 5.22 Total hourly energy savings of the South façade in all the design days

Table 5.6 Hourly energy consumption of all scenarios of South façade in March 21 (shading coefficient 0.6)

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase	
											BIPV	ECG (Dynamic)
March 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.02467	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	0.54371	0.22687	0.68391	0.58603	0.49415	0.40811	0.35256	0.31374	0.30000	58.27%	44.82%
	8:30	0.97282	0.52654	1.05991	0.97947	0.90422	0.83329	0.95197	1.11577	1.06558	45.87%	14.34%
	9:30	1.21969	0.52289	1.28829	1.19367	1.10537	1.02238	1.12823	1.29302	1.24291	57.13%	16.18%
	10:30	1.45552	0.50676	1.50384	1.38945	1.28271	1.18251	1.23856	1.42912	1.36989	65.18%	5.88%
	11:30	1.64654	0.52119	1.67814	1.54821	1.42676	1.31263	1.32268	1.53941	1.47207	68.35%	10.60%
	12:30	1.70645	0.49303	1.72631	1.58742	1.45750	1.33534	1.34726	1.55145	1.47939	71.11%	13.31%
	13:30	1.70393	0.52542	1.71773	1.57806	1.44752	1.32489	1.36089	1.54219	1.46970	69.16%	13.75%
	14:30	1.68011	0.65522	1.69391	1.56136	1.43780	1.32196	1.40330	1.55231	1.48368	61.00%	11.69%
	15:30	1.55006	0.85528	1.57064	1.45809	1.35338	1.25822	1.40770	1.51350	1.45525	44.82%	6.12%
	16:30	1.36857	1.05497	1.39789	1.30811	1.22462	1.23510	1.38552	1.43517	1.38790	22.91%	9.75%
	17:30	1.17890	1.19412	1.21500	1.16919	1.19787	1.27962	1.35134	1.32468	1.28572	-1.29%	-1.61%
	18:30	0.74054	0.52554	0.77859	0.71939	0.66490	0.61421	0.57874	0.54688	0.51409	29.03%	10.21%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**15.76684**	**7.58316**	**16.31416**	**15.07845**	**13.99680**	**13.12826**	**13.82875**	**15.15724**	**14.52618**	**51.90%**	**18.82%**
				Total (Optimal Dynamic Glazing)					**12.79912**			

5.2.3 Lighting sensor @4m and Glass Shading Coefficient 0.27

The results show that the relocation of the sensor has a negative effect on the energy consumption for all the models. When the sensor is moved closer to the back of the room, it detects lower levels of light illuminance compared to when it was near the window edge. Consequently, the lower reading of the daylight increases the demand for lighting energy. Figure 5.23, shows the effect of sensor relocation on the lighting gain for the selected day in December in the base case model. The same lighting gains principle applies to all the model configurations. In addition to lighting energy, the cooling load also increases with the new sensor location. Therefore, the overall energy consumption will be increased in all cases. Figure 5.24 shows the hourly energy consumption of all configurations for one of the design days.

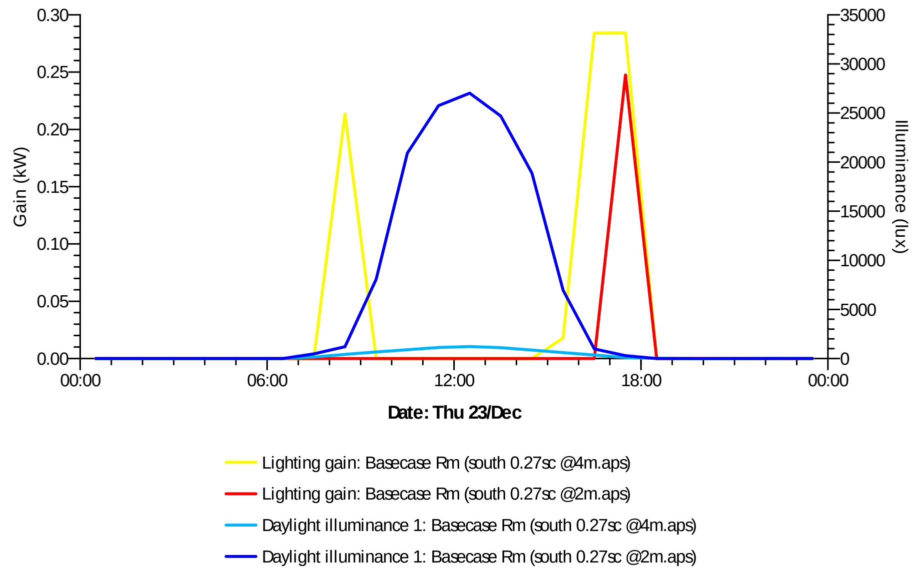


Figure 5.23 Comparison of effect of sensor relocation from 2m to 4m on the lighting gain in December

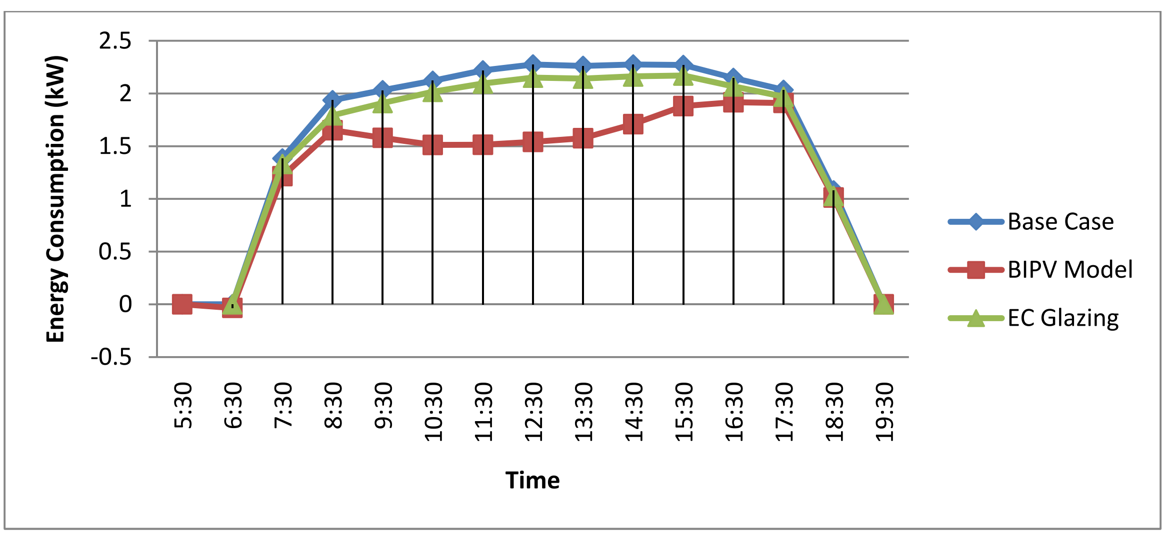


Figure 5.24 Hourly Energy Consumption for all configurations for South façade in September 21 with glass of 0.27 shading coefficient and lighting sensor @ 4m

A summary of the energy savings contribution from all configurations for the south façade with sensor located at 4m and glass shading coefficient of 0.27 is seen in Fig. 5.25. The results show that the relocation of the sensor actually improves the efficiency in all the configurations in comparison to the base case. As before, given these parameters, the BIPV model proves more energy efficient (24.98%) than the EG glazing (1.46%) for the South façade against the base case model. At the same time, Fig. 5.26 shows the trend of optimum tinting percentage in the dynamic EC glazing model. The high frequency of the dark mode state of the EC glazing puts it at a disadvantage compared to the base case scenario. Although this combination gives the best energy consumption for the model, it compromises the quality of natural light in the room and will give the occupant a feeling of isolation in the room.

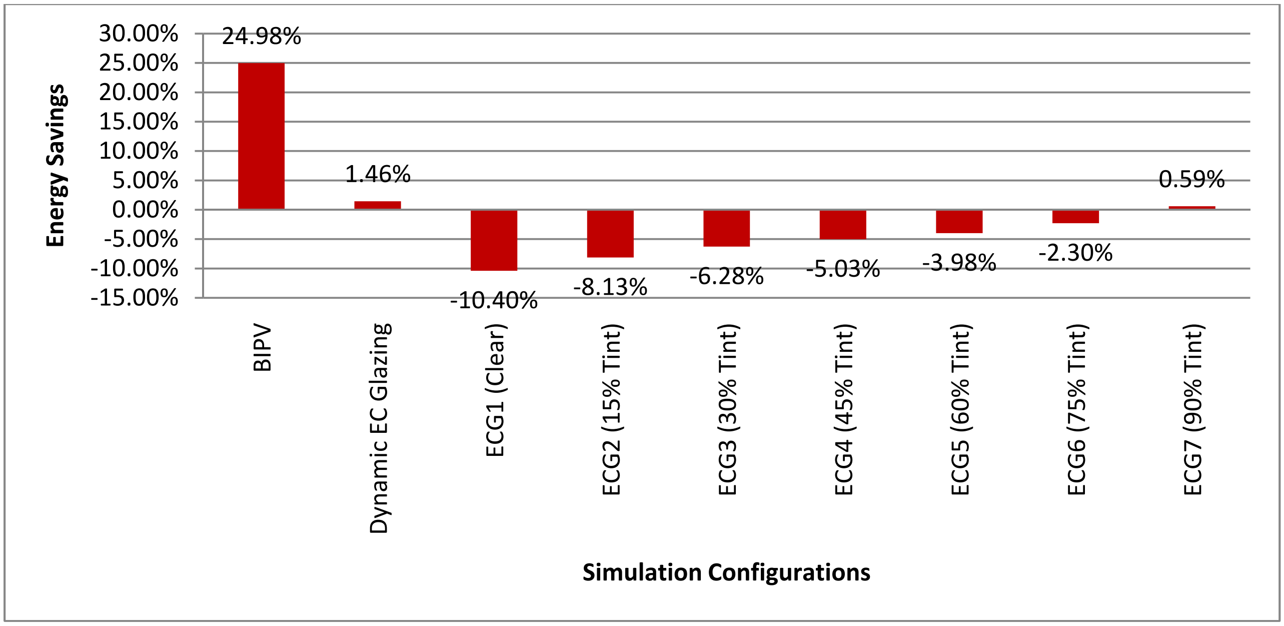


Figure 5.25 Total hourly energy savings of the South façade in all the design days

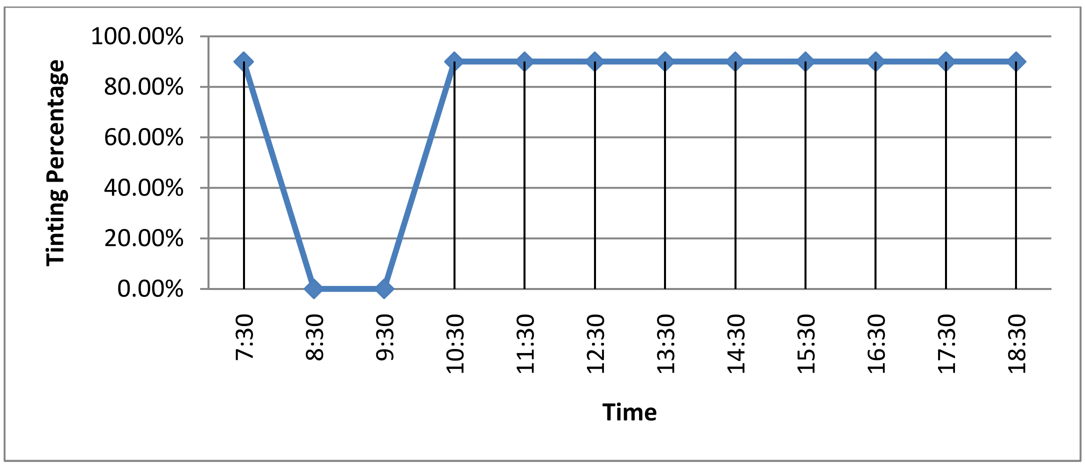


Figure 5.26 Optimum tinting percentage of EC glazing in September 21

Figure 5.27 shows the sensor's (at 4m) daylight illuminance readings of in the various EC glazing models for selected day in December. Not surprisingly, the model with the highest tinting value (ECG 7) gives the poorest lighting quality in the room, with a maximum of only 70 lux at mid day. Such low daylight means the artificial lights need to be on all the time. Furthermore, comparing the models with different sensor positions, Figs. 5.28 and 5.29 show that the higher the tinting value of the EC glazing, the smaller the gap in daylight illuminance and the lighting gain between the two models. This trend is expected since at high tinting values, regardless of sensor location, hardly any light enters the rooms. The results of all the simulations for lighting sensor located at 4m and glass with shading coefficient of 0.27 are in Appendix A.1.

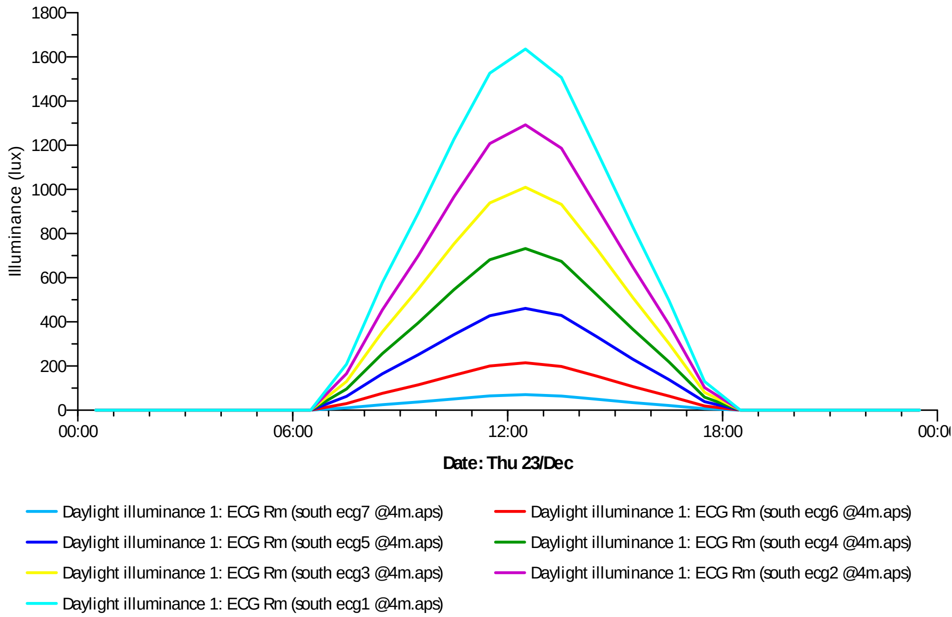


Figure 5.27 Daylight illuminance of all EC glazing models in December 23

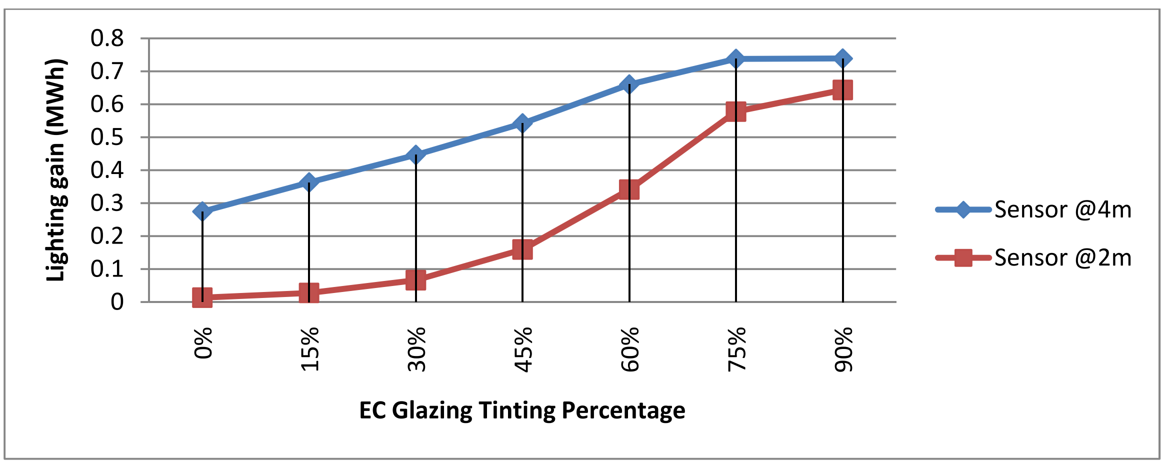


Figure 5.28 Annual lighting gain compared to tinting percentage of EC glazing for South façade

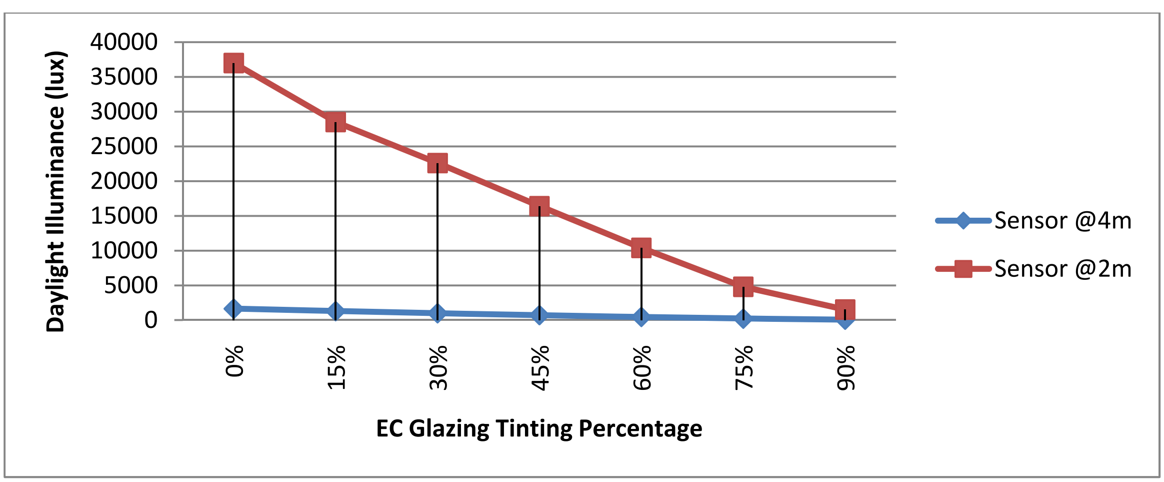


Figure 5.29 Daylight illuminance ratio compared to tinting percentage for South façade in September 21

5.3 EAST FAÇADE ORIENTATION

5.3.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

The full details of all the simulations results for the East façade with glass shading coefficient of 0.27 and sensor location of 2m can be found in Appendix A.2. Figure 5.30 shows a summary of the energy savings contribution from all configurations. The results show that the BIPV model reduces the energy demand (16.69%) in comparison to the base case while the EC glazing model with optimum dynamic range only achieves a slight energy savings (1.35%) against the base case. Since this orientation does not receive as much solar radiation as the South, therefore, it is expected that a lower blockage of solar gain is needed. As Fig. 5.31 suggests, the percentage of times when the glass in the EC glazing model is in dark tint mode has been reduced. In fact, for the first time, the duration of the glass remaining in bleached state (clear-0% tint) has been continuous for several hours from noon until mid afternoon. For the selected day in December (Table A.11, Appendix A.2), the EC glazing achieves its highest energy saving potential for this orientation. However, the trend seen previously where the dynamic EC glazing model turns to its highest tint mode to achieve maximum energy savings in early mornings and late afternoon has not changed. Moreover, due to lower levels of solar radiation, the percentage of PV power output has reduced compared to the South façade which consequently reduces the energy savings potential compared to the base case as seen in Fig.5.30.

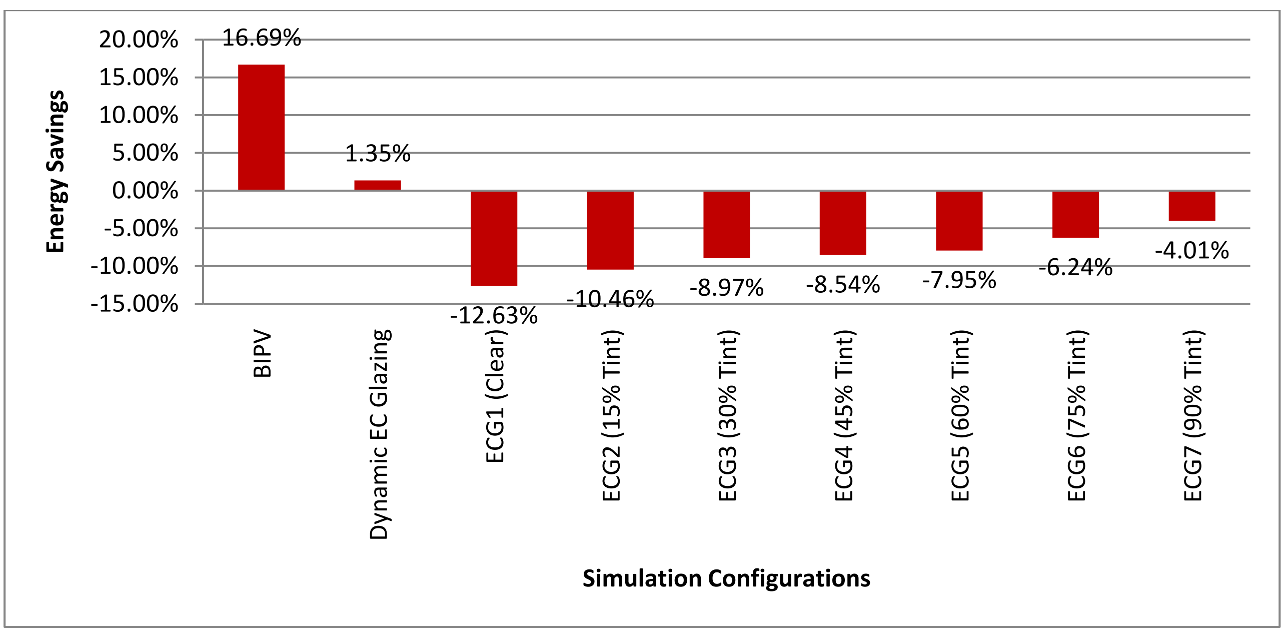


Figure 5.30 Total hourly energy savings of the East façade in all the design days

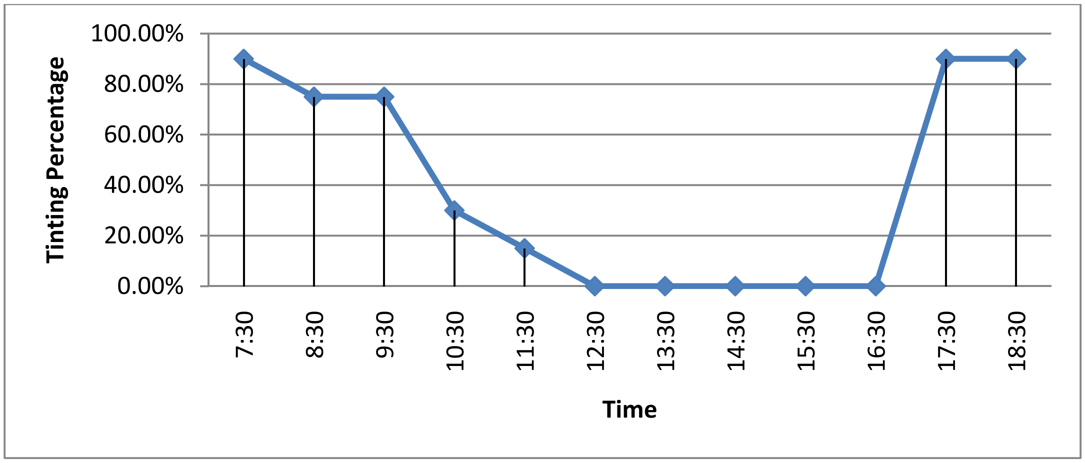


Figure 5.31 Optimum tinting percentage of EC glazing in December 23 for East Facade

Due to the nature of the East and West oriented facades, dealing with direct solar radiation and glare becomes even more problematic. Figure 5.32 shows the yearly cumulative daylight illuminance distribution for the various configurations for the East facades with light sensor located at 2m. This analysis indicates that, with a 2000lux threshold, the base case model will require the use of the blinds approximately 13% throughout the year. Looking at the daylight illuminance for selected day in December, Fig. 5.33 shows that the dynamic EC glazing model has the lowest lux levels and does not experience any glare. This is the main advantage of this type of façade which combines daylight optimization and energy optimization as a control mechanism to give the maximum savings whilst providing adequate lighting level for the occupants. In this scenario, unlike the base case and the BIPV model, which experience illuminance close to 6000 lux, the EC model controls the range of daylight illuminance between 200 to 1100 lux during working hours.

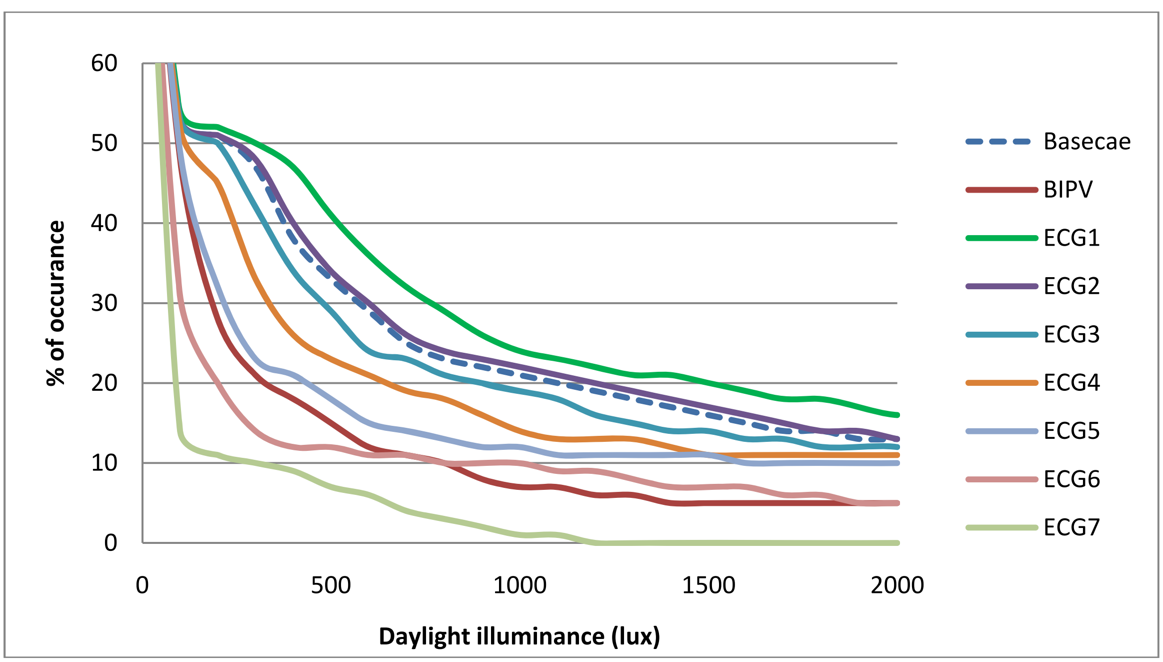


Figure 5.32 Yearly cumulative daylight illuminance distributions for East façade with light sensor @2m

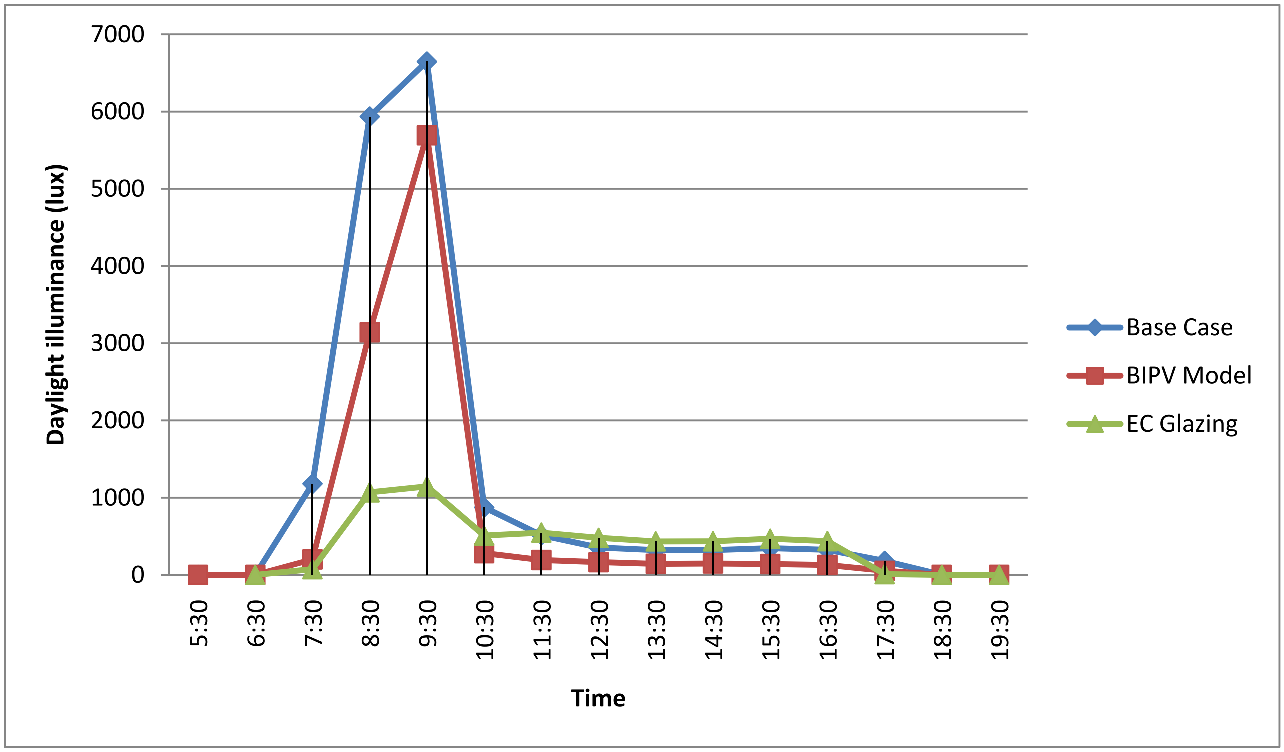


Figure 5.33 Hourly daylight illuminance distributions for all configurations for East façade in March 21

5.4 WEST FAÇADE ORIENTATION

5.4.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

Appendix A.3 shows the full details of all the simulations results for the West façade with glass shading coefficient of 0.27 and sensor location of 2m. Figure 5.34 shows a summary of the energy savings contribution from all configurations. The results show that the BIPV model reduces the energy demand (16.86%) in comparison to the base case while the EC glazing model with optimum dynamic range only achieves a slight energy savings (0.89%) against the base case. These results are very close to that of the East façade, which was originally assumed, as both orientations perform similarly in terms of duration of exposure to direct sun. Figure 5.35 shows the optimum tinting percentage of the EC model indicates that there is a shift from use of dark tinting in morning to afternoon. This is expected as the West façade receives its highest amount of solar radiation in the late afternoon or dawn. For the selected day in December, EC model shows a drastic shift in its energy savings against the base case model. This is not surprising as the use of high tint glazing is capable of blocking most of the solar heat gain into the space particularly by the west sun, which the blinds cannot do as effectively.

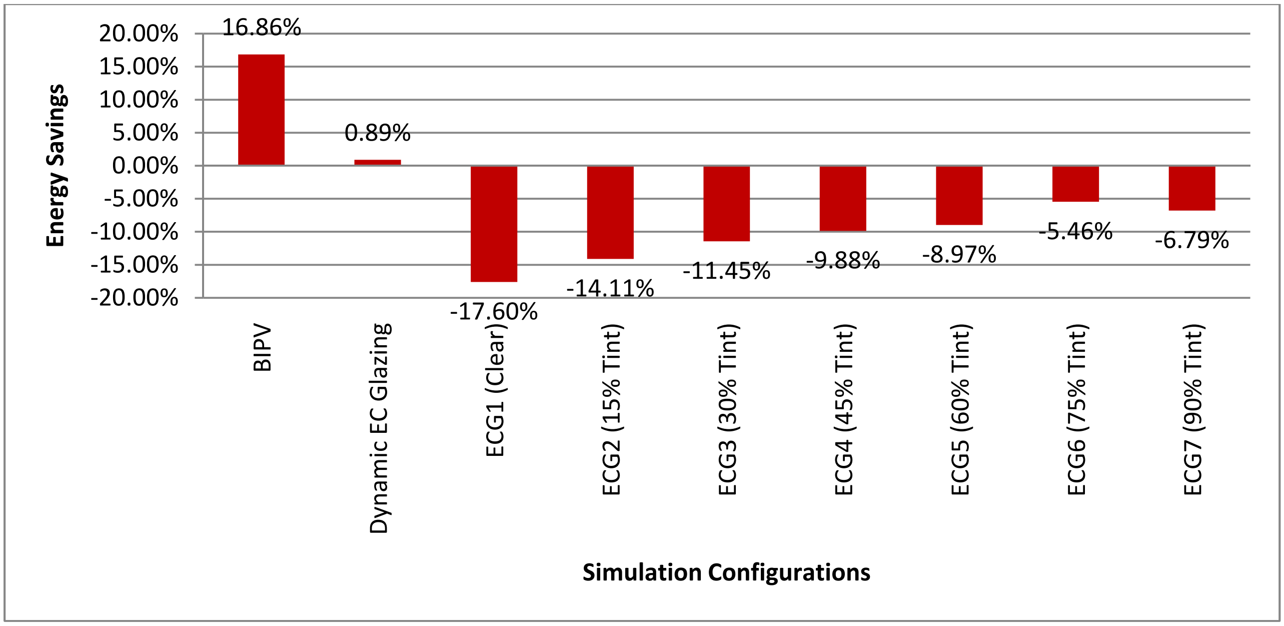


Figure 5.34 Total hourly energy savings of the West façade in all the design days

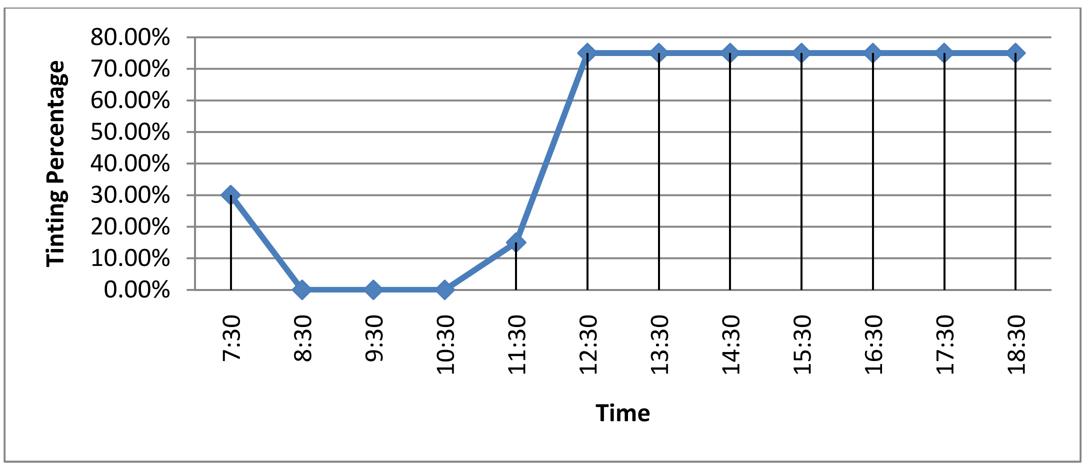


Figure 5.35 Optimum tinting percentage of EC glazing in December 23 for West Facade

5.5 NORTH FAÇADE ORIENTATION

5.5.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

The full details of all the simulations results for the North façade with glass shading coefficient of 0.27 and sensor location of 2m are in Appendix A.4. Figure 5.36 shows a summary of the energy savings contribution from all configurations. The results show that the EC glazing model with optimum dynamic range reduces the energy demand (7.41%) in comparison to the base case while the BIPV model only achieves a slight energy savings (1.35%) against the base case. Figure 5.37 shows the optimum tinting percentage of the EC model for selected day in

December which indicates that except for the late afternoon, the glass can remain in bleached form to achieve maximum energy savings.

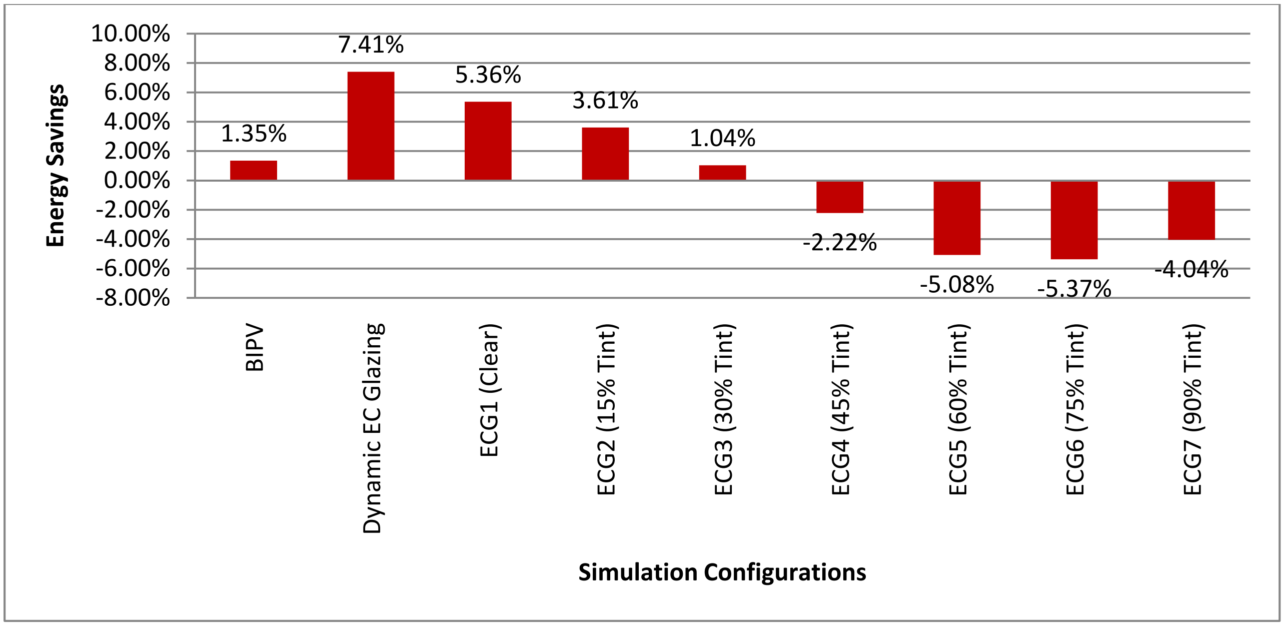


Figure 5.36 Total hourly energy savings of the North façade in all the design days

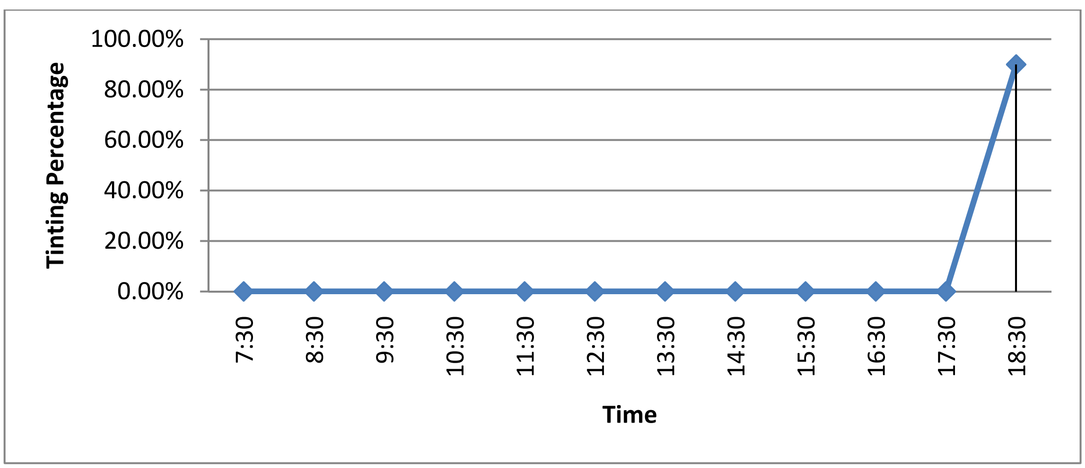


Figure 5.37 Optimum tinting percentage of EC glazing in December 23 for North Facade

5.6 SUMMARY

The BIPV and EC glazing model overall results show that when it comes to energy consumption, the former of these two technologies is usually more advantageous. In all other scenarios, except the North façade, the BIPV model is much more energy efficient that the EC glazing model. There are few instances which they are close in terms of total energy consumption against the base case model. For example, the simulations of South orientation, during summer (June 21) is the only time that the dynamic EC glazing actually proves more energy efficient that the BIPV. For the North orientation, the EC model is more efficient than the BIPV model because EC glazing can take advantage of its clear state to use the north daylight, while the BIPV model still requires artificial light and produces little power. Figure 5.38 shows a summary of the energy savings contribution from all configurations against the base case. The South oriented façade offers the most energy savings for the BIPV model, whilst the North oriented façade is better suited for the EC glazing model.

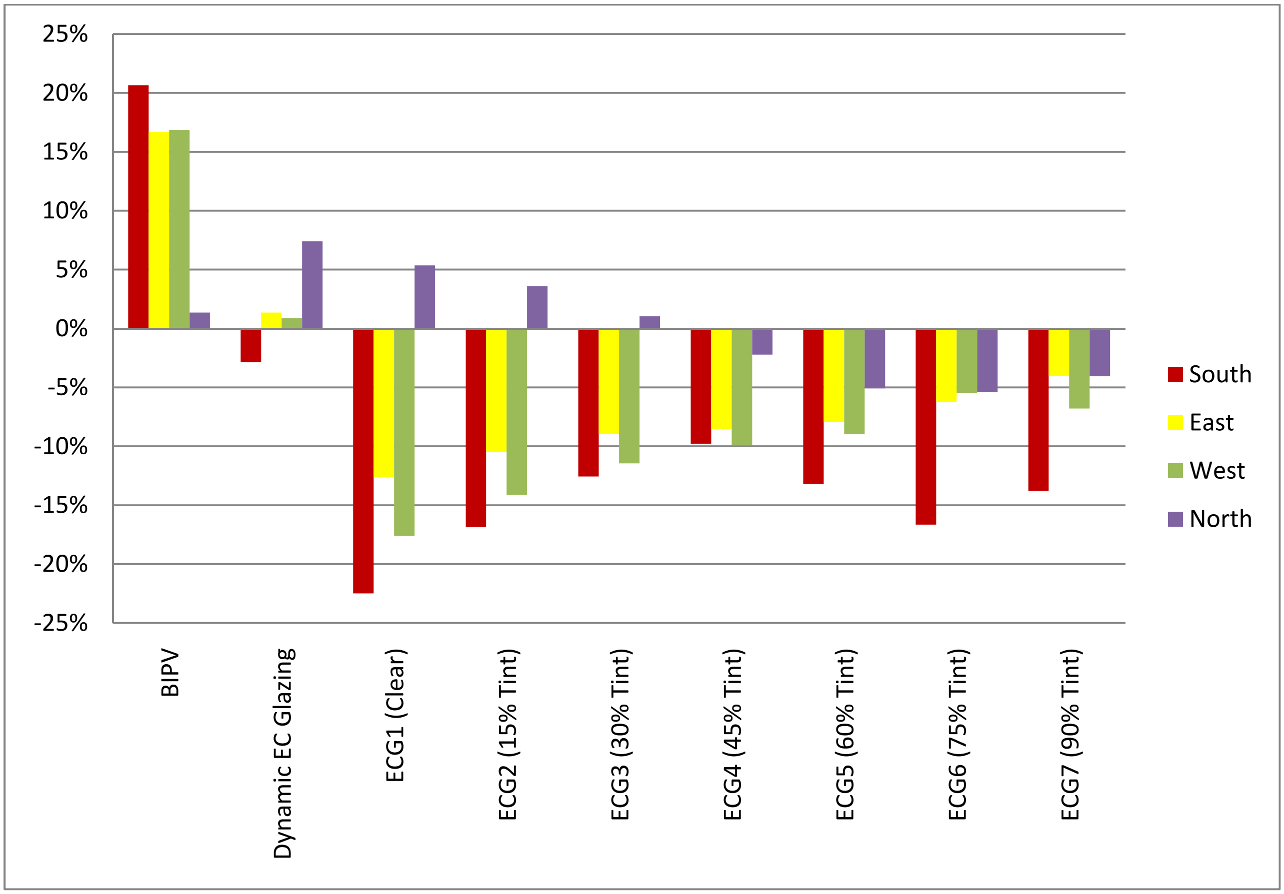


Figure 5.38 Total hourly energy savings of all the orientation in all the design days for all orientations

Figure 5.39 shows the total annual BIPV power produced for all the orientations. The South facade experiences the highest peaks of power generation which occur in the winter months from October to February. In the summer months, however, the other three orientations generate more electricity than the South facing façade. This is because the BIPV vertical position makes it unfavorable for catching the maximum solar rays. At the same time, during the summer months, the high ambient air temperatures cause a reduction in the efficiency of the PV arrays. Figures 5.40 and 5.41 illustrate this condition through a comparison for a week in June for South and East facing window. In general, the peaks in the temperature coincide with power production on the decline, whilst the peak electrical output happens a few hours before the maximum temperature is reached. In this example, particularly evident for the east façade, the most efficient time for the electricity production is in the morning when the sun is low and has the most exposure on the PV cells. Thus, based on the same principle, and as seen in Fig. 5.42, the west facing window generates the most power in the afternoon.

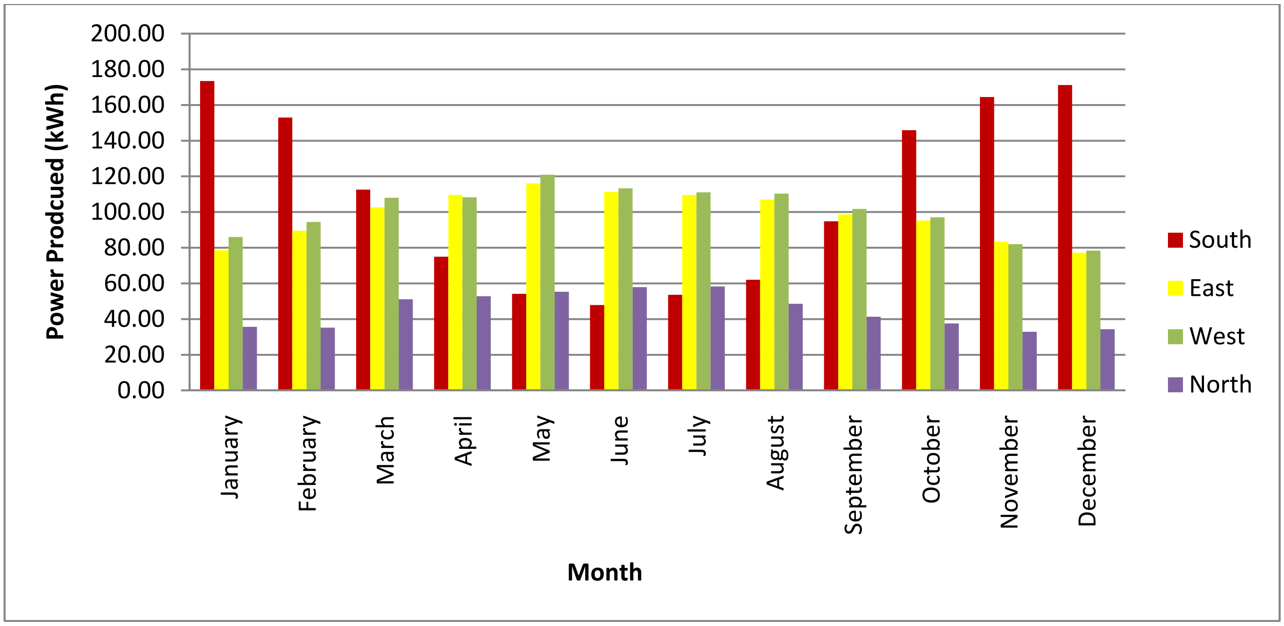


Figure 5.39 Total Annual BIPV power production for all orientations

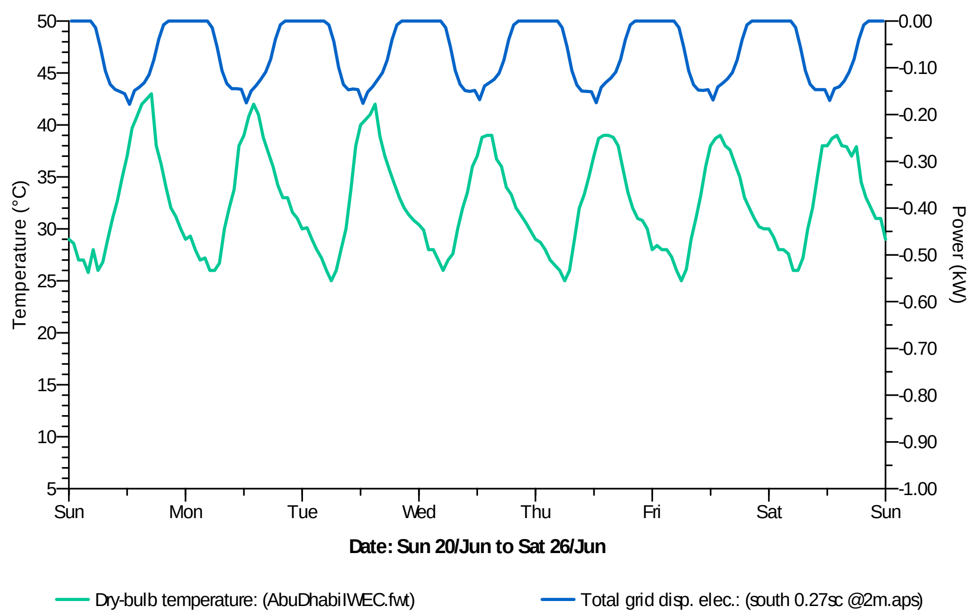


Figure 5.40 Effect of temperature on power output of PV for one week in June for South façade

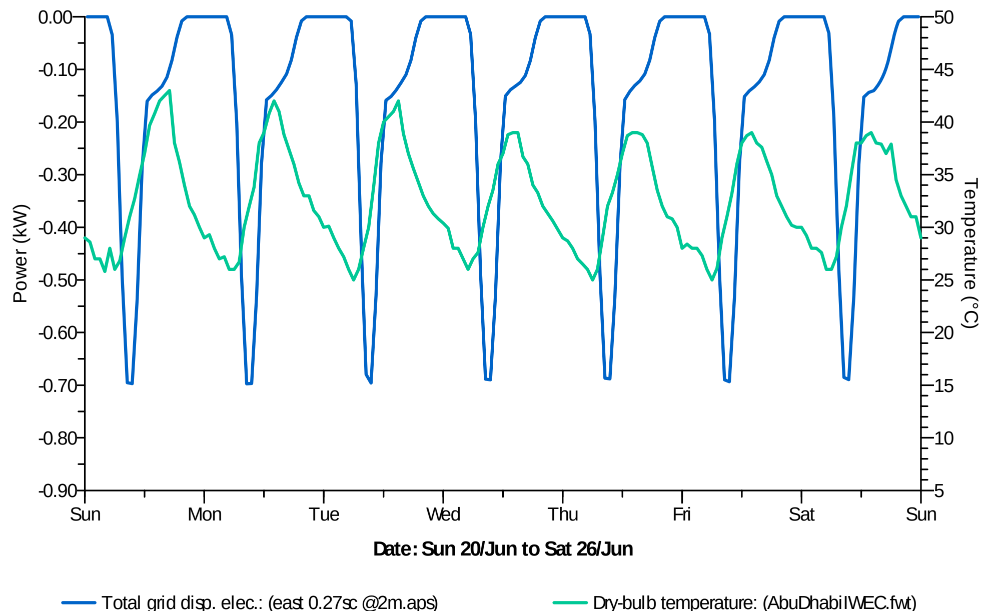


Figure 5.41 Effect of temperature on power output of PV for one week in June for East façade

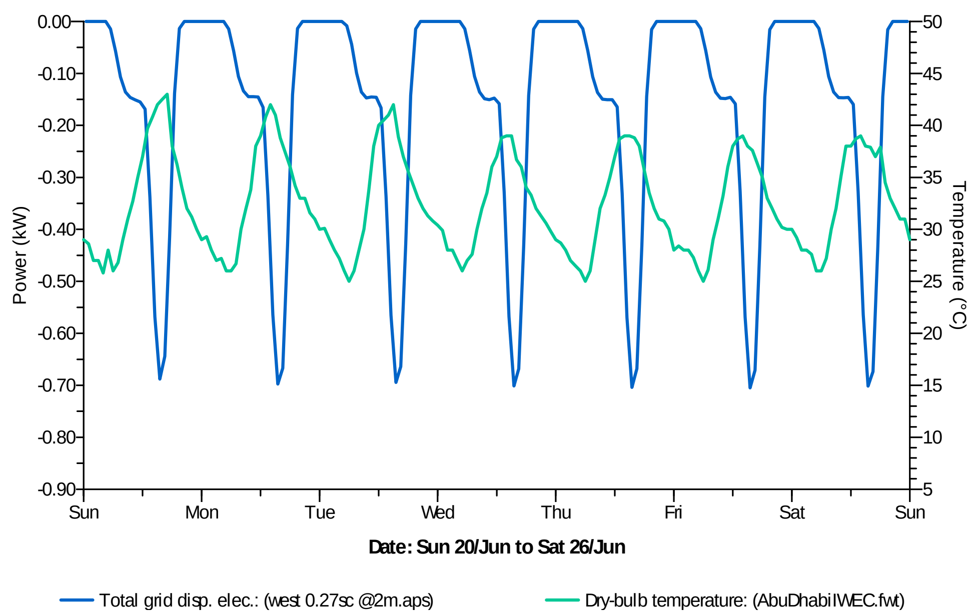


Figure 5.42 Effect of temperature on power output of PV for one week in June for West facade

The results of all simulations indicate that to achieve the most optimum savings, the BIPV should be placed on the East, South, and West facades, while the dynamic EC glazing should be placed on the North. In fact, referring to total energy savings of all configurations in Fig. 5.38, it might be more cost effective to only use a standard clear glazing (ECG 1) without blinds for the north façade, as the energy savings of this case is very close to the dynamic EC glazing. This will also help in the total savings discussed in the next Chapter.

CHAPTER 6: ECONOMIC ANALYSIS

One of the most frequent methods in assessing the usefulness of a new technology is through an economic analysis. Such cost/benefit comparison can help determine the feasibility and practicality of the proposed system and justify its application under similar given constraints as a more cost-effective alternative. This chapter presents an economic analysis and evaluation of the BIPV and EC glazing systems compared to the base case described in previous sections. The objective of this analysis is to explore the viability of these two systems. The analysis is based on results of simulations of model configuration of all four façade orientations with sensor located at 2m and with glass shading coefficient of 0.27. The following are list of potential energy savings associated with these configurations:

- Operational cost savings from reduced artificial lighting demand
- Operations cost savings from lower cooling loads
- Operational cost savings from electricity generated by BIPV facade
- Capital cost savings from reduced cooling energy demand and hence chiller size reduction
- Capital cost savings from removal of conventional shading devices such as blinds

6.1 INPUTS FOR STUDY

The criteria used in this study are based on current local market rates in Abu Dhabi. These findings are not fully applicable for other locations. The analysis in this study assumes the following:

- Cost of electricity is AED 0.15/KWhr
- Electrical consumption by lighting control, blind motorization, and EC glazing automation system is negligible and hence will not be included in this study
- The resizing of cooling system due to positive impact of cooling load reductions is not considered
- The maintenance cost of all systems is considered based on the advice of the suppliers and specialists

6.2 ANNUAL ENERGY CONSUMPTION OF ALL CONFIGURATIONS

This section aims to approximate the energy consumption of all configurations for a whole year. This value is the average of all four different orientations. In order to find the annual values, the following key steps are considered:

1- Daily average energy consumption for all cases is calculated by using the average of the four design days. This is repeated for all the orientations and the average of all four sides is total energy consumption for a full day. This value will represent the typical weekday consumption rate.

2- For the weekends, as explained in chapter four, since the building will not be occupied, therefore, the cooling set point will be assumed at 27˚C instead of 24˚C and hence a reduced energy demand. There are certain differences between the three cases that will affect the outcome. First, for the BIPV model, the panels will keep generating electricity at same rate as normal weekday. Thus, timing does not affect the performance of the BIPV model in this manner. Second, as most occupants tend to fully open their blinds on the final hours of last weekday prior to leaving the office, therefore, for the base case the blinds are assumed to not be in use during the weekends. This is where the EC glazing will be most advantageous, because without the need for daylight into the office room, and by simply switching to full tint mode, the EC façade will have the optimum solar gain strategy. For all models, an average of four weekend days (March 20, June 19, September 18, and December 24) which are closest to the design days will be taken and repeated for each orientation. The results of all the simulations for the calculation of the average weekend consumption rate are shown in Table E.5 of Appendix E.

3- The weekly energy consumption will be calculated by adding five weekday and two weekend average rates respectively found in steps 1 and 2. Furthermore, the annual energy consumption will be based on 52 typical weeks plus one typical weekday. All holidays are ignored for simplicity of the calculations. Table 6.1 shows the summary of the final calculations, while the detailed calculation charts are in Appendix E.

4- Due to the performance of each model in accordance to a specific orientation, a "best" configuration is also shown which combines the most optimum values from each façade technology. For this "best" model, BIPV have been assumed on East, South, and West façade, while clear glazing (dynamic EC glazing in clear state) is put on the North side. These values are represented on the far right column of Table 6.1.

Table 6.1 Annual energy consumption

	Base Case	**BIPV**	**Dynamic EC Glazing**	**Best Combined***
Annual system, equipment, and lighting consumption (KWh)	5110.3	5286.9	5022.1	5143.1
Annual electricity production (KWh)	-	1097.9	-	974.75
Net annual energy consumption (KWh)	5110.3	4189	5022.1	4168.35
Cost of net annual energy (AED)	766.55	628.35	753.31	625.25
Energy consumption reduction compared to base case (%)	-	18.03	1.73	18.43
Total cost savings over base case (AED)	-	138.20	13.24	141.30

* Note: combination of BIPV on East, South, and West façade with clear glazing on North

6.3 CAPITAL COST ESTIMATATION OF ALL MODELS

The cost of each system in this comparison is based on various quotations received from suppliers. In order to make the scenario more realistic, a medium size office building with 40m x 40m floor plate was considered. Assuming a 4m floor to floor height over 5 stories, the total façade area would be about 32,000m^2. In instances where the supplier was unable to provide a quotation for the complete system, an approximate price was calculated based on several correspondences via telephone and email. In the case where a local manufacture was unavailable, the price estimation was based on market analysis of previous studies. It is important to keep in mind that exact cost of these systems requires detailed information, usually entailed to a real project. Hence the costing in this study will only highlight a possible payback period for each system. Table 6.2 shows a summary of capital cost estimation of the three models based on module space in a typical office building. The different quotations from the suppliers can be seen in Appendix E.

Table 6.2 Capital cost estimation

	Base Case	**BIPV**	**Dynamic EC Glazing**	**Best Combined**[1]
Standard Curtain Wall module [2]	23,200	-	-	5,800
EC Window module [3]	-	-	31,116	-
Semitransparent BIPV module [4]	-	62,160	-	46,620
Automated Blinds [5]	4,300	-	-	-
Light Control System components	452 [6]	1,278 [6]	1,278 [6]	1,072
Subtotal	27,952	63,438	32,394	53,492
Maintenance 3%	839	Included [4]	972	174
Total	28,791	63,438	33,366	53,666[7]

Notes:

1- *Note: combination of BIPV on East, South, and West façade with clear glazing on North*
2- *Curtain wall price of AED1,450/m2 (Refer Appendix E)*
3- *System cost includes hollow aluminum frame system and wiring ($55/ft2plus 10% for controls/automation)-(SageGlass, 2010)*
4- *System cost is attributed to all necessary components (PV module, inverter, battery, mechanical and electrical installation, and cleaning/maintenance; (AED 5,180/m^2 - Refer Appendix E)*
5- *System costs include control mechanism, motor, fabric, and installation fee*
6- *For base case, the light control system does not provide dimming, whilst for BIPV and EC glazing, there is a light dimming component (Refer Appendix E)*
7- *This value is representative of the "best" configuration values being averaged for one office module*

6.4 RESULTS

The payback period for the three configurations is based on the simple Pay-back formula as follows:

$$Y = (I + M) / A$$

where Y is the Payback period, I is the extra initial investment over the base case curtain wall, M is the maintenance costs, and A is the annual savings (Wong, 2007). The results of the Pay-back period are shown in Table 6.3.

Table 6.3 Pay-back period for three configurations

	BIPV	**Dynamic EC Glazing**	**Best Combined**
Extra investment and maintenance (AED)	34,647	4,575	24,875
Annual savings (AED)	138.20	13.24	141.30
Pay-back period (years)	251	346	176

The results show that compared to a base case situation the extra investment in both the BIPV and EC glazing is economically unviable. However, in comparison, the payback period of the BIPV is still much more feasible than the EC glazing. The cost of EC glazing cannot be justified at this time by energy savings because the annual savings are very negligible (only 1.73% lower than the base case). Even considering other potential capital and operating costs, for example, the reduction in HVAC capacity and maintenance requirements, and the reduced needs for blinds or shading systems, it cannot be viable.

On the other hand, if the comfort of the occupant could be translated into productivity dollars, then dynamic EC glazing may be ergonomically justified. EC windows allow better visual access to the outside without increasing glare which lead to better indoor lighting condition, and increase the occupants comfort and performance. This could also result in higher rental premiums not considered in this analysis. Figure 6.1 shows the daylight illuminance for a typical design day for the optimal EC glazing model. In comparison to the illuminance levels of the BIPV model, seen in Fig. 6.2, the level of natural lighting and the quality of unobstructed view to outside are definitely better in the EC model. Studies have shown that greater user productivity is associated with higher levels of occupancy comfort. Thus, it is important to note that long pay-back periods driven through capital cost and energy savings could be overcome by boost in business productivity of the user in the space.

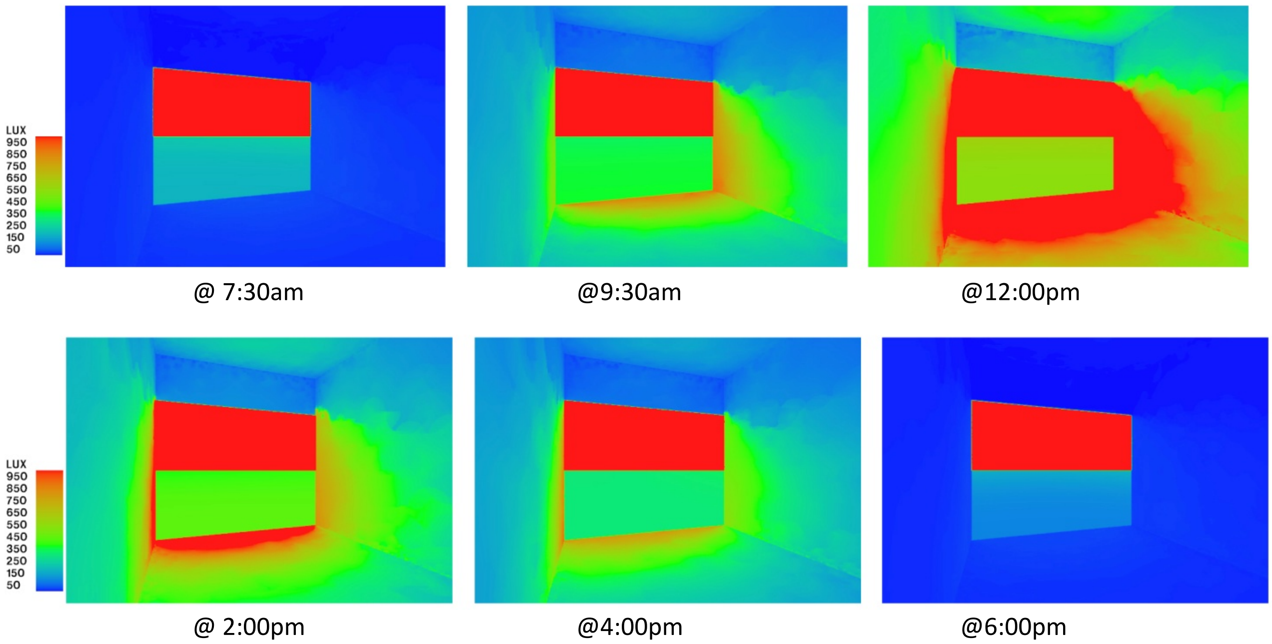


Figure 6.1 Illuminance levels of dynamic EC glazing model South facing window on June 21 under clear skies

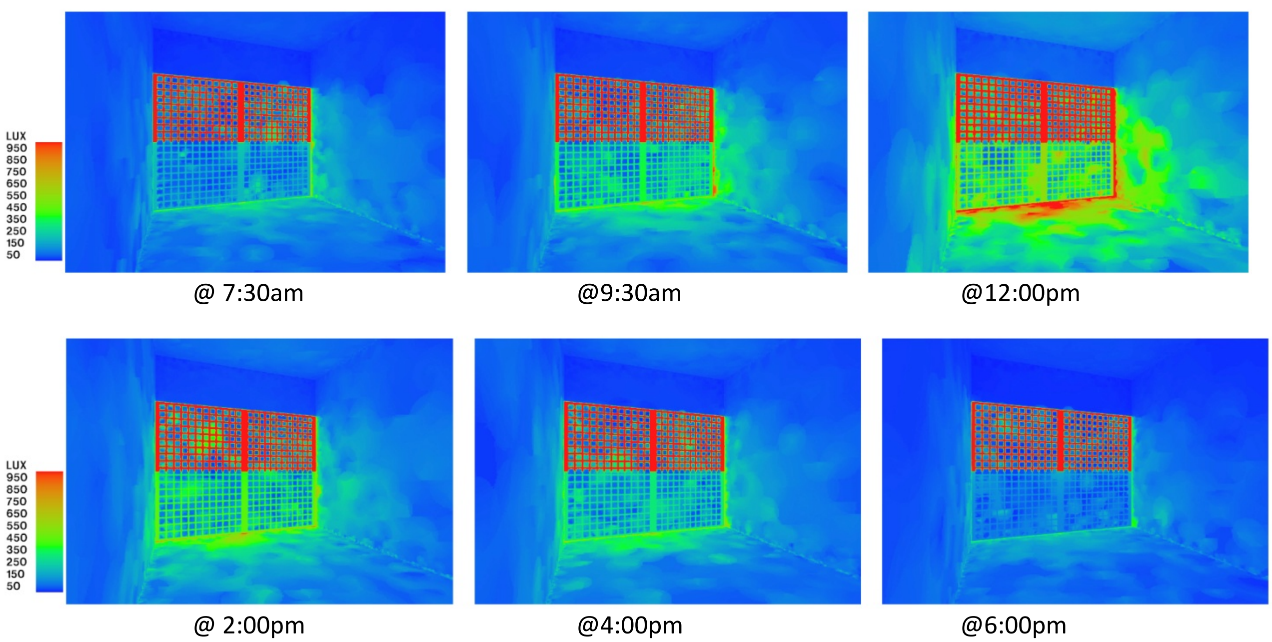


Figure 6.2 Illuminance levels of BIPV model South facing window on June 21 under clear skies

As for the feasibility of BIPV, increase in module efficiencies would definitely boost incentives for the investment of this clean energy technology and help reduce its payback period. As predicted by Green (2008) new advances in technology would be capable of offering modules with efficiency as high as 60% by the year 2020. In order to test this hypothesis, a simulation of a south facing window was conducted to see the change in overall energy use. Figure 6.3 shows the comparison of annual electrical production of the BIPV model used in this research (with the current manufacturing data of maximum 14.5% nominal efficiency) and a new BIPV model with nominal efficiency of 60%.

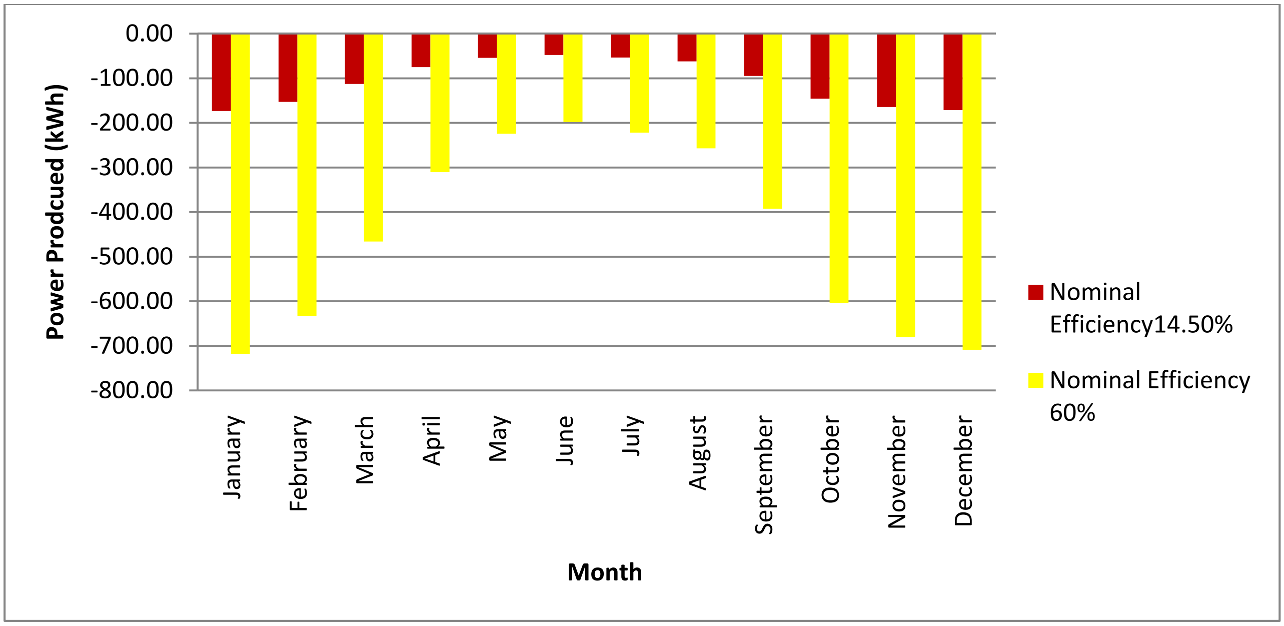


Figure 6.3 Annual power productions of BIPV models with different nominal efficiency for South orientation

The negative values refer to grid displaced electricity and the apparent advantage of using higher efficiency module. Figure 6.4 and 6.5 show the typical weekly summer and winter total energy use of these two models. The maximum benefit is gained through the winter months as seen by larger gap in the energy consumption curves. Furthermore, the calculations show that the annual energy use of the model with more efficient panel results in a surplus of energy produced. Accordingly, this would mean a higher cost savings over the base case seen in Table 6.4 from 18% to 102%; i.e. The building will have a positive net energy production (net zero energy).

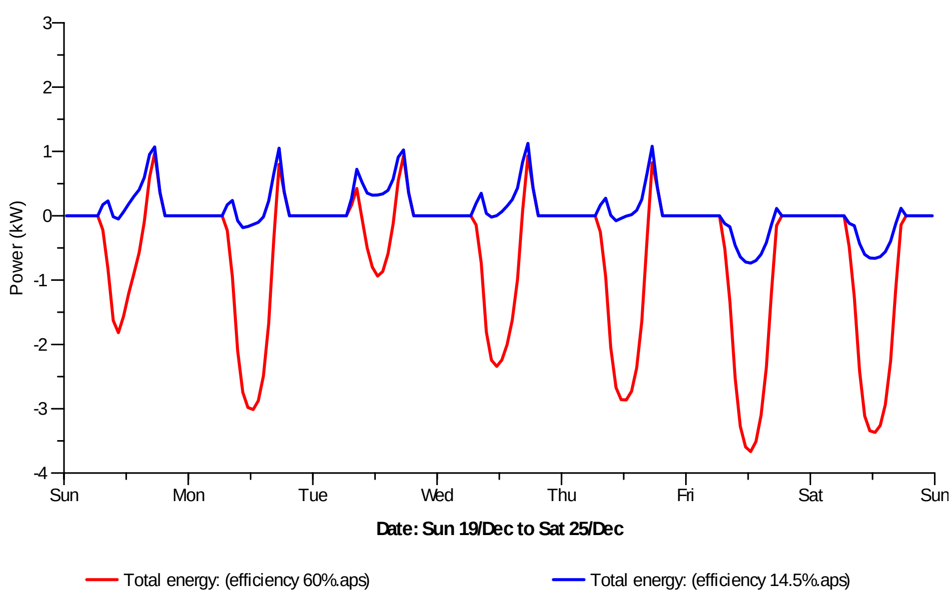


Figure 6.4 Energy comparisons for selected BIPV models for South orientation for typical winter week

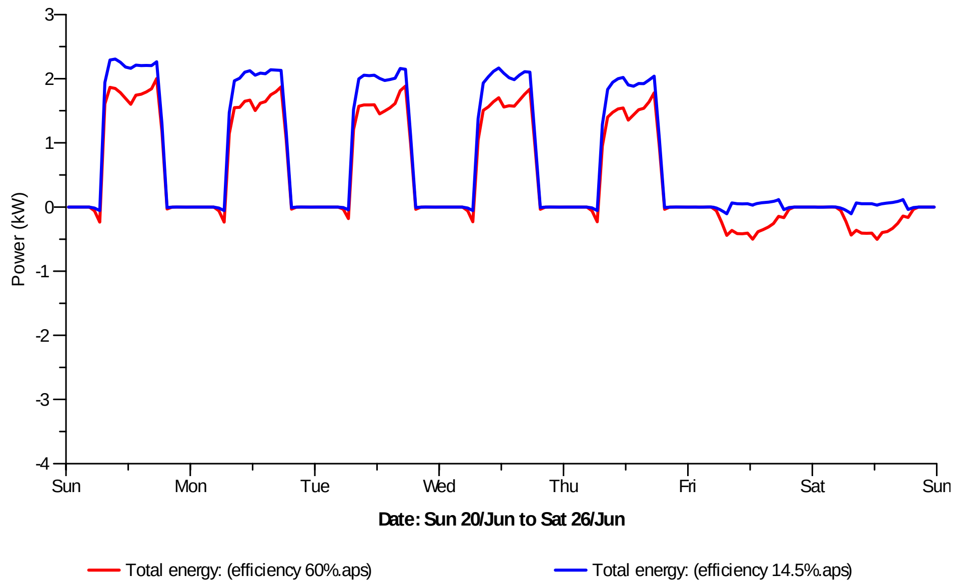


Figure 6.5 Energy comparisons for selected BIPV models for South orientation for typical summer week

Table 6.4 Annual energy consumption with high efficiency BIPV panels

	Base Case	BIPV (14.5%)	BIPV (60%)
Annual system, equipment, and lighting consumption (KWh)	5110.3	5286.9	5286.9
Annual electricity Production (KWh)	-	1097.9	5413.0
Net annual energy consumption (KWh)	5110.3	4189	- 126.1
Cost of net annual energy (AED)	766.55	628.35	-18.9
Energy consumption reduction compared to base case (%)	-	18.03	102.50
Total cost savings over base case (AED)	-	138.20	785.45

Other important considerations are the price of the utilities. The price of electricity is very cheap and this is not expected to last. As illustrated in Fig. 6.6, in some regions the electricity generating cost with PV are already on the level of utility prices (Neuner, 2008). With the aid of government incentives and tax returns, the potential for BIPV could be much higher that current situation. To illustrate, if the price of electricity would increase to AED0.50/KWhr, and using the higher efficient modules, then the payback period would be reduced from 251 years to 13 years. This is a considerable change and clearly shows that further research funding is needed to reach the optimum panel efficiencies. At the same time it proves that having cheap electricity does not provide a good incentive for investing in new yet more expensive green technologies. Fortunately, Abu Dhabi is beginning to allow grid connection with favorable rates. This move can potentially reduce the storage (battery) costs and make this type of investment more attractive.

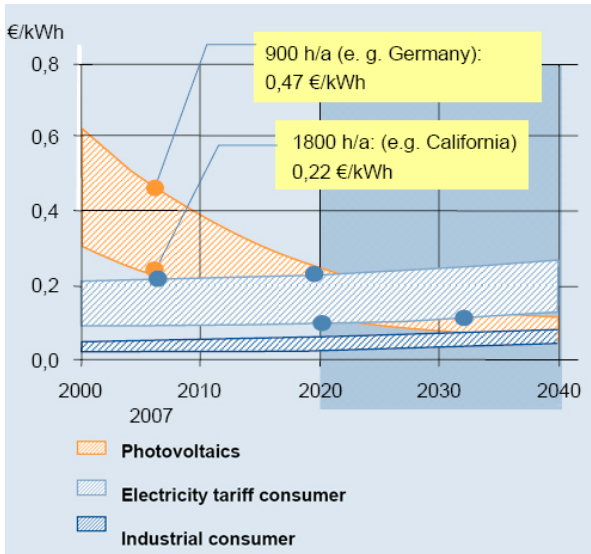


Figure 6.6 Comparison of standard electricity price with PV generated power prices (Neuner, 2008)

CHAPTER 7: CONCLUSIONS AND FURTHER WORK

This research studied the application of BIPV and EC glazing as an alternative façade to conventional glazing and blinds within the climate of Abu Dhabi. The literature review section, which lay the back bone for the research, helped in identifying the objective of the research. Three different simulation models were created to test all the configurations with various changing parameters. The results of all the simulations were used to determine the potential energy savings of each system against the base case model. In order to test the viability of each system, an economic analysis was done. The study showed that computer simulation model can be a powerful tool for architects and engineers in order to select the optimum façade and meet the future need for energy efficiency. It is important that the findings reported in this paper should be treated with some caution, due to concerns about the accuracy of the manufacturers' rated peak power and insolation measurements. However, whilst absolute values may be affected, the conclusions about the physical responses of the different technologies will still hold true.

7.1 CONCLUSIONS

The first stage of this study was the assessment of various BIPV models which helped in choosing the most optimum model configuration to be selected for comparison against the base case and the EC glazing model. Amongst the various available BIPVs, Monocrystalline and thin film cells were chosen and tested in 11 different façade settings. These models varied in transparency of the glazing, area of available PV cells, and the nominal cell efficiency. The final model selected was with semi-transparent Monocrystalline cells which cover the entire façade. This scheme surpassed the other scenarios in terms of energy efficiency and human comfort mainly glare occurrence. The results of this study refer to this selected model as the BIPV model.

The BIPV model showed the most energy saving amongst all configurations, although in very few cases, the EC glazing was more advantageous. For the BIPV model, the south façade showed the highest potential of energy savings whilst the north façade had the lowest. It was found that the BIPV model achieved a maximum energy consumption reduction of about 20.66%, 16.69%, 16.86%, and 1.35% for the south, east, west and north orientation, respectively against the base case model. On the other hand, the EC glazing model had much less benefit against the base case model with -2.86%, 1.35%, 0.89%, and 7.41% energy savings for the same orientations, respectively.

The use of automated light control system with dimming is beneficial in reducing electrical lighting demand for both the BIPV model and EC glazing. The study further assessed the potential of each system through manipulating the glass properties mainly the shading coefficient in the south facade. When the glass shading coefficient was increased from 0.27 to 0.6, there was an increased energy saving potential (15%) in the in the BIPV model against the base case. Similarly, the dynamic EC glazing showed significant improvement in energy savings (11.17%) over the base case which used higher shading coefficient. In general, using a more realistic shading coefficient, minimizing solar gain through dynamic shading coefficient proves little benefit against the replacement of the blinds in the base case. In particular, the dynamic EC model has the worst performance in the most critical façade orientation which is the south. This raises the question of whether it is wise to use EC glazing on south façade.

The study further analyzed glare levels for different configurations and found that although there were few instances of glare in all configurations, the dynamic EC glazing provides the most optimum lighting condition for the occupants. The BIPV model blocks a large quantity of daylight, due to opacity of the PV cells, while the base case requires the use of blinds during high illuminance periods. Moreover, the EC model also proves to give the best feeling of connectivity to the outside. The study further looked at the change in sensor location from 2m to 4m from the window edge. The result showed an increased the energy savings for both cases, although the change was very marginal compared to the change of the glass properties.

The current application of both BIPV and EC glazing are unfeasible as shown in the economic analysis for all orientations. While some of the obvious factors are the high cost of each system and low cost of electricity, it must be pointed out that in the case of the EC, the low margin of energy saving potential over the base case is the biggest hindrance in the viability of the system. The next section will discuss ways which this obstacle could be overcome for future studies to enhance the potential benefit of EC application. Additionally, the economical analysis could further be improved by considering the environmental cost (the embodied energy of each system) and not just the manufacturing and operational cost. This life cycle analysis will give a more comprehensive cost estimation comparison between each system.

It must be mentioned that scientific facts alone are not sufficient to bring change. The right public policies are required to ensure that these systems reach their full potential. Governments can adopt policies to mandate the environmental optimal use of these alternative technologies. Below are some suggestions toward achieving the goal of cutting CO_2 emissions from buildings:

- Encourage and when required enforce the use of alternative facades to control solar gain and lower HVAC and lighting consumption levels
- Ensure that all new public buildings are fitted with the most optimum facade technology adapted to its locale
- Support developers to retrofit existing buildings with more energy efficient facades
- Provide economic incentives to manufacturers and users of environmental friendly products

Manufacturing tax-credits and government funding will make these revolutionary energy-saving technologies more available to architects and developers for their future projects.

7.2 FURTHER WORK

Although the findings of this study should clarify the objectives set forth earlier, it is noteworthy to mention that this research should be repeated every two years for the following reasons:

- The price of energy (electricity) might change (increase) due to growth of human population and thus higher energy demand
- The market price of each system is likely to change (decrease) with new technological advancement
- The manufacturers are likely to bring new types of PV arrays or electrochromic glass to the market

In addition, the research can be continued to examine several different conditions discussed here:

Figure, 7.1 shows how various architectural building shapes can have different energy consumptions because of how the façade is orientated. While this paper assumed the most typical office building shape, other scenarios will behave differently. For instance, in the case of triangular shaped office floor plate, it is not easy to differentiate which side faces any of the four orientations. Therefore, different configurations and shapes will have different performance.

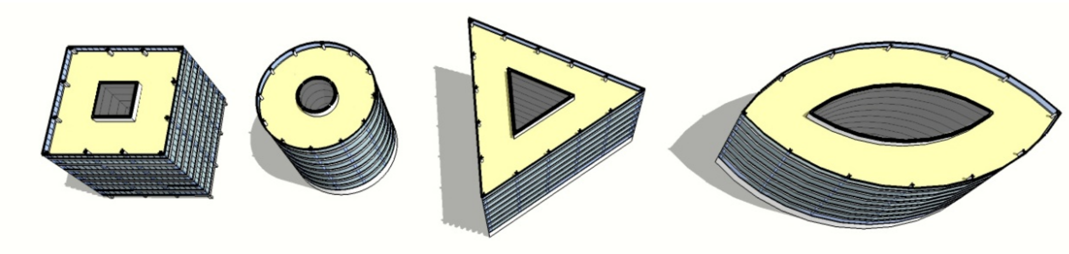


Figure 7.1 Various architectural building shapes with core shown shaded

Studying different combination of façade integration could further enhance this study. As shown in Fig. 7.2a, because the location (latitude) has an effect on PV's angle of incidence, its integration vertically (as an alternative façade) tends to be less efficient that if it was placed horizontally as an additional feature to the façade. Moreover, as shown in Fig. 7.2b, perhaps the potentials of these two could best be achieved when they are considered hand in hand rather than competing with one another.

a b

Figure 7.2 PV array placed horizontally on the façade (a) and combined with EC glazing (b)

Another way of expanding this research is to examine the effect of each system on different building typologies such as residential, mercantile, or educational. Since these building have different operating hours, therefore, the advantage of either system could also be expected to change with change in building function. Furthermore, analyzing these façades under different environmental setting would also be useful as the affect of rural and urban settings on a building would not be the same.

In the case of the BIPV model, the study could further be improved by examining the effect of more regular cleaning of the PV panel. This undoubtedly would increase the efficiency and result in higher performance, but at the same time, the economical aspect of maintenance needs to be kept in mind. Thus, there is a balance between how often is most economically viable to clean the panels from dust, sand, and other deterring factors.

Although this study proved that EC glazing in not more advantageous than regular double glazing with blinds, there are potential aspects that could be studied to favor this technology. For example, if the study is done with only segments of the façade that replace conventional glazing with EC, perhaps the outcome for the EC model would be better. Figure 7.3 show that this approach allows a more personalized control to the room's lighting condition and would allow the occupants to switch the EC window for privacy, glare control, daylight, and view.

Figure 7.3 Diagram of zoned window wall (Lee et al., 2006)

The study can be repeated for different climatic regions in order to see the effect of latitude on the energy potential. Table 7.1 shows a list of ten possible cities for analyzing the systems based on geographical location. Furthermore, in this study only a single light sensor was use in each space. Although, this is not ideal, but it is a limitation which IES is now working on improving for later versions. For future, using multiple sensors would ensure a more uniform light distribution within the room.

Table 7.1 Selected cities based on location and climatic conditions listed in order of latitude

City	Country	Latitude	Longitude	Annual Incident Solar Radiation (kWh/m2)*
Sydney	Australia	-33.8˚	151.2˚	979.90
Hong Kong	China	22.2˚	114.2˚	601.08
Riyadh	KSA	24.6˚	46.7˚	965.08
Dubai	UAE	25.1˚	55.2˚	982.85
Los Angeles	USA	33.9˚	-118.4˚	1,023.79
New York	USA	40.7˚	-73.9˚	891.02
Toronto	Canada	43.7˚	-79.6˚	487.74
Venice	Italy	45.4˚	12.3˚	569.65
London	UK	51.4˚	0.0˚	388.43
Moscow	Russia	55.7˚	37.6˚	409.45

*Note: this value is based on best orientation measured from Autodesk Ecotect Analysis© weather tool

All the conditions mentioned so far can be studied through the use of simulation and may enhance the benefits from each technology. This further proves why using simulations is the most optimum research technique for this study. At the same time, although computer softwares are helpful tools to demonstrate the interdependency of building energy use and design parameters, it is good if the performance of model(s) can be evaluated with recorded data. Hence, if a budget would allow, it would be of value to run a laboratory testing or do field measurements of actual built cases in parallel to the simulation.

Going to the field and surveying the existing building users might be a direct way of finding out the occupants comfort levels within environments that have these systems installed. Unfortunately, currently there are very few buildings in the UAE that have these two façade technologies installed. Therefore, for future, in addition to benefits in terms of energy savings, the study could assess the overall benefits in terms of the occupant's comfort levels through field measurements. The effects of how the interaction between the building envelope and the internal environment shall be evaluated. By analyzing the temperature fluctuations, humidity levels, number of glare occurrences, the research can determine whether the working environment is well suited for the occupants in each scenario. The data for the occupant's comfort conditions must vary according to location because people's tolerance level is different for each culture and country.

In the end, the greatest uncertainty is the willingness of a country to adopt policies to support either technology. The recent focus on sustainable development in the Middle East has created vast opportunities for many professionals in the environment and energy sectors. Some of the leading economies of the region have undertaken massive initiatives to attain sustainability leadership and boost their energy resources. One of the important steps taken by the government of the UAE was the establishment of Estidama, Abu Dhabi's sustainability program, as well as Masdar, a multi-faceted company advancing the development, commercialization and deployment of renewable energy solution and clean technologies. As the region realizes its potential as a hub for renewable energy, many companies will look at sustainable investments to boost the opportunities created by government initiatives. Through such research, they can recognize the long-term benefits of these technologies and support them through subsidization and privatization. Only then can such alternative façades prove their potential and become standards of a sustainable built environment.

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APPENDIX A: SIMULATION RESULTS

A.1 SOUTH FAÇADE SIMULATIONS

A.1.1 Lighting sensor @2m and Glass Shading Coefficient 0.6

Table A.1 Hourly energy consumption of all scenarios of South façade in June 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
June 21, 2010	5:30	0.00000	-0.01442	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.05659	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.70864	1.55651	1.74026	1.70085	1.66457	1.63192	1.60721	1.57939	1.55398	8.90%	9.05%
	8:30	1.87466	1.86982	1.89191	1.85700	1.82455	1.83338	2.02833	2.13839	2.11593	0.26%	2.20%
	9:30	1.90145	1.95489	1.91503	1.87866	1.84575	1.95430	2.11664	2.16020	2.13685	-2.81%	-2.78%
	10:30	1.95347	2.12009	1.96468	1.96370	2.03202	2.14447	2.23306	2.21166	2.18853	-8.53%	-12.03%
	11:30	1.95772	2.10309	1.97397	2.07571	2.15416	2.23402	2.24048	2.21510	2.19211	-7.43%	-11.97%
	12:30	1.95139	2.04922	1.95682	1.99987	2.09292	2.17984	2.21566	2.18759	2.16241	-5.01%	-10.81%
	13:30	1.95146	2.13271	1.95541	1.92764	2.03768	2.14286	2.21959	2.19221	2.16715	-9.29%	-11.05%
	14:30	1.93628	2.12266	1.93931	1.90207	2.00348	2.11646	2.20751	2.18080	2.15617	-9.63%	-11.36%
	15:30	1.98481	2.16325	1.98734	1.95116	2.00734	2.13332	2.25456	2.23544	2.21151	-8.99%	-11.42%
	16:30	1.96675	2.08739	1.96931	1.93535	1.91514	2.04585	2.19957	2.22817	2.20570	-6.13%	-4.02%
	17:30	1.92404	2.09049	1.92757	1.89742	1.87910	2.00880	2.16925	2.20386	2.18388	-8.65%	2.34%
	18:30	1.28476	1.21798	1.29060	1.26618	1.24513	1.22907	1.21786	1.20165	1.18534	5.20%	3.08%
	19:30	0.00000	-0.00791	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**22.39543**	**23.38918**	**22.51221**	**22.35561**	**22.70184**	**23.65429**	**24.70972**	**24.73446**	**24.45956**	**-4.44%**	**1.66%**
				Total (Optimal Dynamic Glazing)					**22.02401**			

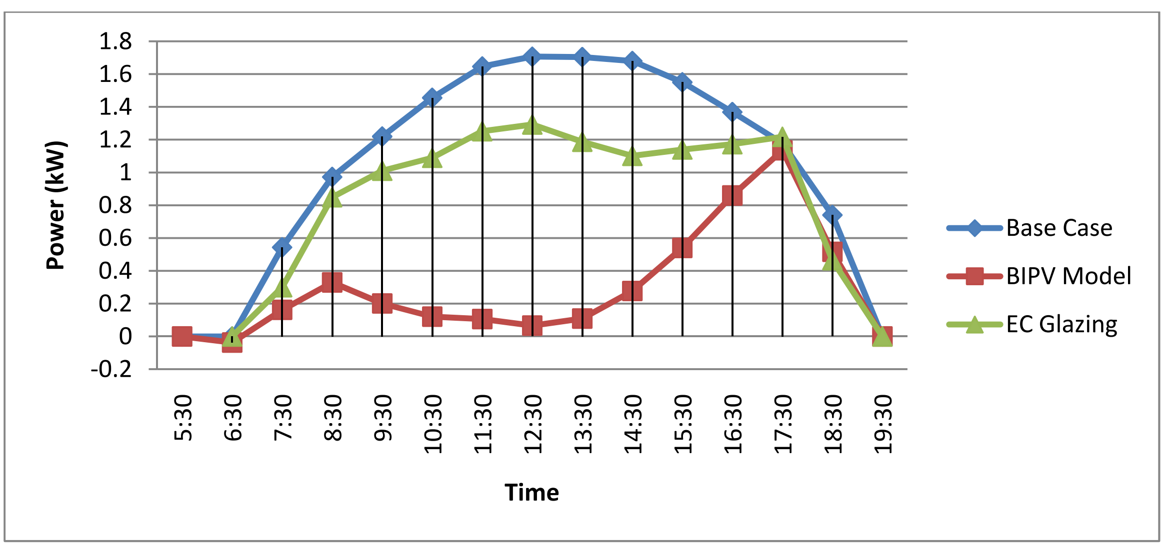


Figure A.1 Hourly Energy Consumption for all configurations for South façade in June 21 with glass of 0.6 shading coefficient and lighting sensor @ 2m

Table A.2 Hourly energy consumption of all scenarios of South façade in September 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
September 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.03370	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.54900	1.25686	1.56218	1.50982	1.46100	1.41523	1.38541	1.35984	1.33104	18.86%	14.07%
	8:30	1.72338	1.30762	1.72310	1.67109	1.62275	1.57745	1.67313	1.90936	1.88141	24.12%	8.47%
	9:30	1.88543	1.24431	1.87212	1.80120	1.73543	1.67399	1.78358	1.98728	1.95050	34.00%	11.21%
	10:30	2.05483	1.19226	2.02773	1.93665	1.85203	1.77297	1.90609	2.06109	2.01465	41.98%	1.96%
	11:30	2.21278	1.23547	2.17520	2.06965	1.97135	1.87934	2.04265	2.14850	2.09463	44.17%	5.34%
	12:30	2.29579	1.23192	2.25326	2.14283	2.03986	1.94337	2.09679	2.20587	2.14977	46.34%	6.36%
	13:30	2.27056	1.26320	2.22854	2.12135	2.02144	1.92786	2.03989	2.19542	2.14120	44.37%	5.70%
	14:30	2.23687	1.46668	2.20022	2.10319	2.01298	1.92864	2.05707	2.21151	2.16250	34.43%	3.32%
	15:30	2.15612	1.62587	2.12909	2.04906	1.97485	1.90551	2.07230	2.21214	2.17089	24.59%	-0.69%
	16:30	1.96131	1.71867	1.94390	1.88181	1.82414	1.78085	1.97130	2.10028	2.06717	12.37%	9.20%
	17:30	1.84163	1.89038	1.79905	1.77844	1.80284	1.88436	1.98341	1.99601	1.96973	-2.65%	2.11%
	18:30	1.19664	1.03505	1.18905	1.15121	1.11657	1.08437	1.06612	1.05002	1.02911	13.50%	6.69%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**23.38434**	**16.43459**	**23.10344**	**22.21630**	**21.43524**	**20.77394**	**22.07774**	**23.43732**	**22.96260**	**29.72%**	**12.21%**
				Total (Optimal Dynamic Glazing)					**20.52857**			

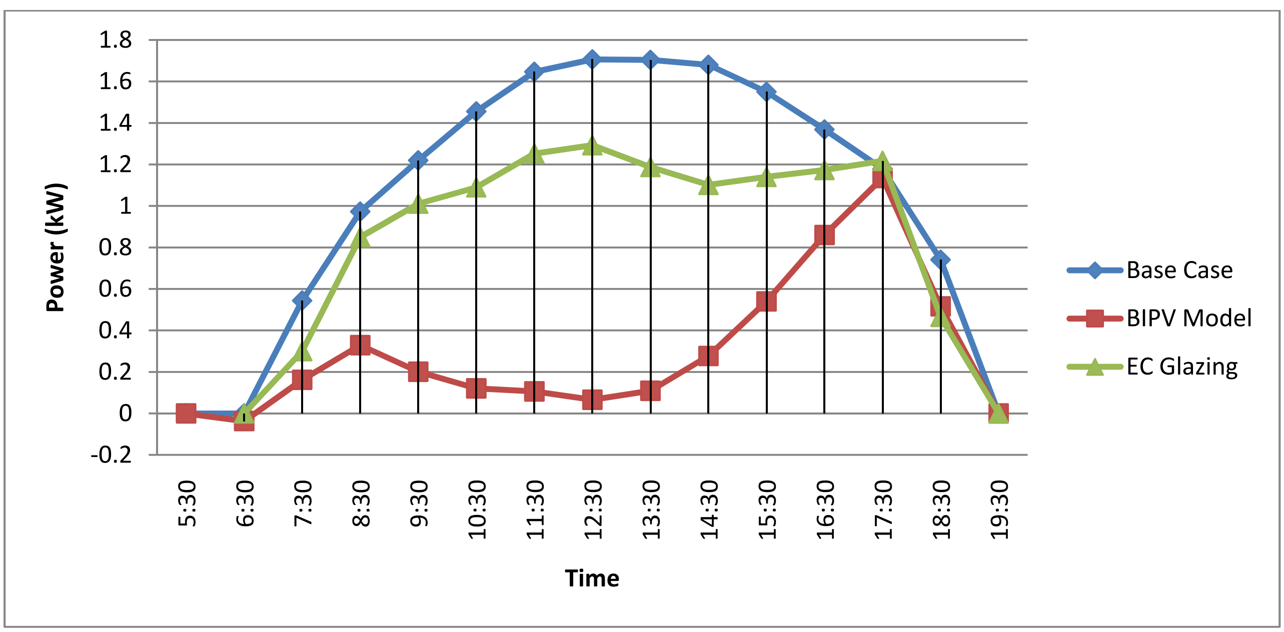


Figure A.2 Hourly Energy Consumption for all configurations for South façade in September 21 with glass of 0.6shading coefficient and lighting sensor @ 2m

Table A.3 Hourly energy consumption of all scenarios of South façade in December 23

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
December 23, 2010	5:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	6:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	7:30	0.3648	0.1662	0.4759	0.4248	0.3803	0.3437	0.3210	0.3050	0.3000	54.43%	17.76%
	8:30	0.9206	0.1936	1.0306	0.9680	0.9078	0.8493	0.8703	1.1194	1.1053	78.97%	7.74%
	9:30	1.1398	0.0454	1.4231	1.3222	1.2251	1.1312	1.0557	1.0107	1.1035	96.02%	0.75%
	10:30	1.3501	-0.0289	1.7546	1.6215	1.4931	1.3684	1.2673	1.1681	1.0894	102.14%	19.31%
	11:30	1.5225	0.0168	2.0298	1.8759	1.7269	1.5817	1.4634	1.3461	1.2519	98.90%	17.78%
	12:30	1.5918	0.0553	2.1537	1.9839	1.8194	1.6589	1.5281	1.3989	1.2928	96.53%	18.78%
	13:30	1.5684	0.0806	2.1157	1.9315	1.7535	1.5802	1.4399	1.3041	1.1876	94.86%	24.28%
	14:30	1.4861	0.1408	1.9911	1.8129	1.6413	1.4748	1.3407	1.2125	1.1016	90.53%	25.88%
	15:30	1.3481	0.2743	1.7802	1.6237	1.4735	1.3285	1.2125	1.1400	1.2107	79.65%	10.19%
	16:30	1.2274	0.5559	1.4852	1.3672	1.2544	1.1731	1.2271	1.3680	1.3039	54.71%	4.42%
	17:30	1.2605	1.0937	1.3736	1.3247	1.3419	1.3319	1.3125	1.2627	1.2173	13.23%	-6.46%
	18:30	0.5846	0.4506	0.7551	0.6958	0.6394	0.5845	0.5412	0.5015	0.4653	22.92%	-9.36%
	19:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	20:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	Total	**14.3645**	**3.0442**	**18.3685**	**16.9520**	**15.6566**	**14.4061**	**13.5797**	**13.1369**	**12.6292**	**78.81%**	**15.91%**
				Total (Optimal Dynamic Glazing)					**12.0788**			

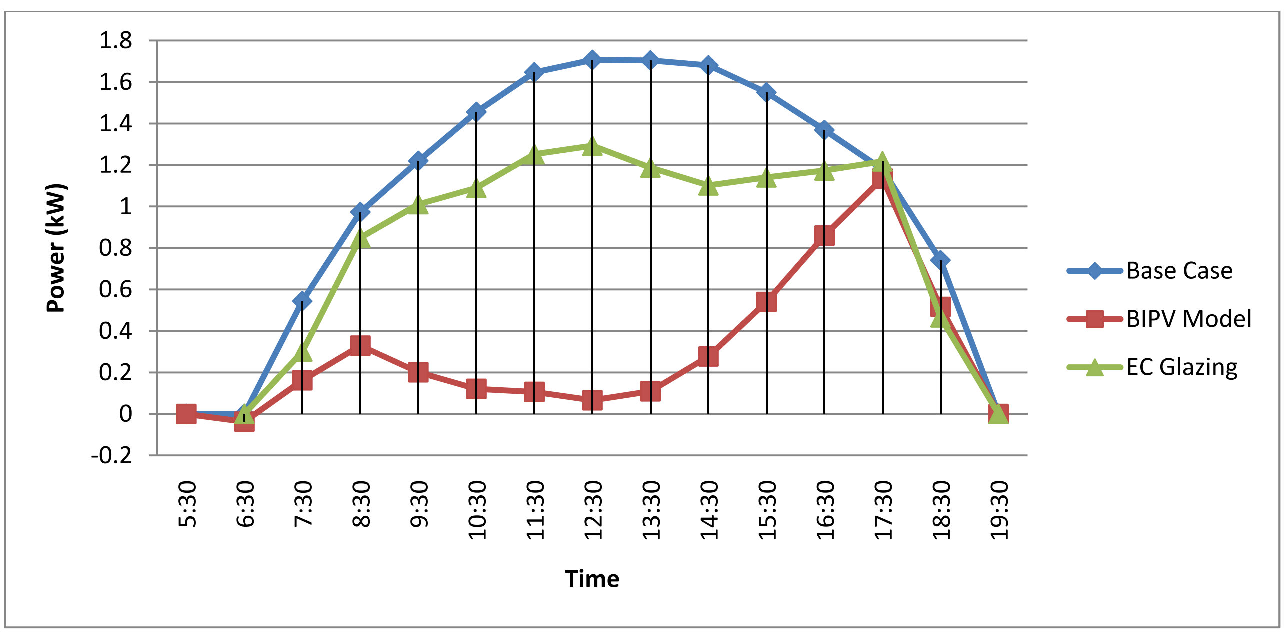


Figure A.3 Hourly Energy Consumption for all configurations for South façade in December 23 with glass of 0.6 shading coefficient and lighting sensor @ 2m

A.1.2 Lighting sensor @4m and Glass Shading Coefficient 0.27

Table A.4 Hourly energy consumption of all scenarios of South façade in March 21

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase BIPV	Savings Over Basecase ECG (Dynamic)
March 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.02467	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	0.32391	0.21273	0.68583	0.58900	0.49865	0.41372	0.35616	0.31400	0.30000	34.32%	7.38%
	8:30	1.13458	0.81116	1.15447	1.19300	1.21328	1.22707	1.17154	1.11600	1.06600	28.51%	-8.15%
	9:30	1.31924	0.82750	1.30129	1.33800	1.36770	1.39874	1.35708	1.29400	1.24300	37.27%	-6.03%
	10:30	1.41126	0.80267	1.50545	1.41600	1.44348	1.49576	1.50530	1.43000	1.37000	43.12%	2.92%
	11:30	1.20886	0.81107	1.67959	1.55100	1.48930	1.55903	1.62482	1.54000	1.47200	32.91%	-21.77%
	12:30	1.22349	0.78069	1.72766	1.59000	1.49570	1.56390	1.63926	1.55200	1.47900	36.19%	-20.88%
	13:30	1.25466	0.81501	1.71899	1.58100	1.53466	1.58397	1.63369	1.54300	1.47000	35.04%	-17.16%
	14:30	1.59636	0.94570	1.69509	1.59200	1.61482	1.64284	1.63772	1.55300	1.48400	40.76%	7.04%
	15:30	1.57391	1.06721	1.61532	1.63100	1.64247	1.64857	1.58593	1.51400	1.45500	32.19%	7.56%
	16:30	1.48084	1.16600	1.60967	1.61800	1.60903	1.55195	1.49327	1.43500	1.38800	21.26%	-4.80%
	17:30	1.36203	1.19735	1.57659	1.53700	1.47766	1.41873	1.37156	1.32500	1.28600	12.09%	-8.49%
	18:30	0.57599	0.48265	0.78626	0.72800	0.67485	0.62568	0.58627	0.54700	0.51400	16.21%	-17.16%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**14.46513**	**9.89507**	**17.05621**	**16.36400**	**16.06160**	**16.12996**	**15.96260**	**15.16300**	**14.52700**	**31.59%**	**-0.43%**
				Total (Optimal Dynamic Glazing)					**14.52700**			

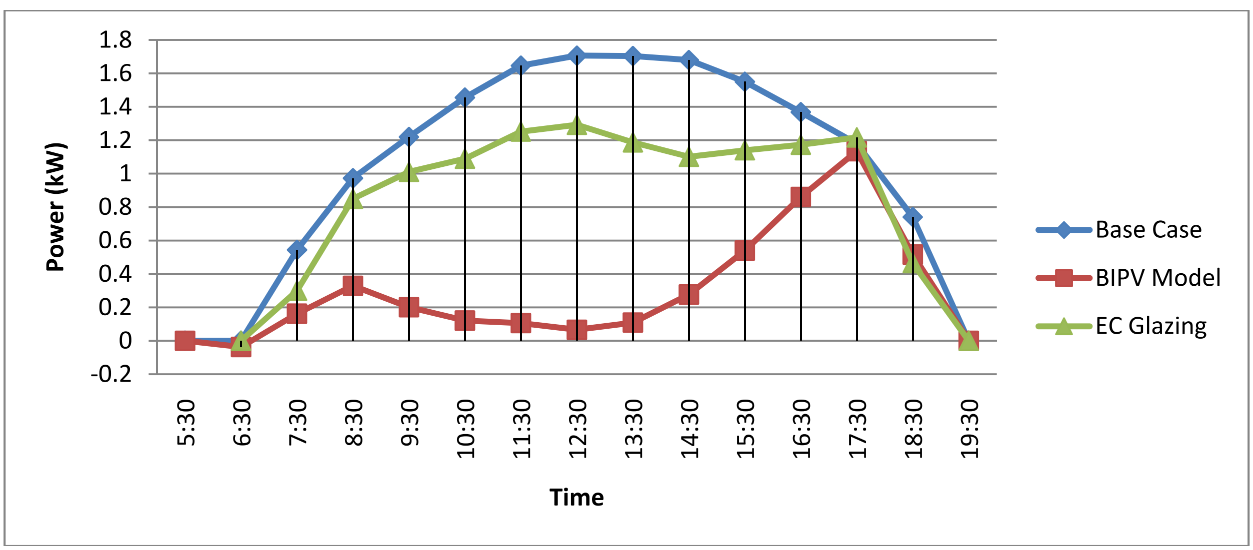


Figure A.4 Hourly Energy Consumption for all configurations for South façade in March 21 with glass of 0.27 shading coefficient and lighting sensor @ 4m

Table A.5 Hourly energy consumption of all scenarios of South façade in June 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
June 21, 2010	5:30	0.00000	-0.01442	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.05659	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.58108	1.47561	1.75189	1.71400	1.67630	1.63914	1.60889	1.57900	1.55400	6.67%	1.71%
	8:30	2.14659	2.01723	2.09504	2.15300	2.19622	2.19103	2.16435	2.13800	2.11600	6.03%	-2.07%
	9:30	2.17073	2.04250	2.19880	2.24200	2.24880	2.21506	2.18727	2.16000	2.13700	5.91%	-2.04%
	10:30	2.22170	2.11092	2.34498	2.33400	2.30034	2.26645	2.23877	2.21200	2.18900	4.99%	1.47%
	11:30	2.22529	2.12571	2.37220	2.33800	2.30364	2.26983	2.24222	2.21500	2.19200	4.47%	1.50%
	12:30	2.20349	2.05438	2.36258	2.32300	2.28521	2.24768	2.21723	2.18800	2.16200	6.77%	1.88%
	13:30	2.21118	2.09247	2.35499	2.32400	2.28735	2.25076	2.22103	2.19200	2.16700	5.37%	2.00%
	14:30	2.20147	2.08338	2.32540	2.31000	2.27366	2.23788	2.20884	2.18100	2.15600	5.36%	2.07%
	15:30	2.25758	2.13940	2.34397	2.36000	2.32499	2.29039	2.26236	2.23500	2.21200	5.23%	2.02%
	16:30	2.24949	2.13608	2.26853	2.31100	2.31203	2.27960	2.25334	2.22800	2.20600	5.04%	-1.34%
	17:30	2.22204	2.12988	2.22132	2.26900	2.27841	2.24959	2.22624	2.20400	2.18400	4.15%	-2.54%
	18:30	1.21606	1.17015	1.30779	1.28500	1.26206	1.23866	1.21971	1.20200	1.18500	3.78%	-3.78%
	19:30	0.00000	-0.00791	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**24.90670**	**23.49879**	**25.94749**	**25.96300**	**25.74901**	**25.37607**	**25.05025**	**24.73400**	**24.46000**	**5.65%**	**1.88%**
				Total (Optimal Dynamic Glazing)					**24.43904**			

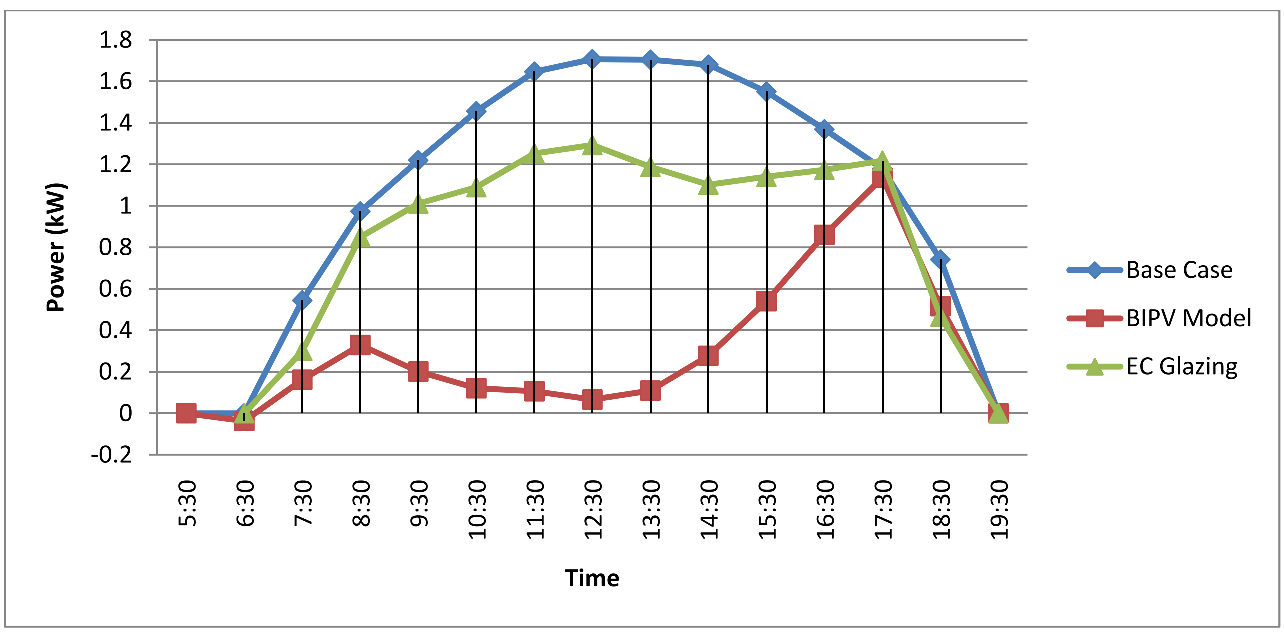


Figure A.5 Hourly Energy Consumption for all configurations for South façade in June 21 with glass of 0.27 shading coefficient and lighting sensor @ 4m

Table A.6 Hourly energy consumption of all scenarios of South façade in September 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
September 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.03370	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.38313	1.21575	1.56560	1.51700	1.47223	1.42964	1.39417	1.36000	1.33100	12.10%	3.77%
	8:30	1.93615	1.65192	1.79292	1.86000	1.91663	1.96910	1.94329	1.90900	1.88100	14.68%	-1.70%
	9:30	2.03056	1.57959	1.90977	1.97600	2.02262	2.06622	2.03248	1.98700	1.95100	22.21%	-1.76%
	10:30	2.12029	1.51208	2.03042	2.08300	2.12008	2.15247	2.11891	2.06100	2.01500	28.69%	4.97%
	11:30	2.21853	1.51374	2.17749	2.19200	2.22438	2.25320	2.21596	2.14800	2.09500	31.77%	5.57%
	12:30	2.27536	1.54121	2.25538	2.24100	2.27276	2.30869	2.27713	2.20600	2.15000	32.27%	5.51%
	13:30	2.26182	1.57590	2.23052	2.22100	2.25143	2.28734	2.26460	2.19500	2.14100	30.33%	5.34%
	14:30	2.27495	1.70970	2.22936	2.26900	2.29299	2.31996	2.27336	2.21200	2.16200	24.85%	4.96%
	15:30	2.27015	1.88107	2.25230	2.29200	2.31385	2.31562	2.26253	2.21200	2.17100	17.14%	4.37%
	16:30	2.14827	1.91738	2.13304	2.17300	2.19866	2.18085	2.13950	2.10000	2.06700	10.75%	-1.52%
	17:30	2.03403	1.90999	2.12682	2.12200	2.09712	2.05890	2.02666	1.99600	1.97000	6.10%	-3.10%
	18:30	1.07969	1.01319	1.19651	1.16200	1.13040	1.10010	1.07443	1.05000	1.02900	6.16%	-4.70%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**24.03293**	**18.98782**	**23.90013**	**24.10800**	**24.31315**	**24.44209**	**24.02302**	**23.43600**	**22.96300**	**20.99%**	**4.99%**
				Total (Optimal Dynamic Glazing)					**22.83369**			

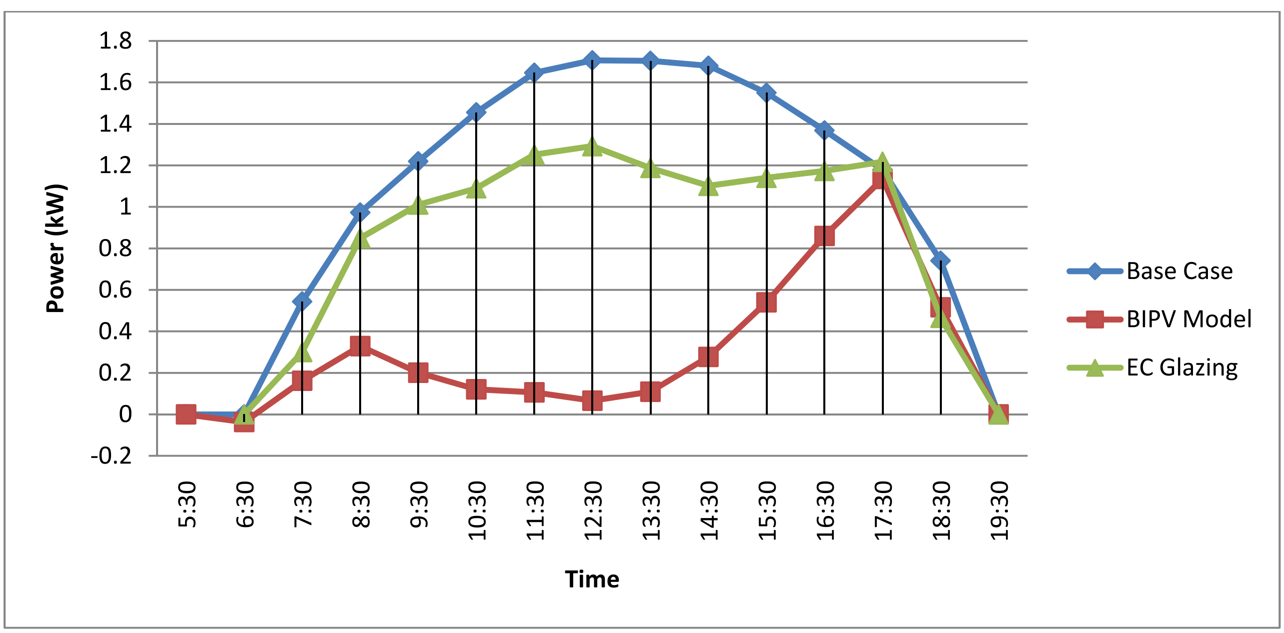


Figure A.6 Hourly Energy Consumption for all configurations for South façade in March 21 with glass of 0.27 shading coefficient and lighting sensor @ 4m

Table A.7 Hourly energy consumption of all scenarios of South façade in December 23

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
December 23, 2010	5:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	6:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	7:30	0.3233	0.1662	0.4784	0.4280	0.3838	0.3471	0.3251	0.3090	0.3000	48.58%	7.20%
	8:30	1.0814	0.5485	1.0517	1.0520	1.1014	1.1700	1.1977	1.1540	1.1140	49.27%	-8.20%
	9:30	1.0359	0.4108	1.4248	1.3250	1.2355	1.2771	1.3921	1.3850	1.3250	60.35%	-23.28%
	10:30	1.2417	0.2870	1.7561	1.6240	1.4964	1.3788	1.4847	1.5720	1.4910	76.88%	-20.08%
	11:30	1.4324	0.2773	2.0312	1.8780	1.7299	1.5866	1.5685	1.7470	1.6550	80.64%	-15.54%
	12:30	1.5075	0.2698	2.1551	1.9860	1.8221	1.6634	1.5883	1.7870	1.6970	82.10%	-12.57%
	13:30	1.4575	0.3154	2.1169	1.9330	1.7560	1.5843	1.5403	1.7070	1.5930	78.36%	-9.30%
	14:30	1.3724	0.4456	1.9923	1.8150	1.6436	1.4954	1.5680	1.6210	1.5080	67.53%	-9.88%
	15:30	1.2738	0.6340	1.7813	1.6250	1.5025	1.5071	1.5725	1.5120	1.4150	50.23%	-11.08%
	16:30	1.4858	0.8787	1.5544	1.5140	1.5128	1.4996	1.4634	1.3880	1.3160	40.86%	-0.93%
	17:30	1.3407	1.0944	1.5776	1.5130	1.4419	1.3742	1.3228	1.2760	1.2280	18.37%	-7.55%
	18:30	0.5645	0.4437	0.7577	0.6990	0.6430	0.5897	0.5497	0.5130	0.4750	21.40%	-13.90%
	19:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	20:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	Total	**14.1169**	**5.7714**	**18.6775**	**17.3920**	**16.2688**	**15.4732**	**15.5730**	**15.9710**	**15.1170**	**59.12%**	**-3.37%**
				Total (Optimal Dynamic Glazing)					**14.5925**			

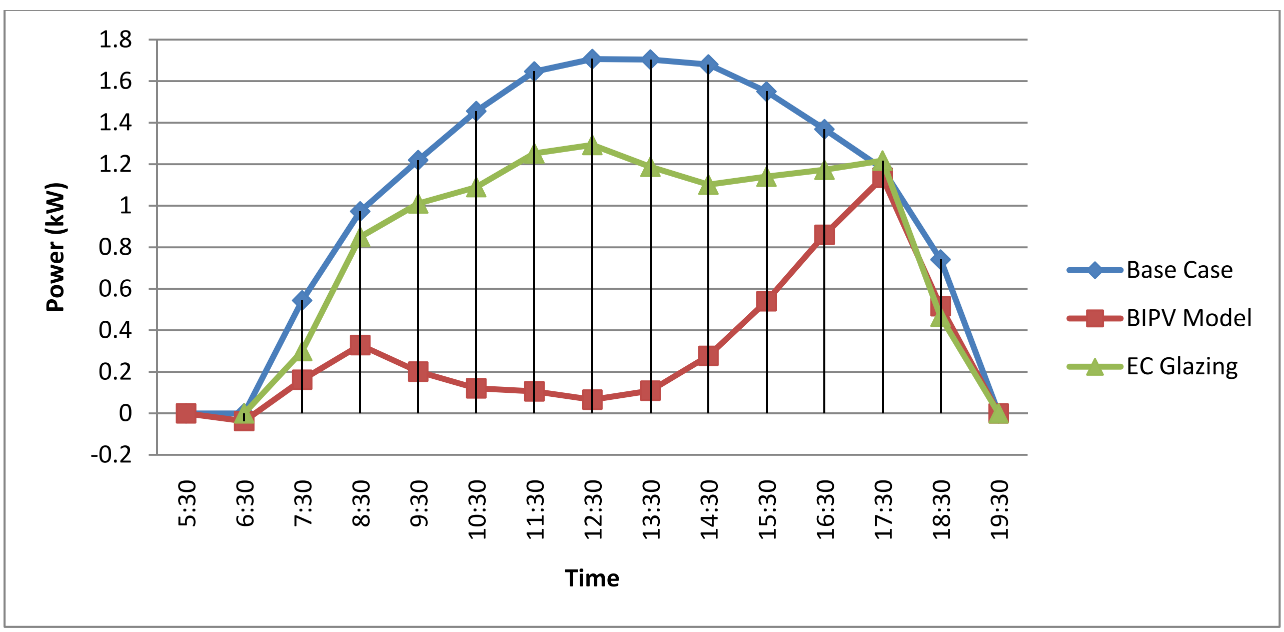


Figure A.7 Hourly Energy Consumption for all configurations for South façade in December 23 with glass of 0.27 shading coefficient and lighting sensor @ 4m

A.2 EAST FAÇADE SIMULATIONS

A.2.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

Table A.8 Hourly energy consumption of all scenarios of East façade in March 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
March 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.11848	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	0.47645	-0.09810	1.00134	0.87980	0.76100	0.64515	0.54953	0.46000	0.38878	120.59%	18.40%
	8:30	0.91999	0.05880	1.65463	1.50780	1.36400	1.22314	1.10662	0.98900	0.88574	93.61%	-32.95%
	9:30	1.01483	0.16229	1.91578	1.74397	1.57800	1.41541	1.28330	1.15300	1.09357	84.01%	-39.47%
	10:30	1.18012	0.47512	1.85435	1.69281	1.53800	1.38975	1.29754	1.48100	1.45102	59.74%	-22.96%
	11:30	1.19455	1.01722	1.62223	1.50401	1.42000	1.38923	1.48775	1.49700	1.42563	14.84%	-19.34%
	12:30	1.41341	1.24646	1.46817	1.49637	1.51300	1.51016	1.46130	1.39800	1.34063	11.81%	5.15%
	13:30	1.40993	1.26354	1.54633	1.56119	1.56500	1.51251	1.45140	1.39300	1.33945	10.38%	5.00%
	14:30	1.45706	1.31738	1.54554	1.57132	1.58300	1.55119	1.49316	1.43800	1.38692	9.59%	4.81%
	15:30	1.44916	1.32378	1.41422	1.46797	1.50000	1.52664	1.48272	1.43100	1.38401	8.65%	4.50%
	16:30	1.40807	1.30248	1.28214	1.29745	1.36100	1.42013	1.43911	1.39200	1.34857	7.50%	-0.86%
	17:30	1.32740	1.25404	1.18464	1.22100	1.28600	1.34486	1.35548	1.31300	1.27444	5.53%	3.12%
	18:30	0.55391	0.51812	0.75915	0.71067	0.66400	0.61876	0.58106	0.54400	0.51047	6.46%	-19.88%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**13.80488**	**9.72265**	**17.24852**	**16.65436**	**16.13300**	**15.54693**	**14.98897**	**14.48900**	**13.82923**	**29.57%**	**2.33%**
				Total (Optimal Dynamic Glazing)					**13.48312**			

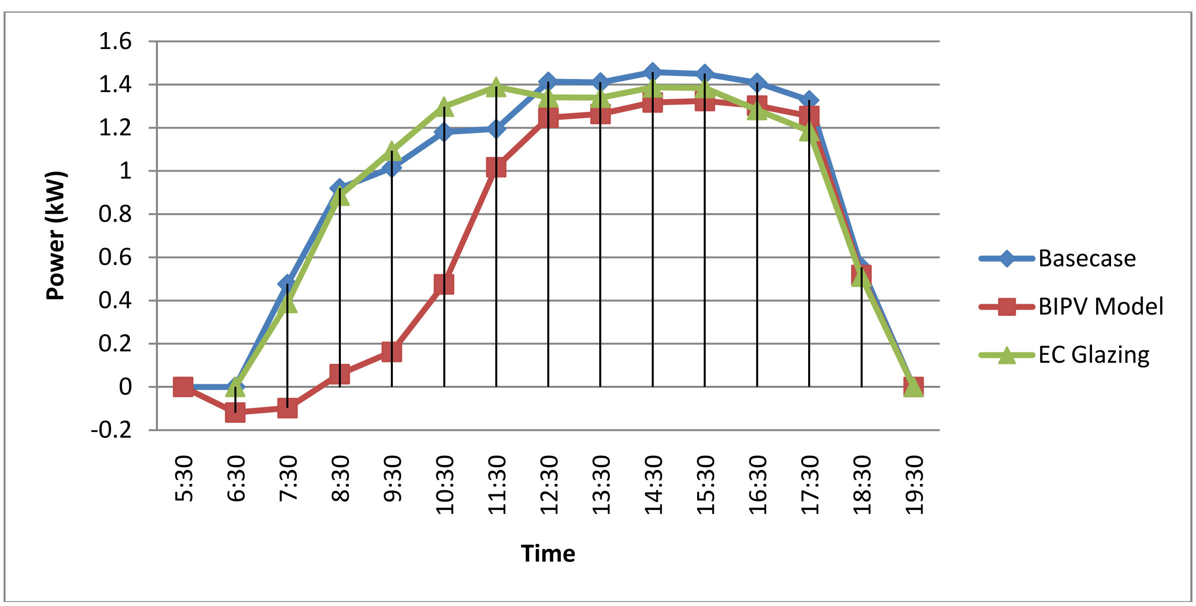


Figure A.8 Hourly Energy Consumption for all configurations for East façade in March 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.9 Hourly energy consumption of all scenarios of East façade in March 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
June 21, 2010	5:30	0.00000	-0.03453	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.20181	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.86038	1.22925	2.35529	2.24207	2.13300	2.02708	1.94086	1.85300	1.77617	33.92%	4.53%
	8:30	1.94861	1.22849	2.66030	2.52523	2.39500	2.26802	2.16491	2.06200	1.97198	36.96%	-16.39%
	9:30	1.92185	1.26056	2.73705	2.58745	2.44400	2.30643	2.19573	2.08700	2.05044	34.41%	-20.01%
	10:30	2.08107	1.55616	2.64854	2.51605	2.39000	2.27119	2.24353	2.42700	2.40249	25.22%	-15.44%
	11:30	2.08228	1.97434	2.37855	2.29269	2.25000	2.29037	2.38738	2.36800	2.31283	5.18%	-11.07%
	12:30	2.24838	2.05962	2.17111	2.20024	2.24700	2.29677	2.29591	2.24400	2.19695	8.40%	2.29%
	13:30	2.25708	2.12171	2.15365	2.20478	2.25400	2.30459	2.29797	2.24900	2.20469	6.00%	2.32%
	14:30	2.24255	2.11283	2.11815	2.17244	2.22700	2.28120	2.27835	2.23200	2.19018	5.78%	2.34%
	15:30	2.30000	2.17635	2.15527	2.14340	2.21800	2.29040	2.33106	2.28800	2.24800	5.38%	2.26%
	16:30	1.95963	2.17114	2.12027	2.06376	2.06300	2.17215	2.28771	2.27400	2.23690	-10.79%	-10.84%
	17:30	1.85834	2.16362	2.06610	2.01512	1.97100	2.08742	2.22727	2.24600	2.21257	-16.43%	-6.06%
	18:30	1.22146	1.18232	1.40084	1.35721	1.31600	1.28073	1.25274	1.22300	1.19434	3.20%	-7.74%
	19:30	0.00000	-0.00791	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**23.98163**	**20.99214**	**26.96512**	**26.32044**	**25.90800**	**25.87635**	**25.90342**	**25.55300**	**24.99754**	**12.47%**	**-1.07%**
				Total (Optimal Dynamic Glazing)					**24.23794**			

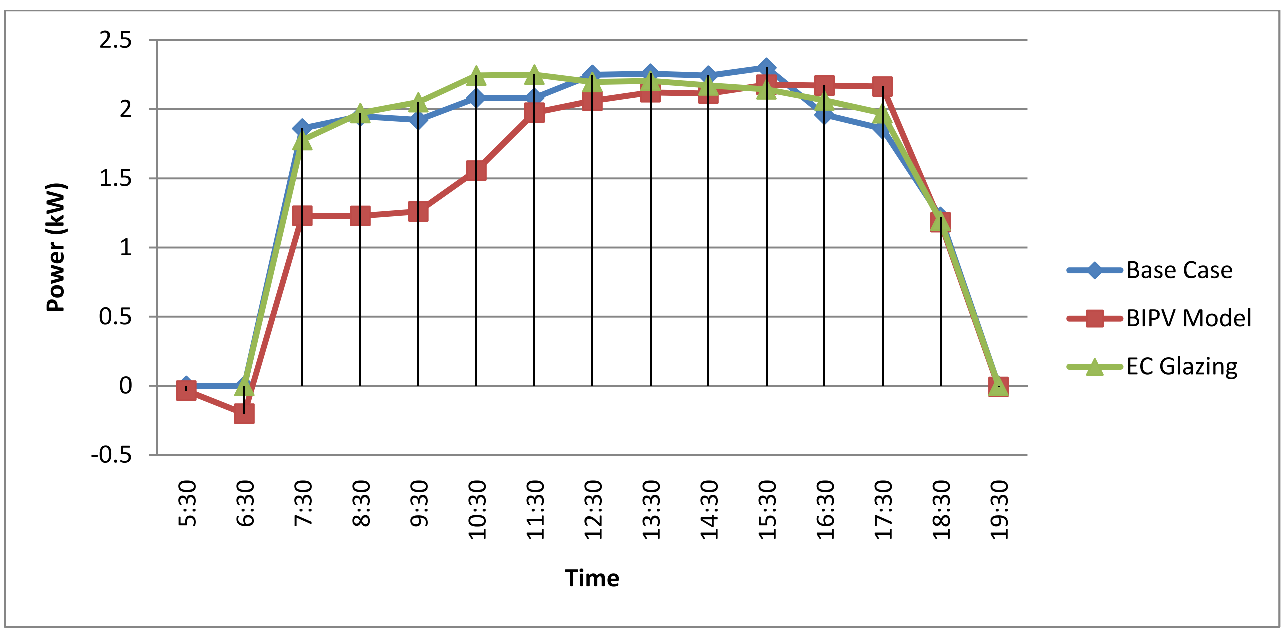


Figure A.9 Hourly Energy Consumption for all configurations for East façade in June 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.10 Hourly energy consumption of all scenarios of East façade in September 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
September 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.09046	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.47351	1.02655	1.77932	1.70390	1.63200	1.56341	1.50773	1.45000	1.39759	30.33%	5.15%
	8:30	1.62824	0.94221	2.19463	2.08032	1.97000	1.86302	1.77573	1.68800	1.60890	42.13%	-14.42%
	9:30	1.64210	0.95428	2.35037	2.20870	2.07300	1.94341	1.83921	1.73800	1.70555	41.89%	-18.35%
	10:30	1.74886	1.20498	2.24104	2.11565	1.99800	1.88614	1.84522	2.04600	2.03592	31.10%	-16.41%
	11:30	1.82596	1.76608	2.01917	1.95516	1.92900	1.96402	2.06877	2.06700	2.01937	3.28%	-10.59%
	12:30	2.05860	1.93258	1.95981	2.02879	2.07800	2.12344	2.08742	2.04700	2.00876	6.12%	2.42%
	13:30	2.05039	1.92447	1.89502	1.96479	2.02600	2.08461	2.07661	2.03800	2.00221	6.14%	2.35%
	14:30	2.10519	1.98159	1.91995	1.94433	2.02100	2.09849	2.12784	2.09100	2.05716	5.87%	2.28%
	15:30	1.95712	2.04071	1.95504	1.91507	1.96600	2.07160	2.16734	2.14200	2.10999	-4.27%	-7.81%
	16:30	1.68954	1.98355	1.86334	1.81817	1.77700	1.89830	2.04148	2.06900	2.03958	-17.40%	-12.36%
	17:30	1.80088	1.92644	1.75416	1.75797	1.79900	1.90372	1.98330	1.97300	1.94807	-6.97%	0.10%
	18:30	1.03104	1.01861	1.14974	1.11990	1.09300	1.06816	1.04844	1.02800	1.00723	1.21%	-6.01%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**21.01143**	**18.61159**	**23.08159**	**22.61275**	**22.36200**	**22.46832**	**22.56909**	**22.37700**	**21.94033**	**11.42%**	**1.41%**
				Total (Optimal Dynamic Glazing)					**20.71450**			

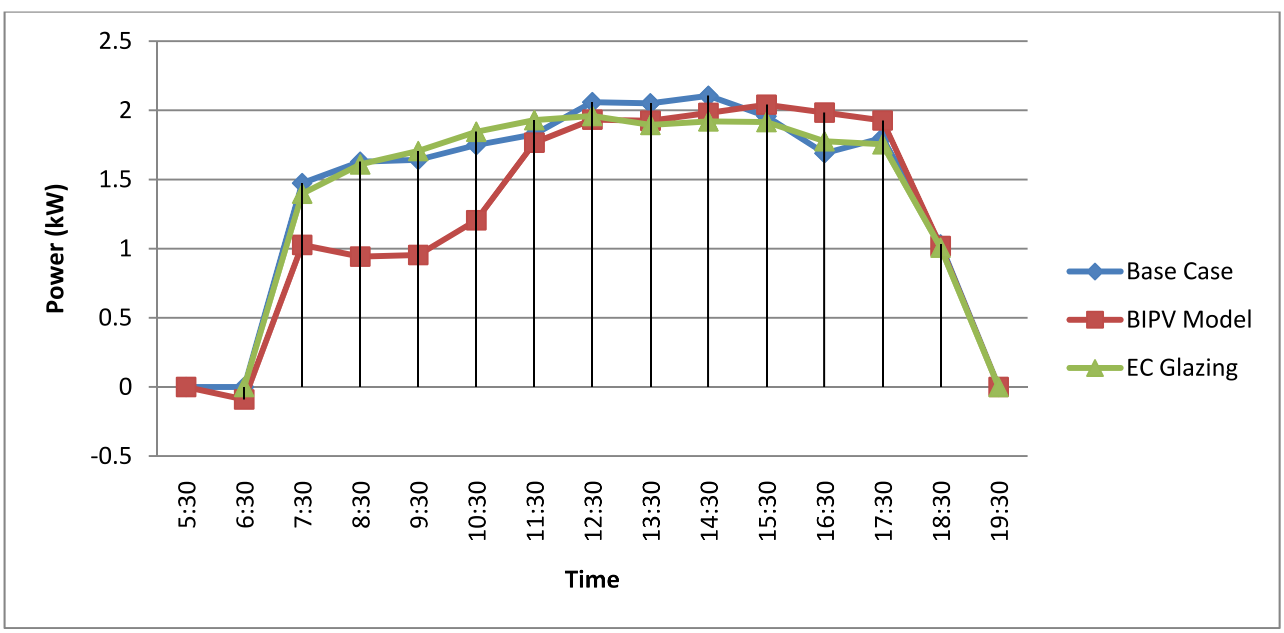


Figure A.10 Hourly Energy Consumption for all configurations for East façade in September 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.11 Hourly energy consumption of all scenarios of East façade in December 23

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase BIPV	Savings Over Basecase ECG (Dynamic)
December 23, 2010	5:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	6:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	7:30	0.3038	0.0684	0.3691	0.3513	0.3370	0.3230	0.3146	0.3070	0.3011	77.48%	0.91%
	8:30	0.7241	0.1373	1.0549	0.9984	0.9430	0.8895	0.8463	0.8030	0.9731	81.04%	-22.84%
	9:30	0.8296	0.1731	1.3308	1.2439	1.1600	1.0797	1.0156	0.9720	1.0744	79.14%	-30.14%
	10:30	0.9634	0.6489	1.3244	1.2409	1.1620	1.1226	1.2647	1.3640	1.3252	32.65%	-37.55%
	11:30	1.1185	1.0651	1.1856	1.1463	1.1760	1.2835	1.3751	1.3470	1.3184	4.77%	-17.87%
	12:30	1.3147	1.2006	1.1124	1.2031	1.2720	1.3416	1.3365	1.3110	1.2880	8.68%	2.03%
	13:30	1.3103	1.2010	1.1541	1.2340	1.2950	1.3516	1.3251	1.3000	1.2780	8.34%	2.47%
	14:30	1.2859	1.1857	1.1168	1.1996	1.2640	1.3227	1.2976	1.2740	1.2530	7.79%	2.56%
	15:30	1.2557	1.1722	1.0274	1.1247	1.2010	1.2754	1.2652	1.2440	1.2248	6.65%	2.47%
	16:30	1.2205	1.1650	1.0116	1.1070	1.1800	1.2417	1.2290	1.2110	1.1945	4.55%	-1.73%
	17:30	1.1887	1.1645	1.1948	1.2231	1.2280	1.2127	1.1970	1.1830	1.1692	2.04%	-3.31%
	18:30	0.4485	0.4460	0.5202	0.5026	0.4850	0.4692	0.4563	0.4450	0.4336	0.55%	-8.15%
	19:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	20:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	Total	**11.9638**	**9.6278**	**12.4021**	**12.5749**	**12.7030**	**12.9132**	**12.9233**	**12.7610**	**12.8333**	**19.53%**	**4.96%**
				Total (Optimal Dynamic Glazing)					**11.3700**			

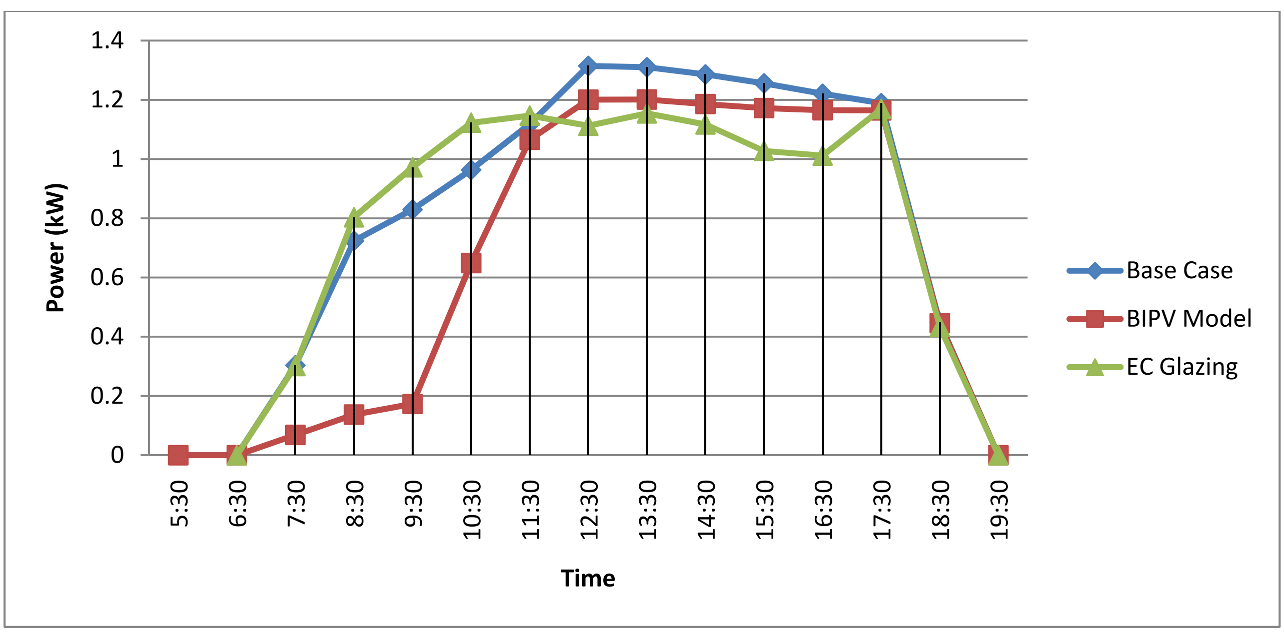


Figure A.11 Hourly Energy Consumption for all configurations for East façade in December 23 with glass of 0.27 shading coefficient and lighting sensor @ 2m

A.3 WEST FAÇADE SIMULATIONS

A.3.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

Table A.12 Hourly energy consumption of all scenarios of West façade in March 21

Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
		T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
0.00000	-0.02400	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
0.32017	0.23500	0.77400	0.66288	0.55581	0.45200	0.37208	0.31476	0.30000	26.60%	6.30%
0.73968	0.97200	1.06200	0.97900	0.93343	1.00700	1.10929	1.08680	1.01951	-31.41%	-36.14%
1.21711	1.09100	1.18100	1.18203	1.22528	1.26800	1.26724	1.20757	1.15280	10.36%	-4.18%
1.30792	1.17500	1.35200	1.38886	1.40712	1.41000	1.35160	1.29331	1.24016	10.16%	5.18%
1.38251	1.24600	1.44300	1.47700	1.49295	1.48100	1.42298	1.36589	1.31406	9.87%	4.95%
1.37803	1.23000	1.37600	1.43050	1.46062	1.47200	1.41633	1.36055	1.31018	10.74%	4.92%
1.17368	0.99800	1.43100	1.35875	1.31741	1.34200	1.43902	1.43556	1.37965	14.97%	-17.55%
1.26414	0.52800	1.78300	1.64458	1.51322	1.38900	1.33724	1.54155	1.50515	58.23%	-19.07%
1.21115	0.37100	2.04100	1.86897	1.70345	1.54400	1.41551	1.29456	1.24564	69.37%	-2.85%
1.17939	0.36600	2.06500	1.88953	1.71876	1.55200	1.41527	1.28148	1.16001	68.97%	-31.59%
1.05141	0.51900	1.74700	1.60354	1.46359	1.32600	1.21280	1.11614	1.19616	50.64%	-39.20%
0.59675	0.42600	0.98000	0.89323	0.80918	0.72700	0.66044	0.59636	0.53896	28.61%	-35.60%
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
12.82194	**9.13300**	**17.23500**	**16.37887**	**15.60082**	**14.97000**	**14.41980**	**13.89453**	**13.36228**	**28.77%**	**-1.12%**
		Total (Optimal Dynamic Glazing)					**12.96603**			

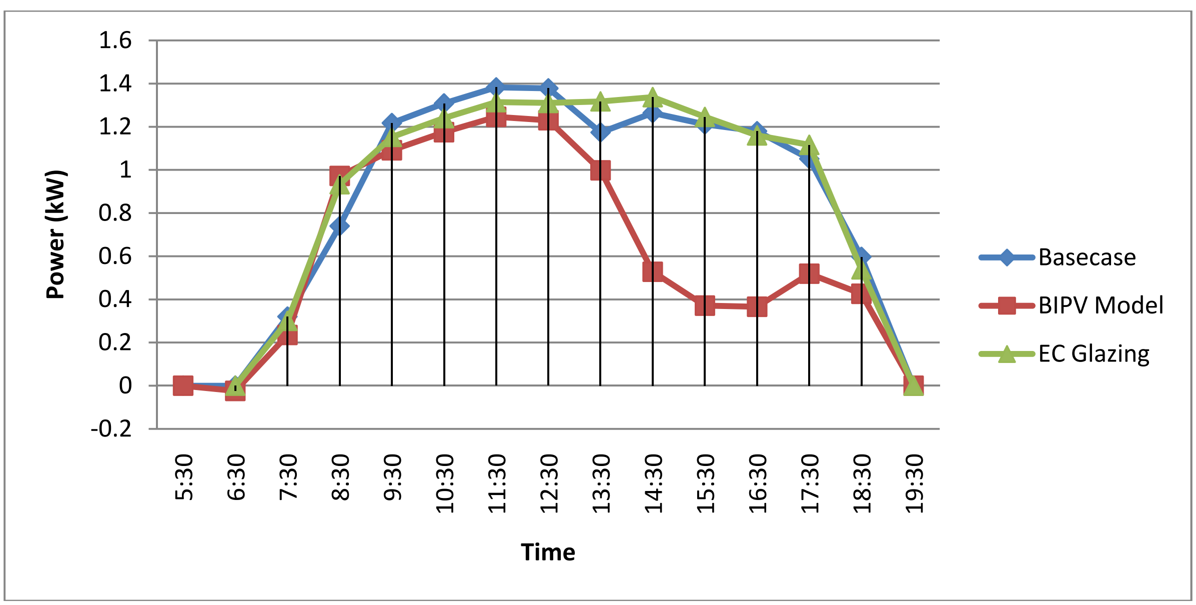


Figure A.12 Hourly Energy Consumption for all configurations for West façade in March 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.13 Hourly energy consumption of all scenarios of West façade in June 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
June 21, 2010	5:30	0.00000	-0.01400	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.05700	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.63060	1.53300	2.00900	1.92597	1.84663	1.77100	1.70978	1.65103	1.59839	5.99%	1.98%
	8:30	1.79158	2.03600	2.07900	2.01408	1.95197	2.00400	2.14935	2.18983	2.14866	-13.64%	-11.86%
	9:30	1.93232	2.07100	2.08600	2.02246	2.03908	2.14000	2.23729	2.20571	2.16503	-7.18%	-10.75%
	10:30	2.24728	2.13100	2.15300	2.19450	2.24806	2.30400	2.29806	2.25403	2.21474	5.17%	1.45%
	11:30	2.24878	2.13900	2.21700	2.27558	2.31230	2.33900	2.29641	2.25344	2.21533	4.88%	1.49%
	12:30	2.13361	2.06500	2.09000	2.08815	2.14595	2.22200	2.25873	2.21622	2.17744	3.22%	-2.05%
	13:30	1.91586	1.80700	2.23500	2.15634	2.08336	2.07200	2.20545	2.29776	2.25189	5.68%	-17.54%
	14:30	2.03435	1.38800	2.49200	2.37021	2.25592	2.14900	2.07853	2.30141	2.30966	31.77%	-13.53%
	15:30	1.98179	1.32400	2.75800	2.60250	2.45484	2.31400	2.20213	2.09851	2.06294	33.19%	-4.09%
	16:30	1.96134	1.34000	2.77700	2.61898	2.46729	2.32100	2.20259	2.08901	1.98569	31.68%	-18.34%
	17:30	1.88972	1.50900	2.54900	2.42520	2.30559	2.19000	2.09543	2.00417	2.02296	20.15%	-22.01%
	18:30	1.26980	1.11300	1.62700	1.54538	1.46741	1.39200	1.33196	1.27415	1.22271	12.35%	-15.56%
	19:30	0.00000	-0.01400	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**23.03703**	**20.37100**	**27.07200**	**26.23935**	**25.57840**	**25.21800**	**25.06571**	**24.83527**	**24.37544**	**11.57%**	**-1.82%**
				Total (Optimal Dynamic Glazing)					**23.45534**			

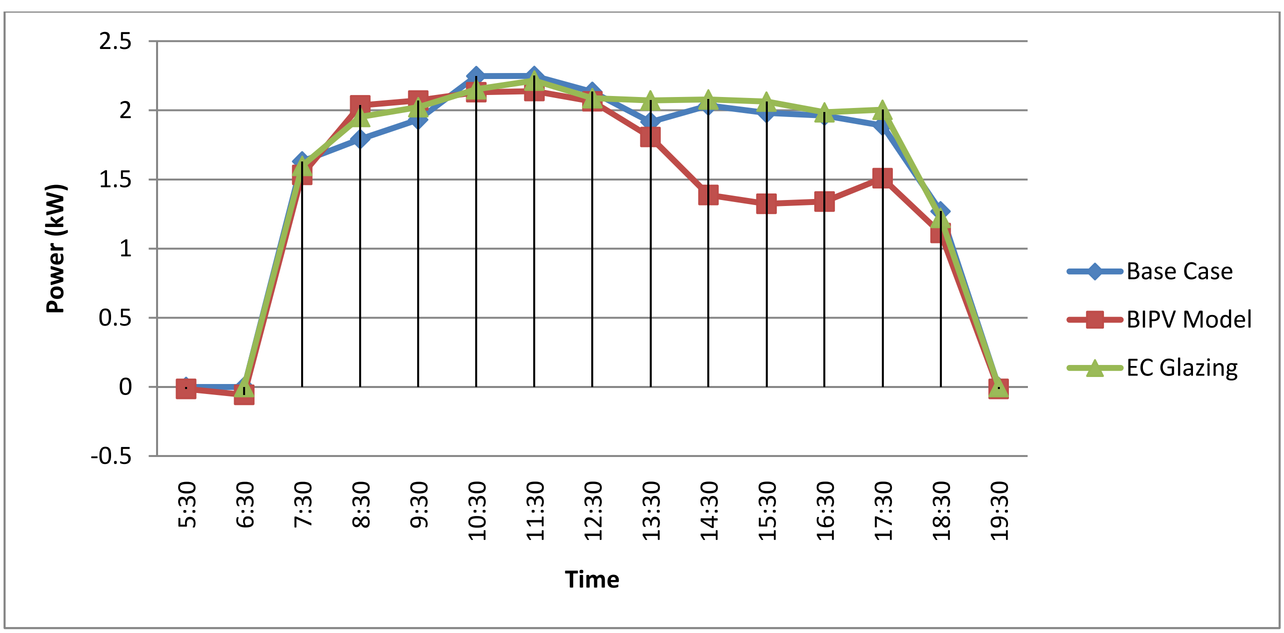


Figure A.13 Hourly Energy Consumption for all configurations for West façade in June 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.14 Hourly energy consumption of all scenarios of West façade in September 21

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase	
											BIPV	ECG (Dynamic)
September 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.03300	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.35097	1.26500	1.60500	1.54836	1.49393	1.44200	1.40087	1.36195	1.32676	6.36%	1.79%
	8:30	1.49603	1.75100	1.70000	1.65209	1.60664	1.65600	1.82088	1.88696	1.85743	-17.04%	-10.69%
	9:30	1.69291	1.79800	1.73600	1.69209	1.73003	1.84100	1.94480	1.92428	1.89392	-6.21%	-8.75%
	10:30	1.95457	1.83000	1.77800	1.83809	1.90682	1.97700	1.98369	1.95055	1.92034	6.37%	1.75%
	11:30	2.00646	1.88800	1.91600	1.98362	2.03577	2.06700	2.03342	2.00069	1.97106	5.90%	1.76%
	12:30	1.98537	1.89600	1.87200	1.89503	1.96566	2.04300	2.07698	2.04369	2.01436	4.50%	-1.46%
	13:30	1.75391	1.51100	2.04000	1.96741	1.90098	1.88100	1.98688	2.12967	2.09338	13.85%	-19.36%
	14:30	1.90202	1.18600	2.39200	2.27548	2.16551	2.06200	1.98046	2.14812	2.23067	37.65%	-17.28%
	15:30	1.85400	1.18100	2.60500	2.46196	2.32483	2.19300	2.08705	1.98758	1.96286	36.30%	-5.87%
	16:30	1.75789	1.24000	2.43200	2.30254	2.17734	2.05500	1.95636	1.86075	1.79167	29.46%	-16.90%
	17:30	1.61249	1.41200	2.04600	1.96091	1.87853	1.79800	1.74471	1.77978	1.95649	12.43%	-16.50%
	18:30	1.04679	1.00400	1.27100	1.22046	1.17170	1.12500	1.08830	1.05621	1.02482	4.09%	-11.93%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**20.41341**	**17.92900**	**23.39300**	**22.79804**	**22.35774**	**22.14000**	**22.10440**	**22.13023**	**22.04376**	**12.17%**	**-0.80%**
				Total (Optimal Dynamic Glazing)					**20.57701**			

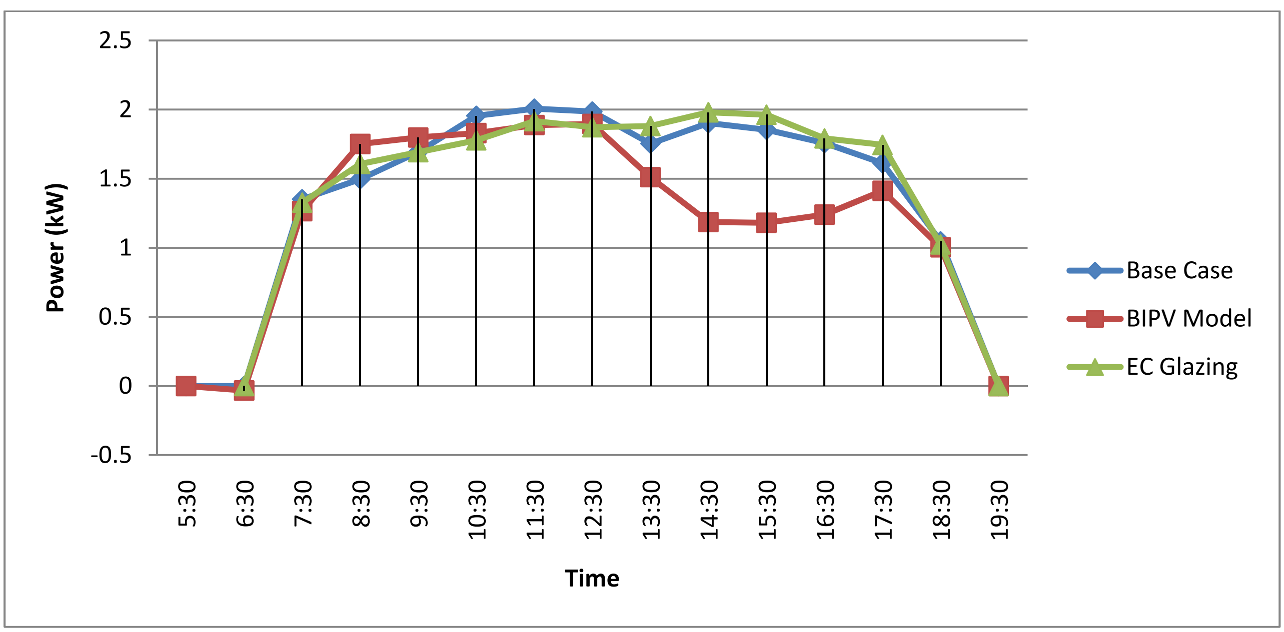


Figure A.14 Hourly Energy Consumption for all configurations for West façade in September 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.15 Hourly energy consumption of all scenarios of West façade in December 23

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
December 23, 2010	5:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	6:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	7:30	0.3000	0.2670	0.3210	0.3052	0.3000	0.3000	0.3000	0.3000	0.3000	11.00%	0.00%
	8:30	0.9427	0.8670	0.6660	0.6910	0.7924	0.8920	0.9569	0.8959	0.9265	8.03%	5.38%
	9:30	1.0675	0.9780	0.8110	0.8907	0.9765	1.0590	1.0780	1.0080	1.0485	8.38%	0.79%
	10:30	1.1436	1.0500	0.9970	1.0803	1.1420	1.1720	1.1539	1.0160	1.1229	8.18%	1.80%
	11:30	1.2463	1.1450	1.0530	1.1435	1.2143	1.2740	1.2573	1.0064	1.2245	8.13%	1.75%
	12:30	1.2914	1.1600	1.0180	1.0551	1.1605	1.2660	1.3109	1.0161	1.2759	10.17%	1.20%
	13:30	0.9856	0.8910	1.1580	1.1111	1.0809	1.1280	1.2963	0.9979	1.3348	9.59%	-35.44%
	14:30	1.0762	0.4670	1.3800	1.2944	1.2139	1.1390	1.1321	0.9800	1.3745	56.60%	-27.72%
	15:30	1.0020	0.3080	1.5030	1.3933	1.2893	1.1900	1.1116	0.8767	1.1502	69.26%	-14.79%
	16:30	0.9343	0.4240	1.3850	1.2902	1.1987	1.1100	1.0393	1.0292	1.1728	54.62%	-18.81%
	17:30	1.0339	0.8900	1.1120	1.0995	1.0909	1.0970	1.1307	1.0867	1.2002	13.91%	-5.52%
	18:30	0.4547	0.4490	0.5690	0.5410	0.5137	0.4880	0.4681	0.3787	0.4356	1.25%	-12.99%
	19:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	20:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	Total	**11.4779**	**8.8960**	**11.9730**	**11.8953**	**11.9731**	**12.1150**	**12.2353**	**10.5915**	**12.5663**	**22.49%**	**11.61%**
				Total (Optimal Dynamic Glazing)					**10.1456**			

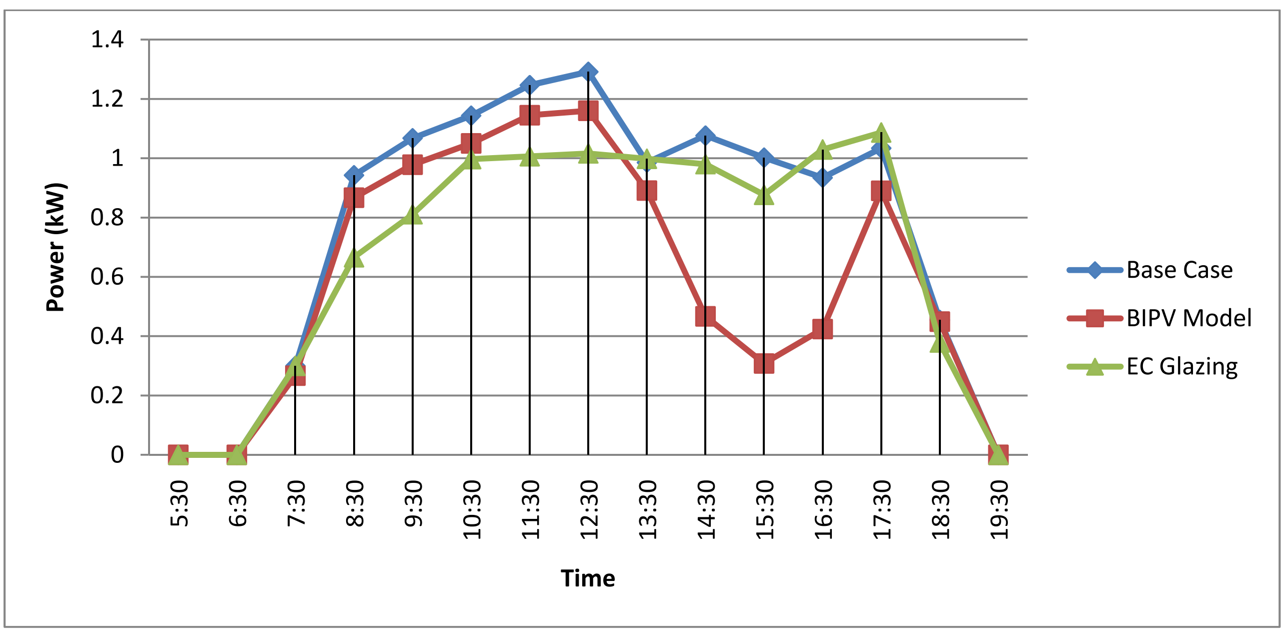


Figure A.15 Hourly Energy Consumption for all configurations for West façade in December 23 with glass of 0.27 shading coefficient and lighting sensor @ 2m

A.4 NORTH FAÇADE SIMULATIONS

A.4.1 Lighting sensor @2m and Glass Shading Coefficient 0.27

Table A.16 Hourly energy consumption of all scenarios of North façade in March 21

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
March 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.02450	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	0.30000	0.22846	0.37102	0.33633	0.31034	0.30000	0.30000	0.30000	0.30000	23.85%	0.00%
	8:30	0.62496	0.90069	0.78291	0.74320	0.72759	0.83721	0.96758	0.97318	0.94242	-44.12%	-33.96%
	9:30	1.12694	1.04003	0.91447	0.93896	1.02302	1.11004	1.15536	1.12518	1.09798	7.71%	1.50%
	10:30	1.24583	1.12758	1.09730	1.17131	1.23086	1.27707	1.24772	1.21688	1.18933	9.49%	4.54%
	11:30	1.32368	1.20079	1.25862	1.31662	1.36043	1.35596	1.32503	1.29364	1.26572	9.28%	4.38%
	12:30	1.31999	1.19738	1.31564	1.36314	1.38874	1.35184	1.32084	1.28953	1.26172	9.29%	4.41%
	13:30	1.33030	1.20924	1.31461	1.36410	1.39389	1.36024	1.32954	1.29870	1.27118	9.10%	4.44%
	14:30	1.38598	1.26944	1.28977	1.35595	1.40303	1.41310	1.38284	1.35267	1.32548	8.41%	4.37%
	15:30	1.38273	1.27862	1.15583	1.24478	1.31668	1.38588	1.37976	1.35140	1.32585	7.53%	4.11%
	16:30	1.34721	1.26130	1.07111	1.09262	1.19267	1.28899	1.34412	1.31827	1.29488	6.38%	4.32%
	17:30	1.27105	1.21595	0.99248	1.05570	1.14766	1.23703	1.26717	1.24483	1.22437	4.33%	9.71%
	18:30	0.50009	0.48126	0.57588	0.55473	0.53458	0.51471	0.49724	0.47900	0.46221	3.77%	-6.90%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**13.15876**	**12.38624**	**12.13964**	**12.53744**	**13.02949**	**13.43207**	**13.51720**	**13.24328**	**12.96114**	**5.87%**	**10.31%**
				Total (Optimal Dynamic Glazing)					**11.80228**			

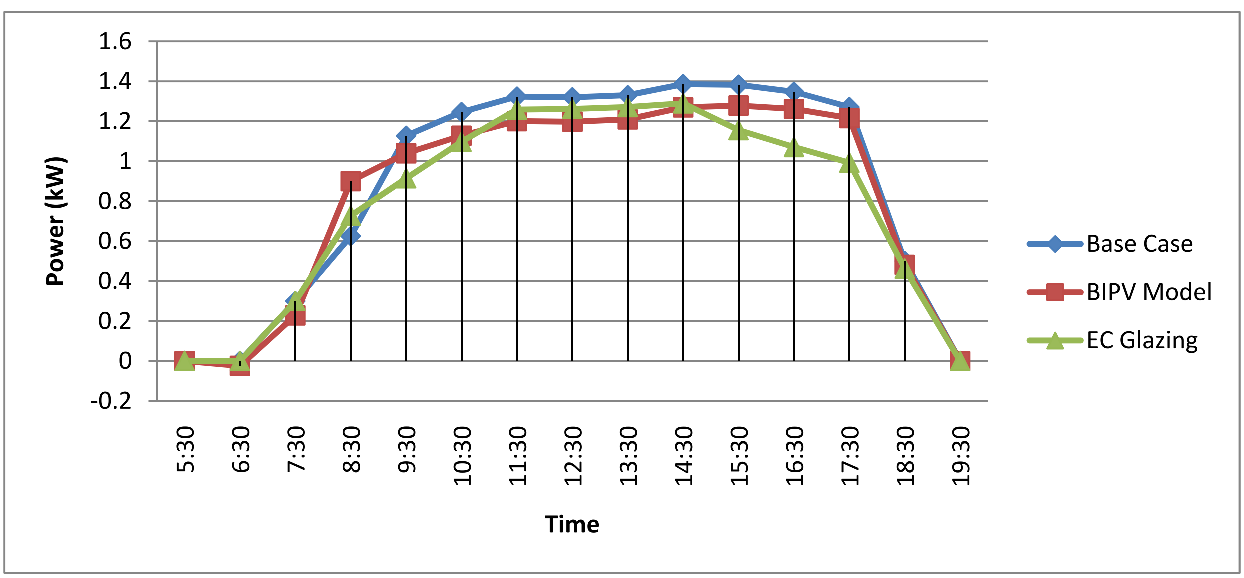


Figure A.16 Hourly Energy Consumption for all configurations for North façade in March 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.17 Hourly energy consumption of all scenarios of North façade in June 21

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase BIPV	Savings Over Basecase ECG (Dynamic)
June 21, 2010	5:30	0.00000	-0.02264	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.09776	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.62513	1.44046	1.82962	1.77967	1.73342	1.69030	1.65849	1.62642	1.59702	11.36%	1.73%
	8:30	1.78747	1.84548	1.95905	1.91529	1.87476	1.83686	1.94751	2.17089	2.14586	-3.25%	-2.76%
	9:30	1.79057	1.97219	1.95346	1.91160	1.87257	1.90207	2.08723	2.17759	2.15225	-10.14%	-6.23%
	10:30	2.04465	2.09944	1.98521	1.97314	2.02522	2.13776	2.23394	2.21983	2.19545	-2.68%	-7.38%
	11:30	2.22499	2.11806	1.99807	2.09633	2.17154	2.24481	2.24431	2.21955	2.19558	4.81%	1.32%
	12:30	2.19081	2.07260	1.95026	2.01243	2.09846	2.18070	2.20502	2.17891	2.15362	5.40%	1.70%
	13:30	2.20790	2.08963	1.96334	1.93741	2.04215	2.14383	2.22081	2.19422	2.16854	5.36%	1.78%
	14:30	1.92939	2.07933	1.94797	1.90921	1.96305	2.08381	2.20509	2.18329	2.15803	-7.77%	-11.85%
	15:30	1.87500	2.09845	1.99913	1.96157	1.93276	2.04348	2.20577	2.24147	2.21695	-11.92%	-18.24%
	16:30	1.87744	2.00991	1.97882	1.94357	1.91136	1.89665	2.08055	2.23231	2.20929	-7.06%	-1.02%
	17:30	1.85507	1.99509	1.93696	1.90560	1.87696	1.85094	2.00143	2.20824	2.18774	-7.55%	-1.18%
	18:30	1.22485	1.15490	1.29916	1.27360	1.25042	1.22950	1.21804	1.20552	1.18872	5.71%	-2.09%
	19:30	0.00000	-0.01049	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**22.63327**	**22.84465**	**22.80105**	**22.61942**	**22.75267**	**23.24071**	**24.30819**	**24.85824**	**24.56905**	**-0.93%**	**2.34%**
				Total (Optimal Dynamic Glazing)					**22.10404**			

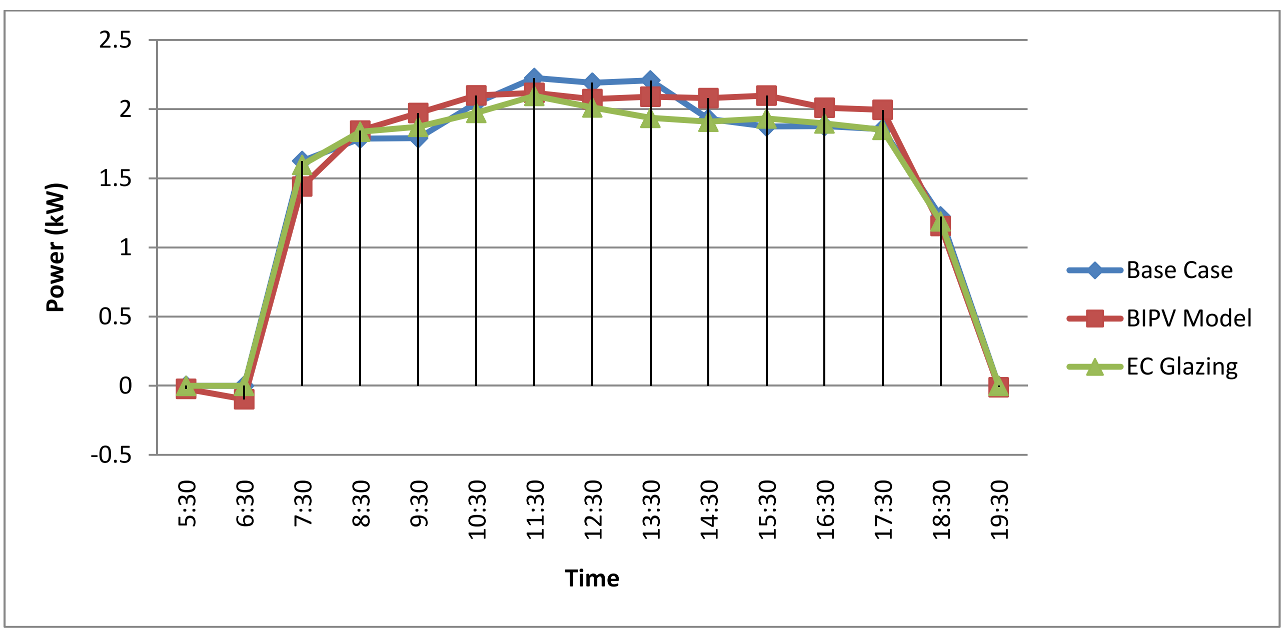


Figure A.17 Hourly Energy Consumption for all configurations for North façade in June 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.18 Hourly energy consumption of all scenarios of North façade in September 23

Date	Time	Basecase	BIPV	ECG 1 T_{vis}=62%	ECG2 T_{vis}=50%	ECG3 T_{vis}=40%	ECG 4 T_{vis}=30%	ECG 5 T_{vis}=20%	ECG 6 T_{vis}=10%	ECG 7 T_{vis}=3.5%	Savings Over Basecase BIPV	Savings Over Basecase ECG (Dynamic)
September 21, 2010	5:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	6:30	0.00000	-0.03347	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	7:30	1.31704	1.23748	1.41823	1.39245	1.36871	1.34781	1.33188	1.31319	1.29538	6.04%	1.64%
	8:30	1.47198	1.71866	1.57050	1.54436	1.51996	1.54607	1.74351	1.85272	1.83510	-16.76%	-5.03%
	9:30	1.58135	1.78073	1.62065	1.59180	1.61187	1.74389	1.88706	1.89655	1.87721	-12.61%	-10.28%
	10:30	1.93809	1.81823	1.66811	1.72989	1.82186	1.91398	1.94755	1.92663	1.90669	6.18%	1.62%
	11:30	1.99080	1.87608	1.86173	1.93789	1.99677	2.01753	1.99858	1.97722	1.95719	5.76%	1.69%
	12:30	2.01972	1.90848	1.90581	1.97857	2.03508	2.04768	2.02831	2.00679	1.98699	5.51%	1.62%
	13:30	2.01610	1.90196	1.76602	1.85823	1.93905	2.01823	2.02453	2.00263	1.98266	5.66%	1.66%
	14:30	2.07357	1.96057	1.78522	1.79134	1.90010	2.00819	2.08009	2.05836	2.03847	5.45%	1.69%
	15:30	1.80905	2.02635	1.83784	1.81037	1.83734	1.97444	2.11380	2.11680	2.09747	-12.01%	-15.94%
	16:30	1.66643	1.97006	1.75621	1.73058	1.70725	1.80793	1.98519	2.04555	2.02753	-18.22%	-8.49%
	17:30	1.76721	1.92099	1.66161	1.67860	1.73250	1.85217	1.95237	1.95841	1.94376	-8.70%	1.96%
	18:30	1.02041	1.01591	1.06798	1.05457	1.04287	1.03366	1.02656	1.01624	1.00553	0.44%	-2.20%
	19:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	20:30	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00%	0.00%
	Total	**20.67175**	**21.10203**	**19.91991**	**20.09865**	**20.51336**	**21.31158**	**22.11943**	**22.17109**	**21.95398**	**-2.08%**	**5.29%**
				Total (Optimal Dynamic Glazing)					**19.57879**			

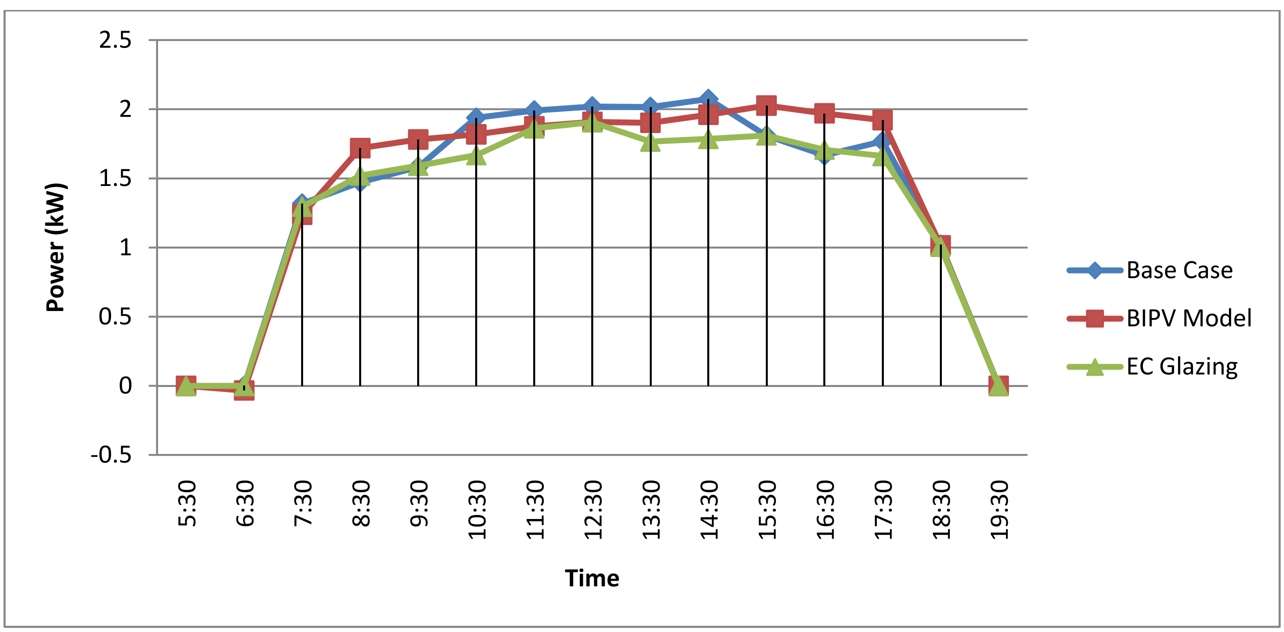


Figure A.18 Hourly Energy Consumption for all configurations for North façade in September 21 with glass of 0.27 shading coefficient and lighting sensor @ 2m

Table A.19 Hourly energy consumption of all scenarios of North façade in December 23

Date	Time	Basecase	BIPV	ECG 1	ECG2	ECG3	ECG 4	ECG 5	ECG 6	ECG 7	Savings Over Basecase	
				T_{vis}=62%	T_{vis}=50%	T_{vis}=40%	T_{vis}=30%	T_{vis}=20%	T_{vis}=10%	T_{vis}=3.5%	BIPV	ECG (Dynamic)
December 23, 2010	5:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	6:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	7:30	0.3000	0.2672	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000	10.95%	0.00%
	8:30	0.9286	0.8609	0.6035	0.6406	0.7516	0.8621	0.9351	0.9262	0.9157	7.29%	7.15%
	9:30	1.0562	0.9727	0.7614	0.8483	0.9441	1.0349	1.0616	1.0511	1.0399	7.91%	2.02%
	10:30	1.1332	1.0453	0.9670	1.0542	1.1220	1.1497	1.1388	1.1271	1.1151	7.76%	1.60%
	11:30	1.2365	1.1407	1.0668	1.1545	1.2229	1.2554	1.2430	1.2299	1.2171	7.75%	1.57%
	12:30	1.2835	1.1840	1.0959	1.1873	1.2580	1.3027	1.2890	1.2748	1.2610	7.76%	1.75%
	13:30	1.2842	1.1840	1.0930	1.1825	1.2528	1.2999	1.2851	1.2702	1.2555	7.80%	2.24%
	14:30	1.2614	1.1692	1.0318	1.1291	1.2060	1.2746	1.2604	1.2460	1.2315	7.30%	2.37%
	15:30	1.2343	1.1581	0.9507	1.0605	1.1481	1.2323	1.2322	1.2193	1.2060	6.17%	2.29%
	16:30	1.2022	1.1535	0.9607	1.0622	1.1443	1.2067	1.2001	1.1896	1.1786	4.06%	-0.38%
	17:30	1.1702	1.1522	1.1424	1.1742	1.1843	1.1761	1.1687	1.1611	1.1527	1.53%	-1.21%
	18:30	0.4318	0.4351	0.4551	0.4485	0.4420	0.4358	0.4305	0.4252	0.4189	-0.78%	-2.38%
	19:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	20:30	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00%	0.00%
	Total	**12.5221**	**11.7228**	**10.4282**	**11.2417**	**11.9760**	**12.5301**	**12.5445**	**12.4206**	**12.2919**	**6.38%**	**17.01%**
				Total (Optimal Dynamic Glazing)					**10.3920**			

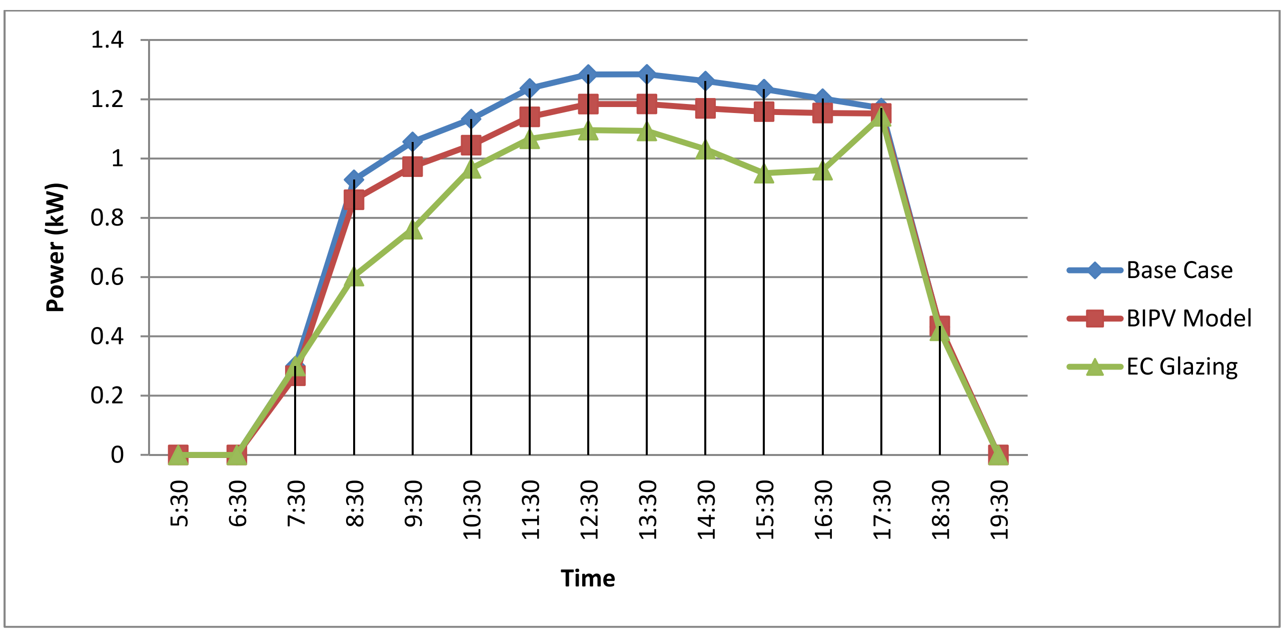


Figure A.19 Hourly Energy Consumption for all configurations for North façade in December 23 with glass of 0.27 shading coefficient and lighting sensor @ 2m

APPENDIX B: PRODUCT SUPPLIERS

The following is a list of EC glazing and PV products and suppliers in the UAE and worldwide:

PV

Enviromena - http://www.enviromena.com/Eng/Index.aspx

Enviromena Power Systems is the leading developer of solar projects in the Middle East and North Africa (MENA). The experienced team finances, designs, installs and operates solar power plants.

Guandong Golden Glass Technologies Limited - http://jingang.glassinchina.com/

A leading architectural specialty glass manufacturer since 1992, it includes subsidiaries such as Shenzhen Golden Glass BIPV that began research in this field since 2000. They represent PV manufacturers such as Suntech, and curtain wall manufactures like Jangho in this region.

Gulf International Trading Group – http://www.gulf-group.ae/

Headquartered in the United Arab Emirates, Gulf International Trading Group has strategically partnered with leading international experts like Romag to provide innovative construction products to the region.

PTL Solar http://www.ptlsolar.com/index.html

TL Solar™ has a reputation for providing the affordable and reliable energy efficient solutions. With the backing of largest International Renewable Energy companies, it offers world class energy efficient / renewable energy solutions for solar street light, solar billboard light, solar flood light and solar solutions for road, airport, marine, industrial (oil and gas, telecommunication), commercial, government, military, rural development, residential and customized applications.

Ruiha Construction Co. Ltd - http://rhc.com/

Established in 1993, Shenzhen Ruihua Construction is a high-tech curtain wall company providing services in the fields of research, design, production, installation and maintenance of curtain walls, building integrated photovoltaic (BIPV), metal doors & windows, as well as the advanced building-shell maintenance system for both Chinese and international customers.

Sole SA - http://www.soleuae.com/

Sole S.A is one of two companies in the world to be accepted by OBO (Overseas building organization) for the supply of solar water heating systems. In 1999, Sole S.A became the first and only company in the world to produce a commercial solar air-conditioning plant using the famous "Climasol" super selective Tinox flat plate solar collectors.

Technovalutions - http://www.technovalutions.com/

Innovative renewable energy solutions in the UAE and Middle East. Sales and installation of solar energy systems, solar cooling or water heating, solar street lights, wind power, industrial solar solutions, hydrogen fuel cells and much more from leading manufacturers.

EC Glazing

There are no local suppliers of this product; however, this is a list of some international companies:

SAGE Electrochromics Inc. - http://www.sage-ec.com

This company was found in 1989 and is one of the world's leading manufacturers in high-performance energy-saving electrochromic technology for buildings windows and skylights. SageGlass windows are installed in hundreds of buildings worldwide, including commercial, institutional and high-end residential applications. The use of SageGlass products can also earn LEED credits from the U.S. Green Building Council for building projects. Windows using SageGlass can transition from a clear state to a darkly tinted state at the click of a button, or programmed to respond automatically to changing sunlight and heat conditions. The technology not only provides dramatic energy savings, it also enhances the occupants' comfort and productivity by providing natural daylight and preserving their connection to the outdoors – the very reason windows are put in a building.

Smart Glass International - http://www.smartglassinternational.com

Smart Glass International (SGI) is the dedicated manufacturer of Electronically Switchable Glass. Also known as privacy glass, switchable glass, intelligent glass and electric glass these technologically advanced glass products are fast breaking from being niche to becoming mainstream for use particularly in the commercial, retail, security, transport, healthcare and hospitality sectors. The main products are LC Smart Glass offering Privacy on demand and SPD Smart Glass offering Solar-Control.

Polytronix - http://www.polytronix.com/

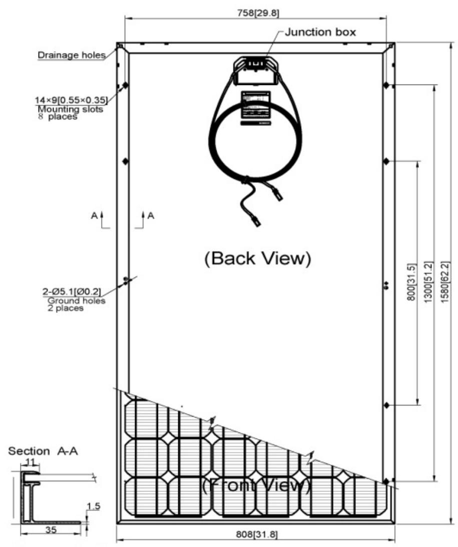
Founded in 1980, Polytronix has been an innovator in the design, manufacturing and marketing of liquid crystal displays (LCDs) and assemblies. The company has the ability to develop and produce such innovative products as twisted nematic displays, dichroic displays and polymer dispersed liquid crystal (PDLC).

APPENDIX C: DATA SHEETS

The following are the data sheets for products used in the simulations.

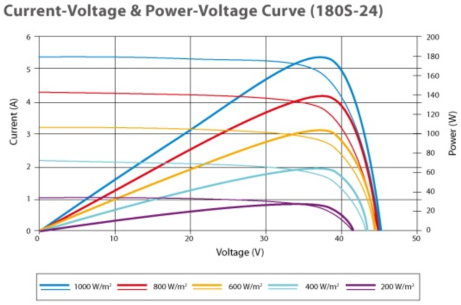
A.C.1. BIPV panels

STP185S - 24/Ad
STP180S - 24/Ad



Note: mm [inch]

Current-Voltage & Power-Voltage Curve (180S-24)



Temperature Characteristics

Nominal Operating Cell Temperature (**NOCT**)	45±2°C
Temperature Coefficient of Pmax	-0.48 %/°C
Temperature Coefficient of Voc	-0.34 %/°C
Temperature Coefficient of Isc	0.037 %/°C

Dealer information box

Specifications are subject to change without further notification

Electrical Characteristics

STC	STP185S-24/Ad	STP180S-24/Ad
Optimum Operating Voltage (Vmp)	36.4 V	36.0 V
Optimum Operating Current (Imp)	5.09 A	5.00 A
Open - Circuit Voltage (Voc)	45.0 V	44.8 V
Short - Circuit Current (Isc)	5.43 A	5.29 A
Maximum Power at STC (Pmax)	185 W	180 W
Module Efficiency	14.5%	14.1%
Operating Temperature	-40 °C to +85 °C	-40°C to +85°C
Maximum System Voltage	1000 V DC	1000 V DC
Maximum Series Fuse Rating	15 A	15 A
Power Tolerance	0/+5 W	0/+5 W

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

NOCT	STP185S-24/Ad	STP180S-24/Ad
Maximum Power (W)	135 W	131 W
Maximum Power Voltage (V)	33.0 V	32.8 V
Maximum Power Current (A)	4.10 A	4.01 A
Open Circuit Voltage (Voc)	41.0 V	40.6 V
Short Circuit Current (Isc)	4.40 A	4.32 A
Efficiency Reduction (from 1000 W/m² to 200 W/m²)	<4.5%	<4.5%

NOCT: Irradiance 800 W/m², ambient temperature 20 °C, wind speed 1 m/s

Mechanical Characteristics

Solar Cell	Monocrystalline 125 × 125 mm (5 inches)
No. of Cells	72 (6 × 12)
Dimensions	1580 × 808 × 35mm (62.2 × 31.8 × 1.4 inches)
Weight	17.2 kgs (37.9 lbs.)
Front Glass	4.0 mm (0.16 inches) tempered glass
Frame	Anodized aluminium alloy
Junction Box	IP67 rated
Output Cables	H+S RADOX® SMART cable 4.0 mm² (0.006 inches²), symmetrical lengths (-) 1000 mm (39.4 inches) and (+) 1000 mm (39.4 inches), RADOX® SOLAR integrated twist locking connectors

Packing Configuration

Container	20' GP	40' GP
Pieces per pallet	26	26
Pallet per container	12	28
Pieces per container	312	728

www.suntech-power.com | E-mail: sales@suntech-power.com **EN-STD-Ads-NO1.01-Rev 2010**

Figure C.1 Specification of PV used in the simulations (Suntech, 2010)

A.C.2. EC glazing

SageGlass products consume little power. It takes less electricity to power and control 1,500 square feet of SageGlass glazing (approximately 100 windows) per day than it does to power a 60-Watt light bulb.

SAGE ELECTROCHROMICS, INC.

SageGlass® Classic™

SAGE Electrochromics, Inc. Performance Data

February 11, 2010

Calculated using Window 5.2a v5.2.17a

Center pane values

Make up: SageGlass® Classic Insulated Glass Unit

1/4" SageGlass® outboard lite

1/2" stainless steel air spacer – argon filled

1/4" clear glass inboard lite

	Clear State	Tinted State
Visible Light:	62%	3.5%
Solar Heat Gain Coefficient:	.48	.09
Shading Coefficient:	.55	.11
U Value:		
Winter	.29	.29
Summer	.28	.28

Figure C.2 Specification obtained for the EC glazing used in the study (SageGlass, 2010)

A.C.3. Roller Blinds

VRL-2008
GECA 28-2006–
Furniture and Fittings

FABRIC INFORMATION

Flame Retardant

TRANSPARENT - Metallised

SYSTEMS AVAILABLE

Roller Blinds

Pleated Blinds

Verosol®

816 FABRIC

SPECIFICATIONS

Integrated and thermal optical properties	Fabric density	816 Transparent	
	Fabric colour	000	
	Solar transmittance	29%	
	Solar reflectance outside	44%	
	Solar absorbtance	27%	
	Luminous transmittance	29%	
	Luminous reflectance outside	43%	
	Luminous absorbtance	28%	
	UV transmittance	27%	
	Openness factor (nominal)	23%	
	Ra[Colour rendering index]	98	
Glazing Type		Single 3mm Clear Glass	Solar Control Glazing
	Light transmittance	28%	22%
	G-value	44%	24%
	Shading coefficient	51%	28%
	U-value (W/m²K)	2.5	0.8
Fabric	Yarn composition: Trevira CS	Weight (g/m²): 70	Thickness (mm): 0.23
Aluminium adhesion		ISO 2409 classification 0	
Aluminium retention	Water vapour test	Percentage loss aluminium	
		After 30mins - 0% After 2hrs - 50%	
	Sulphur dioxide test	Percentage loss aluminium	
		After 3hrs - 0% After 5hrs - 40%	
Pleat retention	AWTA test - 100% heat applied to 30 pleats	Retention - 10 pleats	
Corrosion resistance		Metal layer EN ISO 3231	
Noise Reduction	ASTM test C423-84a	Coefficient of 0.35 sabin/sq.ft	
Colour fastness		Colour >5	
DIN 54004		Metal 8	
816 fabric is Anti static, PVC Free and Formaldehyde Free			
Flame retardancy	Ignitability index	0	Range [0–20]
AS 1530.3-1989	Spread of flame index	0	Range [0–10]
	Heat evolved index	0	Range [0–10]
	Smoke developed index	0-1	Range [0–10]

FEATURES

816 is a highly transparent, metal backed fabric, woven from 100% Trevira CS and is inherently fibre flame retardant. 816 provides excellent vision out, heat control in summer and insulation against heat loss in winter.

816 offers high performance, independent of colour.

816 is woven to 2200mm in width and designed specifically for pleated, roller, twin and motorised blind systems.

Note: All presented data calculated in WIS 3.0.1 (Advanced Windows Information System) with spectral data. Specifications and other data are based on information available at the time of preparation of this document and are subject to production tolerances and/or change without prior notice. Fire retardancy information is sourced from AWTA testing results. Please note that test results may vary slightly depending on fabric colour. [Solar Control Glazing EN 13363-2, ISO 15099, Measurements according to EN410], [3mm Single Glass(Pilkington OptI_3.plg) according to EN410, ISO 9050 and ISO 15099 without ventilation]

12/08

Figure C.3 Specifications of roller blinds fabric (Verosol, 2010)

APPENDIX D: HAP 4.5 COOLING ANALYSIS

The following tables are the results of the office module cooling and heating load analysis from HAP 4.5. This work was undertaken by mechanical engineer Hani Ibrahim from KEO International Consultants. The safety factors in the heat gain calculation are as per authority regulations.

Table D.1 Component Loads for office space in June

TABLE 1.1.A. COMPONENT LOADS FOR SPACE " OFFICE " IN ZONE " Zone 1 "						
	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jun 1500 COOLING OA DB / WB 45.4 °C / 29.0 °C OCCUPIED T-STAT 24.0 °C			HEATING DATA AT DES HTG HEATING OA DB / WB 11.1 °C / 6.4 °C OCCUPIED T-STAT 21.1 °C		
		Sensible	Latent		Sensible	Latent
SPACE LOADS	Details	(W)	(W)	Details	(W)	(W)
Window & Skylight Solar Loads	12 m²	240	-	12 m²	-	-
Wall Transmission	4 m²	21	-	4 m²	13	-
Roof Transmission	0 m²	0	-	0 m²	0	-
Window Transmission	12 m²	474	-	12 m²	247	-
Skylight Transmission	0 m²	0	-	0 m²	0	-
Door Loads	0 m²	0	-	0 m²	0	-
Floor Transmission	0 m²	0	-	0 m²	0	-
Partitions	0 m²	0	-	0 m²	0	-
Ceiling	0 m²	0	-	0 m²	0	-
Overhead Lighting	360 W	360	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	300 W	300	-	0	0	-
People	2	180	110	0	0	0
Infiltration	-	172	143	-	0	0
Miscellaneous	-	0	0	-	0	0
Safety Factor	10% / 5%	175	13	0%	0	0
>> Total Zone Loads	-	1921	266	-	260	0

Table D.2 Envelope Loads for office space in June

TABLE 1.1.B. ENVELOPE LOADS FOR SPACE " OFFICE " IN ZONE " Zone 1 "						
				COOLING	COOLING	HEATING
	Area	U-Value	Shade	TRANS	SOLAR	TRANS
	(m²)	(W/(m²-°K))	Coeff.	(W)	(W)	(W)
S EXPOSURE						
WALL	4	0.328	-	21	-	13
WINDOW 1	12	2.060	0.270	474	240	247

Table D.3 Design inputs for June

ZONE: Zone 1 DESIGN MONTH: JUNE									
Hour	OA TEMP (°C)	ZONE TEMP (°C)	RH (%)	ZONE AIRFLOW (L/s)	ZONE SENSIBLE LOAD (W)	ZONE COND (W)	TERMINAL COOLING COIL (W)	TERMINAL HEATING COIL (W)	ZONE HEATING UNIT (W)
0000	35.0	23.9	67	201.1	1513.3	1541.9	0.0	0.0	0.0
0100	34.3	24.0	68	201.1	1484.7	1495.1	0.0	0.0	0.0
0200	33.7	23.9	68	201.1	1456.4	1485.7	0.0	0.0	0.0
0300	33.2	23.8	68	201.1	1431.8	1476.5	0.0	0.0	0.0
0400	32.8	24.3	71	201.1	1411.1	1326.7	0.0	0.0	0.0
0500	32.7	24.3	71	201.1	1397.7	1327.1	0.0	0.0	0.0
0600	32.9	23.8	68	201.1	1415.8	1476.8	0.0	0.0	0.0
0700	33.6	23.9	68	201.1	1454.0	1485.3	0.0	0.0	0.0
0800	34.7	24.1	68	201.1	1508.3	1465.8	0.0	0.0	0.0
0900	36.4	24.1	67	201.1	1577.5	1563.4	0.0	0.0	0.0
1000	38.3	24.0	65	201.1	1654.0	1663.6	0.0	0.0	0.0
1100	40.5	24.0	64	201.1	1736.3	1729.3	0.0	0.0	0.0
1200	42.5	23.9	61	201.1	1812.6	1857.6	0.0	0.0	0.0
1300	44.0	23.9	61	201.1	1869.6	1891.3	0.0	0.0	0.0
1400	45.1	24.0	61	201.1	1907.3	1904.8	0.0	0.0	0.0
1500	45.4	24.0	61	201.1	1920.8	1910.4	0.0	0.0	0.0
1600	45.1	24.1	61	201.1	1905.7	1883.0	0.0	0.0	0.0
1700	44.2	23.9	61	201.1	1867.4	1892.0	0.0	0.0	0.0
1800	42.8	24.0	63	201.1	1802.5	1789.0	0.0	0.0	0.0
1900	41.1	24.0	63	201.1	1737.1	1739.0	0.0	0.0	0.0
2000	39.4	24.0	65	201.1	1680.8	1670.8	0.0	0.0	0.0
2100	38.0	23.9	65	201.1	1631.2	1664.1	0.0	0.0	0.0
2200	36.8	24.1	67	201.1	1585.0	1562.9	0.0	0.0	0.0
2300	35.7	24.0	67	201.1	1545.6	1551.4	0.0	0.0	0.0

Table D.4 Component Loads for office space in June

TABLE 1.1.A. COMPONENT LOADS FOR SPACE " OFFICE " IN ZONE " Zone 1 "						
	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Dec 1400 COOLING OA DB / WB 30.6 °C / 21.1 °C OCCUPIED T-STAT 24.0 °C			HEATING DATA AT DES HTG HEATING OA DB / WB 11.1 °C / 6.4 °C OCCUPIED T-STAT 21.1 °C		
		Sensible	Latent		Sensible	Latent
SPACE LOADS	Details	(W)	(W)	Details	(W)	(W)
Window & Skylight Solar Loads	12 m²	1217	-	12 m²	-	-
Wall Transmission	4 m²	10	-	4 m²	13	-
Roof Transmission	0 m²	0	-	0 m²	0	-
Window Transmission	12 m²	106	-	12 m²	247	-
Skylight Transmission	0 m²	0	-	0 m²	0	-
Door Loads	0 m²	0	-	0 m²	0	-
Floor Transmission	0 m²	0	-	0 m²	0	-
Partitions	0 m²	0	-	0 m²	0	-
Ceiling	0 m²	0	-	0 m²	0	-
Overhead Lighting	360 W	360	-	0	0	-
Task Lighting	0 W	0	-	0	0	-
Electric Equipment	300 W	300	-	0	0	-
People	2	180	110	0	0	0
Infiltration	-	53	53	-	0	0
Miscellaneous		0	0	-	0	0
Safety Factor	10% / 5%	223	8	0%	0	0
>> Total Zone Loads	-	2449	171	-	260	0

Table D.5 Envelope Loads for office space in June

TABLE 1.1.B. ENVELOPE LOADS FOR SPACE " OFFICE " IN ZONE " Zone 1 "						
				COOLING	COOLING	HEATING
	Area	U-Value	Shade	TRANS	SOLAR	TRANS
	(m²)	(W/(m²-°K))	Coeff.	(W)	(W)	(W)
S EXPOSURE						
WALL	4	0.328	-	10	-	13
WINDOW 1	12	2.060	0.270	106	1217	247

Table D.6 Design inputs for December

ZONE: Zone 1 DESIGN MONTH: DECEMBER									
Hour	OA TEMP (°C)	ZONE TEMP (°C)	RH (%)	ZONE AIRFLOW (L/s)	ZONE SENSIBLE LOAD (W)	ZONE COND (W)	TERMINAL COOLING COIL (W)	TERMINAL HEATING COIL (W)	ZONE HEATING UNIT (W)
0000	20.5	23.9	64	181.7	1452.4	1499.6	0.0	0.0	0.0
0100	19.9	24.0	66	181.7	1392.7	1393.8	0.0	0.0	0.0
0200	19.2	24.1	67	181.7	1335.3	1307.6	0.0	0.0	0.0
0300	18.7	23.9	67	181.7	1283.4	1327.8	0.0	0.0	0.0
0400	18.4	24.2	70	181.7	1237.2	1176.9	0.0	0.0	0.0
0500	18.2	24.1	70	181.7	1199.9	1169.7	0.0	0.0	0.0
0600	18.5	24.1	70	181.7	1175.1	1163.7	0.0	0.0	0.0
0700	19.1	24.3	70	181.7	1238.1	1180.8	0.0	0.0	0.0
0800	20.3	24.0	64	181.7	1483.4	1499.2	0.0	0.0	0.0
0900	21.9	24.2	61	181.7	1698.9	1664.6	0.0	0.0	0.0
1000	23.8	23.9	56	181.7	1906.1	1947.8	0.0	0.0	0.0
1100	26.0	24.1	53	181.7	2102.2	2101.0	0.0	0.0	0.0
1200	28.1	24.1	51	181.7	2269.1	2251.7	0.0	0.0	0.0
1300	29.6	24.1	48	181.7	2387.6	2387.3	0.0	0.0	0.0
1400	30.6	24.2	48	181.7	2449.1	2401.6	0.0	0.0	0.0
1500	31.0	24.2	48	181.7	2438.8	2416.3	0.0	0.0	0.0
1600	30.6	24.0	49	181.7	2328.0	2364.9	0.0	0.0	0.0
1700	29.7	24.0	53	181.7	2064.4	2087.7	0.0	0.0	0.0
1800	28.3	24.0	55	181.7	1967.0	1968.9	0.0	0.0	0.0
1900	26.7	24.1	57	181.7	1865.4	1846.9	0.0	0.0	0.0
2000	25.0	24.2	59	181.7	1766.4	1741.3	0.0	0.0	0.0
2100	23.6	24.0	60	181.7	1676.6	1710.6	0.0	0.0	0.0
2200	22.3	24.0	62	181.7	1592.7	1605.6	0.0	0.0	0.0
2300	21.3	24.1	63	181.7	1517.9	1511.6	0.0	0.0	0.0

APPENDIX E: ECONOMIC ANALYSIS

Table E.1 Average energy consumption of a typical weekday

	Base Case	BIPV	Dynamic EC Glazing	BEST*
Daily system, equipment, and lighting consumption (KWh)	16.8352	17.7063	16.7661	17.1875
Daily electricity production (KWh)	-	3.0063	-	2.6688
Net daily energy consumption (KWh)	16.8352	14.7000	16.7661	14.5187
Energy consumption reduction compared to base case (%)	-	12.68	0.41	13.76

* Note: combination of BIPV on East, South, and West façade with clear glazing on North

Table E.2 Average energy consumption of a typical weekend

	Base Case	BIPV	EC Glazing *	BEST
Daily system, and equipment consumption (KWh)	6.8875	6.4000	6.2125	6.3188
Daily electricity production (KWh)	-	3.0125	-	2.6750
Net daily energy consumption (KWh)	6.8875	3.3875	6.2125	3.6438
Energy consumption reduction compared to base case (%)	-	50.82	9.80	47.10

*Note: for weekends, the EC glazing model is assumed to be in full tint model

Table E.3 Average energy consumption of a typical full week

	Base Case	BIPV	Dynamic EC Glazing	BEST
Weekly system, equipment, and lighting consumption (KWh)	97.9510	101.3315	96.2555	98.5751
Weekly electricity Production (KWh)	-	21.0565	-	18.6940
Net weekly energy consumption (KWh)	97.9510	80.275	96.2555	79.8811
Energy consumption reduction compared to base case (%)	-	18.05	1.73	18.45

Table E.4 Annual energy consumption

	Base Case	BIPV	Dynamic EC Glazing	BEST
Annual system, equipment, and lighting consumption (KWh)	5110.3	5286.9	5022.1	5143.1
Annual electricity Production (KWh)	-	1097.9	-	974.75
Net annual energy consumption (KWh)	5110.3	4189	5022.1	4168.35
Energy consumption reduction compared to base case (%)	-	18.03	1.73	18.43

Table E.5 Detail energy consumption of all models for all weekend design days in all orientations

	Day	Daily system, and equipment consumption (KWh)			Daily electricity production (KWh)
		Base Case	BIPV	EC Glazing*	BIPV
South	March 20	2.0	2.0	2.0	4.0
	June 19	10.4	10.3	9.7	1.6
	Sept 18	11.6	10	10.4	3.3
	Dec 24	3.9	2.5	2.1	6.6
East	March 20	2.0	2.0	2.0	4.0
	June 19	12.4	11.2	10.8	3.7
	Sept 18	11.6	10.6	10.1	3.2
	Dec 24	2.2	2.4	2.4	2.5
West	March 20	2.2	2.0	2.0	4.0
	June 19	12.4	11.2	10.7	3.8
	Sept 18	12	10.8	10.6	3.4
	Dec 24	2.2	2.4	2.5	2.7
North	March 20	2.0	2.0	2.0	1.3
	June 19	10.7	10	9.5	1.9
	Sept 18	10	10	9.5	1.3
	Dec 24	2.6	2.6	2.7	0.9
Total Average		6.8875	6.4000	6.2125	3.0125

*Note: for weekends, the EC glazing model is assumed to be in full tint model

ELECTRA ABU DHABI L.L.C.
SINCE 1965

Quotation

Date : Sunday, November 7, 2010
Quotation # : ELECTRA/QTN/SA394/2010

To :	KEO	PROJECT NAME	
Attention :			
Tel :		SYSTEM PROPOSED	
Fax :		LIGHTING CONTROL	

We thank you for your inquiry and have pleasure in submitting our offer for your consideration as follows :

No.	Item #	Description	Tot. Qty	Unit Price	Tot. Price
	Solution 1				
1	W-500A	Ultrasonic Ceiling Occupancy Sensor 24 VDC, 500 sq ft	1	**343.00**	**343.00**
2	B230E-P	Power Pack, 220-240 VAC, 20 A ballast load, 150mA	1	**109.00**	**109.00**
	Solution 2				
1	W-500A	Ultrasonic Ceiling Occupancy Sensor 24 VDC, 500 sq ft	1	**343.00**	**343.00**
2	LS-301	Daylighting Sensor, 0 - 10 VDCdimming ballastsWhite	1	**535.00**	**535.00**
3	LSR-301-S	Daylighting Sensor,Handheld remote control for LS-301 setup	1	**91.00**	**91.00**
4	LSR-301-P	Daylighting Sensor,Handheld remote control for LS-301	1	**91.00**	**91.00**
5	B230E-P	Power Pack, 220-240 VAC, 20 A ballast load, 150mA	2	**109.00**	**218.00**
			TOTAL PRICE IN AED		AED **1,730.00**

- ***<u>Terms and Conditions</u>*** **:**

1 - Brand : **LEGRAND - WATTSTOPPER - USA**
2 - Payment : **CASH**
3 - Availability : **EXSTOCK PRIOR TO SALE**
4 - Warranty : **1 Year**
5 - Quote Validity : **15 Days**

We hope the above quotation is acceptable to you and looking forward to hear from you.
With best regards,
For Electra Abu Dhabi LLC,

Sherif A. Ibrahim
Head of ELV Systems Department

P.O.Box : 121
ELECTRA ABU DHABI L.L.C.

PO Box: 121, Abu Dhabi (U.A.E.), Phone: +971 2 6778077, Fax: +971 2 6777479, E-mail: electra@emirates.net.ae
Page 1 of 1

Figure E.1 Quotation received for light controls system (Electra, 2010)

-----Original Message-----
From: Charles Zhang [mailto:charles.zhang@jangho-uae.com]
Sent: Sat 11/6/2010 4:28 PM
To: Mohammad Katanbaf
Cc: 'wilson.lo'
Subject: BIPV laminate

Hi, Mohammad,

As we talked last Thursday, please see below budgetary price for the project we've been discussing.
Based on our assumption of 30,000 SQM facade (all with BIPV panel),
Rate: AED 5,180.00/sqm
Includes:
1. Supply of the PV panel (6mm,extra clear + 3mm monocrystalline + 6mm), providing 60 WP/sqm.
2. Supply of the motor & control system of the BIPV.
3. Supply of the CW system. (alum. extrusion, steel brackets, sealants, gasket, bolts, etc.)
4. Fabrication and Installation of the BIPV and CW system.
5. Mock ups & Testing, finial cleaning and maintenance.

Aside from the projects in UAE, we are now looking for some projects in North Africa area, especially in Libya. Maybe you or your colleagues are handling some projects there.

We are keen to serve you in that region if you have some jobs ongoing or some realistic jobs coming very soon.

Should you require any assistance from me, please feel free to keep me informed.

Regards

Charles Zhang

Business Development Manager
Mobile: +971 (0) 50 9104 982
Email: <mailto:charles.zhang@jangho-uae.com> charles.zhang@jangho-uae.com
Beijing Jangho Curtain Wall Co. Ltd., Gulf Headquarter, J&H Emirates L. L. C.
Tel : +971 (0)2 550 6060 ext. 283
Fax: +971 (0)2 550 6061
<http://www.janghogroup.com/> www.janghogroup.com

P.O. Box 113328, Room 305-308, 3rd Floor, Block B Building, AUH business Hub, ICAD 1, Mussafah, Abu Dhabi, United Arab Emirates

Figure E.2 Email correspondence with quotation for BIPV (Jangho, 2010)

-----Original Message-----
From: Charles Zhang [mailto:charles.zhang@jangho-uae.com]
Sent: Sat 11/10/2010 2:59 PM
To: Mohammad Katanbaf
Cc: 'wilson.lo'
Subject: Curtain Wall

Hi, Mohammad,

1. In general, what I mentioned in last email, the maintenance is the works that required during the defects liability period (DLP) due to the defects of our work done and the cost is covered within the tender sum such as for replacing PV panel due to scratch on surface during transportation / installation period etc.
As we are specialist façade contractor, our scope of works are typically include design, supply, fabricate, installation and maintenance till the completion of the DLP. We do not provide service for regular maintenance after the DLP. Usually the Property Maintenance Office of the building will do their regular or ad hoc maintenance service as per their own requirement. We have little idea how is their planning and the associated cost that may be incurred.
2. For a budgetary cost of typical curtain wall, as there is little information provided, we can only list the range of the unit rate with some criteria as below :
2.1 Assuming Qty - 30,000.00m2
2.2 Typical module - 1200mm wide x 4000mm high with vision glass 3000mm high while spandrel 1000mm high
2.2 Type of system - Unitized curtain wall
2.3 Typical type of glass - Vision glass - Insulated Glass with 6mm Low e coating (outer) + air space + 6mm clear (inner)
- Spandrel glass – 6mm ceramic fritted glass
2.4 Aluminium Finishes – Powder coating for exterior and interior with standard colour available in the market
2.5 Other items includes – fire insulation / thermal insulation / back pan / EPDM flashing etc.
2.6 Unit Rate - AED1450m2

Should there be any queries, please feel free to let me know.

Regards
Charles Zhang

Business Development Manager
Mobile: +971 (0) 50 9104 982
Email: <mailto:charles.zhang@jangho-uae.com> charles.zhang@jangho-uae.com
Beijing Jangho Curtain Wall Co. Ltd., Gulf Headquarter, J&H Emirates L. L. C.
Tel : +971 (0)2 550 6060 ext. 283
Fax: +971 (0)2 550 6061
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P.O. Box 113328, Room 305-308, 3rd Floor, Block B Building, AUH business
Hub, ICAD 1, Mussafah, Abu Dhabi, United Arab Emirates

Figure E.3 Email correspondence with quotation for BIPV (Jangho, 2010)

APPENDIX F: ABU DHABI CONFERENCE ON RENEWABLE ENERGY

Following are scanned pages of a hand-out of the lecture by Helen Pelosse, the Interim Director-General of the International Renewable Energy Agency (IRENA) in Abu Dhabi. The author attended this lecture which was held at the Emirates Center for Strategic Studies and Research on April 28th, 2010.

مركز الإمارات للدراسات والبحوث الاستراتيجية
The Emirates Center for Strategic Studies and Research

Lecture Series No. (326) — سلسلة محاضرات (326)

RENEWABLE ENERGY: A NEW ENERGY PARADIGM

Abstract & Biography

HÉLÈNE PELOSSE

INTERIM DIRECTOR-GENERAL
INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA)
ABU DHABI

The Emirates Center for Strategic Studies & Research

28 April, 2010

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Figure F.1 Excerpt from Pelosse lecture, page 1 of 3 (Pelosse, 2010)

Renewable Energy: A New Energy Paradigm

Abstract

In 2008 investment in renewable energy power generation (approximately US$140 billion, including large-scale hydropower) exceeded for the first time investment in fossil-fuel technologies (approximately US$110 billion). Increasing investment in renewable energy is a strong indicator of the new emerging energy paradigm. From 2004–2008 investment in renewable energy technologies quadrupled, and this trend is expected to continue.

Although there is on-going debate about the exact date for peak oil and gas, it is clear that we are on the verge of an important energy transition where renewable energies will play a key role. Transformations of energy patterns, such as the use of coal followed by oil and nuclear energy in the past, have always been linked to major advances in technology. Today, renewable energy technologies are, in their turn, leading towards a new era—a new energy paradigm that will be a Copernican revolution in our mindset.

We have always known that fossil energy resources were finite, yet the potential yield from renewable energy stands at more than 2,000 times the world's current energy consumption, while the sun has a predicted lifespan of five billion years. Previously, we were living within a centralized energy system; now we will move towards a decentralized system consisting of numerous production sources including "prosumers"—combining the role of energy producers and consumers. We have been used to a rigid, non-interactive electricity network; in the future smart grids will be intelligent and flexible. In addition, we believed that electricity could not be efficiently stored and have therefore invested in excess capacity to cope with peak hours of power demand; tomorrow the batteries of millions of vehicles will drastically change this pattern.

Due to its great potential – in particular solar energy – the Gulf region can become a major draw for renewable energy investors. Well designed, comprehensive and reliable support mechanisms for the market entry of renewable energy technology – including research, development and incentive programs – are needed to boost initial investment and to create attractive market conditions. The UAE has taken the lead with the commitment to 7 percent renewable energy in its electricity production by 2020, as well as the MASDAR initiative.

The International Renewable Energy Agency (IRENA), with its headquarters in Abu Dhabi, will support its members in the Gulf region in accelerating the awareness and adoption of renewable energy technology through its advice on policies, regulatory frameworks and financial instruments, capacity building, statistical data and supportive information. By combining efforts we can tap the vast potential of renewable energy for the benefit of current and future generations.

Figure F.2 Excerpts from Pelosse lecture, page 2 of 3 (Pelosse, 2010)

مركز الإمارات للدراسات والبحوث الاستراتيجية
The Emirates Center for Strategic Studies and Research

HÉLÈNE PELOSSE

BIOGRAPHY

On June 29, 2009, Mrs. Hélène Pelosse was elected Interim Director-General of the International Renewable Energy Agency (IRENA) by the Agency's member states.

Prior to this position, Mrs. Pelosse was in charge of international affairs at the Private Office of the French Minister for Ecology, Energy, Sustainable Development, and Town and Country Planning, where she served as Deputy Head of Staff. In this post since 2007, she managed the French negotiations for the EU's Climate and Energy Package, focusing in particular on the Renewable Energy Directive, and was also responsible for designing the Renewable Energy Plan for France. Moreover, she has taken part in several international climate negotiations and has been closely engaged with international organizations in the field of energy during her career, such as the International Energy Agency (IEA), United Nations Environment Program (UNEP), and the United Nations Development Program (UNDP).

Mrs. Pelosse has held a number of senior international positions including: Advisor to the Private Office of German Chancellor Angela Merkel, during the German presidency of the European Union (2006–2007), where as a core member of the steering committee of the German presidency she helped adopt EU political objectives on energy efficiency, renewable energy and greenhouse gas (GHG) emissions; Financial and Trade Advisor at the French Prime Minister's Office (2001–2005), where she helped define France's position in Europe's Economic and Financial Affairs Council (ECOFIN), and also participated in World Trade Organization (WTO) negotiations at ministerial level; Director of Strategic Affairs for the Saint Gobain Group in Massachusetts, United States (1999–2000); and she has also served in the French Ministry of Finance (1996–1998), where she focused primarily on the transition to the Euro currency.

Mrs. Pelosse graduated from the Ecole Nationale d'Administration (ENA), Paris, in 1996, after which she gained a Master's degree in Public Law and Political Science from the Institut d'Etudes Politiques, Paris; and a Master's degree from the ESSEC Business School of Management, France.

Figure F.3 Excerpts from Pelosse lecture, page 3 of 3 (Pelosse, 2010)