SEMI-TRANSPARENT BUILDING-INTEGRATED PHOTOVOLTAIC (BIPV) WINDOWS FOR THE TROPICS

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A THESIS SUBMITTED
FOR THE DEGREE OF DOCTOR OF PHILISOPY

DEPARTMENT OF ARCHITECTURE
NATIONAL UNIVERSITY OF SINGAPORE
2014

DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

The thesis has also not been submitted for any degree in any university previously.

Ng Poh Khai
06 January 2014

ACKNOWLEDGEMENTS

Many people have contributed directly or indirectly towards the successful completion of this doctoral thesis and I would like to take this opportunity to thank them.

First, I would like to thank Associate Professor Nalanie Mithraratne for her constant guidance for my research and taking me under her expert supervision when I needed to find a new main supervisor. I appreciate her efforts in reviewing my publications and numerous versions of this thesis and also her time in checking my progress despite her busy schedule with her teaching and other research commitments. Her support was tremendous whenever I faced difficulties and she would always provide me with the utmost backing to ensure that all goes to plan. She will constantly serve as an inspirational figure to me, whenever I take on supervision or managerial roles in my future work capacities. In addition, I am also thankful of my other thesis committee members: Assistant Professor Kua Harn Wei, for being there whenever I needed kind advice or assistance in both academic and non-academic areas, and Professor Stephen Wittkopf, for his direction in my initial years of research and providing me the opportunity to commence my PhD study.

Second, I would like to thank the staff from School of Design and Environment as well as the Department of Architecture. Special thanks are due to Associate Professor Wong Yunn Chii (Head of Department) and Associate Professor Bobby Wong Chong Thai (Deputy Head for Research) for admitting me into the department and also awarding me with a research scholarship to pursue a doctoral degree. Sincere appreciation also goes out to Assistant Professor Abel Tablada for allowing me to assist him in teaching duties and sharing his experiences with me. Special mention goes out to non-academic staffs such as Miss Goh Lay Fong and Miss Katherine Chong who were always there for me whenever I needed help or assistance in administrative paper work. Also, I would like to express my heartfelt thanks to my friends and colleagues at the Solar Energy Research Institute of Singapore (SERIS) where they were always there to support my research work and provide assistance. These people include Dr. Thomas Reindl, Mr. Choo Thian Siong, Dr. Daniel Sun Weimeng, Dr. Chen Fangzhi, Dr. Lipi Mohanty, Mr. Pang Chee Kok, Mr. Yang Xiaoming, Mr. Ouyang Jieer, Mr. Du Hui, Mr. Selvam Valliappan, Mr. Zhang Xiangjing, Miss Marinel Dungca, Miss Shimalee Fathima and Miss Religiana Hendarti.

Third, I would like to thank my family for their constant care and concern which I am deeply indebted towards. Their unconditional love has been a strong pillar of support for me to sustain my momentum throughout my past eight years of studies.

Last but not least, I dedicate this thesis to my fiancée, Miss Alina Hah Min Ee, who was always there for me for the past 12 years of my life. Her endless giving towards me and our relationship despite our ups and downs is something I am sincerely appreciative for and will always treasure.

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SUMMARY

In recent years, climate change mitigation has been one of the global agendas. Due to the significant contribution by the building energy use to this issue, there has not only been an increasing awareness in not only improving building energy efficiency but also promoting the use of clean or renewable technologies. Designing for energy efficient buildings can reduce electricity consumption and the adoption of renewable technologies in such buildings can result in zero- (or even plus-) energy buildings, which consume zero energy (or even generate more energy for other users) over a year. For tropical areas, the abundance of sunlight makes it more appropriate for solar technologies to be integrated in buildings. In many cities worldwide, such as Singapore, high-rise buildings are dominant in the urban areas. With limited roof area, the next possible area for photovoltaic integration is the vertical façade where semi-transparent building-integrated photovoltaic (BIPV) windows can be installed. Combining photovoltaic technology in building fabric can contribute to overall energy efficiency through electricity generation, solar heat gain effects and daylighting.

This study investigated the performance of semi-transparent BIPV windows in Singapore's tropical climate. First, commercially-available BIPV modules were laboratory tested for their electrical, thermal and optical properties. The electrical measurements analysed the effects on power generation of modules consisting of different photovoltaic technologies when exposed to different irradiance (direct/diffuse) and shading conditions. The thermal and optical

measurements determined the U-value, solar heat gain coefficient and visible light transmittance of both single and double-glazed modules.

The measured data were utilised in building energy simulations to determine their impacts on building energy consumption in tropical conditions in Singapore. By first examining Singapore's weather data, it was realised that all orientations received relatively high sunlight due to its highly diffused nature. The six selected semi-transparent BIPV modules were then used to perform a parametric study on different window-to-wall ratios and orientations in Singapore. A new index was formulated to evaluate the overall annual performance of semi-transparent BIPV modules in terms of multifunctional effects on building energy, by comparing them to double-glazed windows.

The results indicated that the Net Energy Benefits of BIPV can be very different and depend on the Window-to-Wall Ratio adopted, when compared to an opaque wall. The double-glazed modules showed good performance due to their better thermal performance, even though they have slightly lower photovoltaic efficiencies. It is also possible to integrate semi-transparent BIPV modules on facades that do not face the sun path in Singapore. An analysis to compare performance of the six modules against conventional double-glazed windows indicated that the semi-transparent BIPV modules are capable of increasing a building's energy efficiency and is a much better alternative for double-glazed window when choosing window façade materials.

Subsequently, a life cycle assessment was conducted to determine their long term environmental and economic performances. The life cycle resource uses (materials, energy, transport, etc.) were first investigated using up-to-date databases before adopting the building energy simulation results to assess the life time performance. The environmental performance indicators selected include greenhouse gas emissions, energy intensities, energy payback time and energy return on energy investment. Economic performance indicators used are payback period and return on investment. Sensitivity analyses were also included to consider alternative manufacturing locations, effects of façade shading from nearby buildings and possible future increases in electricity tariffs.

The life cycle environmental performance results indicated Energy Pay Back Time of less than two years and Energy Return On Energy Investment of up to 35 times for different modules and orientations. As for their economic performance, the modules achieved varying results. Some modules are already cheaper than double-glazed facades, after considering 30% subsidy that is handed out by the Singapore government. The sensitivity results suggested that manufacturing the modules in a nearby country can greatly decrease its life cycle energy use. In addition, the shadowing effects of surrounding buildings can decrease the overall effectiveness of BIPV systems. Results from the economic sensitivity analysis indicated that any increase in electricity prices improves the economic viability of semi-transparent BIPV systems. It can greatly reduce the payback periods and even some BIPV systems which did not achieve payback previously were able to do so with increased electricity prices.

Lastly, the results were used to derive a framework aimed at providing a simplified approach to facilitate the implementation of solar building applications. The selection matrix included performance indicators which would allow building designers to make quick and informed decisions.

LIST OF PUBLICATIONS

Throughout the course of this graduate study research, the following publications were produced (listed in chronological order):

Journal Papers

CHEN, F., WITTKOPF, S. K., NG, P. K. & DU, H. 2012. Solar heat gain coefficient measurement of semi-transparent photovoltaic modules with indoor calorimetric hot box and solar simulator. *Energy and* Buildings, 53, 74-84.

NG, P. K., MITHRARATNE, N. & KUA, H. W. 2013. Energy analysis of semi-transparent BIPV in Singapore buildings. *Energy and Buildings*, 66, 274-81.

NG, P. K., & MITHRARATNE, N. Lifetime performance of semi-transparent building-integrated photovoltaic (BIPV) glazing systems in the tropics. *Renewable and Sustainable Energy Reviews*, doi: 10.1016/j.rser.2013.12.044.

Conference Papers

Oral Presentations

SUN, W., NG, P. K. & OUYANG, J. E. 2011. Study of the Partial Shading Impact on the PV Roof in Zero-Energy Building in Singapore with PVSYS Simulations. Building Simulation 2011, 14-16 November 2011, Sydney, Australia. International Building Performance Simulation Association (IBPSA).

NG, P. K. & MITHRARATNE, N. 2012. A Selection Framework for the Integration of Semi-Transparent BIPV Windows in Singapore. *4th International Network for Tropical Architecture.* Singapore.

NG, P. K., MITHRARATNE, N. & WITTKOPF, S. 2012. Semi-Transparent Building-Integrated Photovoltaic Windows: Potential Energy Savings of Office Buildings in Tropical Singapore. *Passive and Low-Energy Architecture*. Lima, Peru: PLEA.

NG, P.K.& MITHRARATE, N. 2013. Life Cycle Energy Performance of Semi-Transaparent Building-Integrated Photovoltaic (BIPV) Windows in Tropical Singapore. Sustainable Building 2013, 25-28 September 2013 Graz, Austria.

Poster Presentations

WITTKOPF, S., KAMBADKONE, A., HE, Q. & NG, P. K. Development of a Solar Radiation and BIPV Design tool as EnergyPlus plugin for Google SketchUp. Building Simulation 2009, 27-30 July 2009, Glasgow, Scotland. International Building Performance Simulation Association (IBPSA).

SUN, W., WITTKOPF, S. & NG, P. K. Performance evaluation of selected photovoltaic arrays in an zero-energy building in Singapore. Renewable Energy 2010, 27 June - 2 July 2010 Yokohama, Japan.

NG, P. K., WITTKOPF, S. K. & SUN, W. Modelling the Impact of Glazing Selection on Daylighting Performance of an Office Building in Singapore Using EnergyPlus. Building Simulation 2011, 14-16 November 2011, Sydney, Australia. International Building Performance Simulation Association (IBPSA).

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ABBREVIATIONS

BIPV	-	Building-Integrated Photovoltaic
BOS	-	Balance of Systems
CdTe	-	Cadium Telluride
CED	-	Cumulative Energy Demand
CH	-	Switzerland
CIGS	-	Copper Indium Gallium Selenide
COP	-	Coefficient of Performance
EPBT	-	Energy Payback Time
EROEI	-	Energy Return on Energy Investment
GHG	-	Greenhouse Gas
GLO	-	Global
LCA	-	Life Cycle Assessment
LCCA	-	Life Cycle Cost Analysis
LSG	-	Light-to-Solar-Gain
OCE	-	Oceanic
NEB	-	Net Energy Benefit
RER	-	Europe
SERIS	-	Solar Energy Research Institute of Singapore
SHGC	-	Solar Heat Gain Coefficient
SVF	-	Sky View Factor
VLT	-	Visible Light Transmittance
WWR	-	Window-to-wall Ratio

CHAPTER 1 INTRODUCTION

1.1 Global Energy Use

As shown in Figure 1:1, the world energy consumption increased by nearly 40% between 1990 and 2007. With the population growth rate expected to increase at a rate of 0.8–1% annually (UN, 2009), coupled with rapid urbanisation and development in developing countries, it can be safely assumed that the world energy consumption will continue to increase. It has been predicted that the global energy consumption will increase by another 8–10% every five years till 2035 (EIA, 2010).

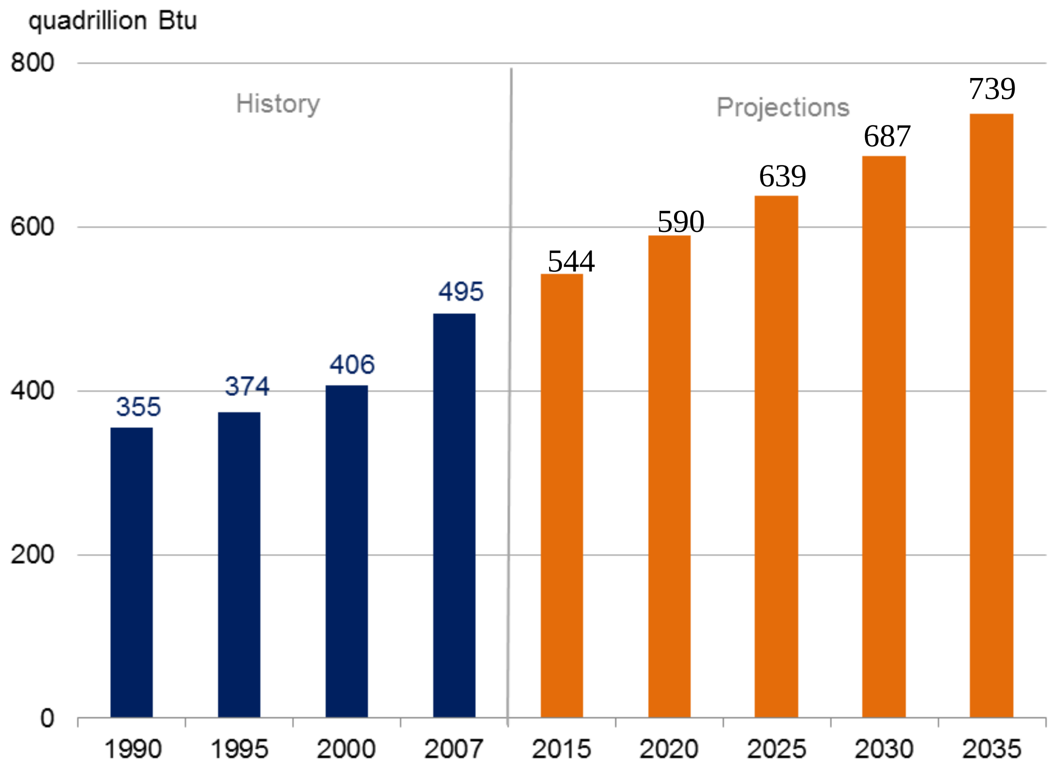


Figure 1:1 – World Energy Consumption
(Source: EIA, International Energy Outlook 2010, July 2010, pp. 9)

Globally, buildings represent 40% of primary energy usage and if the energy consumed in manufacturing steel, cement, aluminium and glass used in building construction is included, this number grows to more than 50% (WBCSD, 2005). Several factors contribute to produce two broad trends resulting in the alarming increase in building energy consumption. Within the developing countries, there is increasing population growth, prosperity and urbanisation. Urban living, higher incomes and more access to technologies are associated with higher building energy use, especially for space and water heating, appliances and equipment (Figure 1:2). In developed countries, there is an inefficient building stock and also an increase in usage of services and appliances. Many such properties are old, built before energy efficiency regulations were enacted and with average annual replacement rate of around 2% (Gordon, 2008), will still be in use in 2050 (WBCSD, 2005).

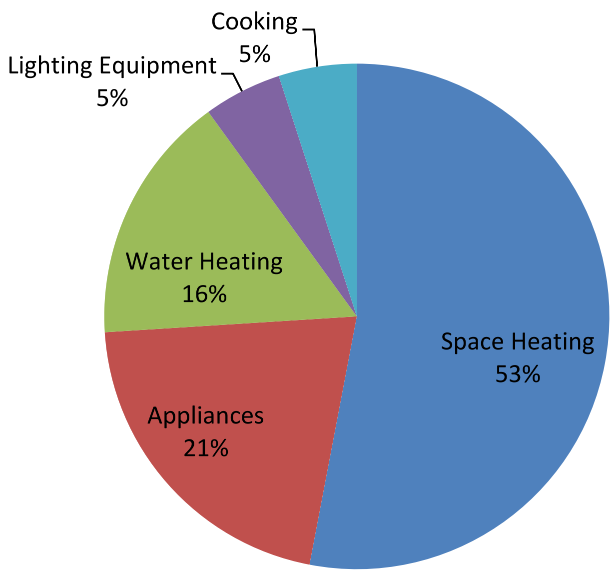


Figure 1:2 – Global Energy Consumption in Buildings
(Based on: International Energy Agency, 2008, Worldwide Trends in Energy Use and Efficiency)

1.2 Energy Consumption in Singapore's Building Sector

The building sector consumes about a third of Singapore's total electricity production (BCA, 2010). The total operating energy consumption of a building is usually attributed to heating, ventilating and air-conditioning (HVAC) equipment, electrical artificial lighting, lifts and escalators, equipment and appliances. Based on an audit conducted on 104 office buildings, Lee and Majid (2004) concluded that in Singapore, the average annual electricity consumption in the commercial building sector is 180–260 kWh/m^2/yr. Past studies have shown the electrical consumption of individual commercial buildings' end-uses. In general, the distribution of energy by end-use for commercial buildings was: air-conditioning, 50–60%; lighting, 15–20%; vertical transportation, 5% and equipment, 10–15% (Lee and Majid, 2004, Chou et al., 1994).

With a large amount of energy consumed by buildings being channelled for air-conditioning, there is also literature on the distribution of thermal loads. The base cooling load is attributable to various sources as follows:

1. Solar radiation (25%);
2. Lighting (23%);
3. Ventilation and infiltration (19%);
4. Occupants (16%);
5. Wall and glass conduction (13%); and,
6. Others (4%). (Chou and Chang, 1997).

With Singapore's tropical climate, it is easy to understand that commercial buildings require a large amount of cooling and the main heat contributors are actually from the facade (solar radiation, wall and glass conduction) and artificial lighting, which generates heat in the process of providing sufficient illumination. The design of high performance building facades to combat heat gains has been imperative as a preferred passive design strategy as opposed to active measures. Besides affecting the performance of office buildings through thermal heat gains and daylighting, facades also play an important role in their visual appeal.

In city states such as Singapore, land is a limited and valuable resource. With many different land uses such as transportation, residential, nature reserve and commercial competing for land, developments have to ensure that land use is carefully designed and its potential is maximized. With the current population of 5.31 million projected to reach 6.5–6.9 million by 2030 (NPTD, 2013), the demand for high-rise buildings is increasing as they can help to alleviate land constraints by fully utilizing the plot ratio to achieve maximum gross floor area.

1.3 Solar Energy

Solar energy is widely regarded as a potential application of renewable energy in buildings due to good availability in many places, especially in the tropics with high sunshine hours all year round. The different uses of solar energy for buildings can be classified into passive and active strategies (Eicker, 2003). For passive solar energy use, the most important component is the window and contributes to space heating and daylighting. As for active use, it is primarily used to meet electricity requirements by photovoltaics, and to warm water heating by solar thermal collectors. In air-conditioned buildings, thermal cooling sorption processes can be powered by active solar components.

Photovoltaic (PV) technology can harness and convert incident solar energy into electricity and has been used in many applications. In modern urban areas with numerous high-rise buildings, PV systems that integrate renewable energy with buildings known as building-integrated photovoltaic (BIPV) can be a suitable form. With BIPV, the architectural, structural and aesthetic integration of photovoltaic into buildings can allow the incorporation of energy generation into urban structures (Pagliaro et al., 2010). According to this concept, the photovoltaic modules become true construction elements structurally serving as building exteriors, such as roofs, façade or skylight.

Building integration of photovoltaic is usually restricted to rooftop installations or as opaque solar façade claddings. The rooftop provides the best view factor and likely to receive more solar gains than any other building façade, and therefore, likely to generate more electricity. However, in high-rise buildings, roof top spaces are very limited, in addition to being sought after by other building systems such as air-conditioning equipment, water tanks and green roof applications. With limited rooftop areas, BIPV applications could make use of the abundant façade areas to generate electricity (Yun and Steemers, 2009).

Semi-transparent BIPV can provide a novel method to increase energy efficiency, while enhancing the façade's aesthetic designs by replacing traditional window glazing (Hagemann, 1996a). Although the cost of PV technology is still high, such cost can be mitigated by the overall energy benefits in the long term and also the reduced capital cost by requiring a down-sized air-conditioning system. By replacing traditional window glazing, semi-transparent BIPV inherits the energy-related roles of fenestration (thermal protection and optical daylight control) in additional to electricity-generation capability (Li and Lam, 2008).

Compared to opaque walls, applying semi-transparent BIPV to the façade enable daylight to be transmitted to reduce the dependency on artificial lighting. With less artificial lighting required, less energy is consumed through its direct savings and also the indirect savings from the reduction in cooling load as the artificial lighting can act as a heat source. Semi-transparent BIPV can also affect the heat gain/loss from the solar radiation that is transmitted into the building's interiors. This can affect the demand for air-conditioning which can possibly lead to down-sizing of the system and consumption of less energy. Together with the production of electricity, semi-transparent BIPV provide a new dimension to solar façade technologies when solar shading, daylighting and electricity production are simultaneous benefits (Li et al., 2009).

Despite the various benefits and potential of semi-transparent BIPV, their wider take-up has been faced with several issues. First, there is a lack of design tools considering the influence of semi-transparent BIPV on design which allows architects to make competent decisions (Hagemann, 1996b). The lack of technical knowledge reduces the confidence of architects in adopting BIPV systems in the early stages of building design, where they should be included for good integrated results (Petter Jelle et al., 2012). Where there is a need to design for energy efficient buildings, such information and knowledge should include the multifunctional effects semi-transparent BIPV systems have on building energy consumption such as heating/cooling demand, effects on artificial lighting consumption and photovoltaic electricity generation (Attia and De Herde, 2010, Yun et al., 2007, Miyazaki et al., 2005). The lack of lifetime performance information of semi-transparent BIPV systems in environmental and economic terms also serve as barriers, especially since BIPV systems are known for their high costs of implementation (Peng et al., 2013, Lim et al., 2008, Raugei et al., 2007)

The main aim of this research is therefore to explore the potential benefits of adopting semi-transparent BIPV facades in buildings located in Singapore's tropical climate. In hot and humid areas, performance of façade glazing systems plays an important role in minimizing heat gain from the environment into the interiors. At the same time, it is also desirable for natural daylight to penetrate indoors to reduce the need for artificial lighting. The study looks at the optimal application of semi-transparent BIPV facades from not only these two aspects of traditional glazing, but also the PV electricity generation. Also, a life cycle assessment is performed to identify the long-term benefits, in terms of environmental and economic performance. The knowledge created in this area serves to provide critical information for architects to assist them in adopting photovoltaic technology in their building design.

1.4 Statement and Research Objectives

1.4.1 Semi-Transparent BIPV for the Tropics

Semi-transparent photovoltaic plays an important role in BIPV due to its light admission characteristics to buildings’ interiors. Compared to opaque PV modules that have been adopted as cladding and shading devices in many BIPV case studies, semi-transparent photovoltaic can actually replace traditional windows while adding a third dimension of electrical generating capability to buildings. In tropics where there is abundant sunlight and cooling loads are high all year round, semi-transparent BIPV installed as windows can contribute to the energy efficiency of buildings. High-rise commercial buildings are also popular within the construction industry which underlines the statement that window glazing plays an important role as a building material which semi-transparent BIPV can replace. (However, their integration may be limited, in cases where high visual connection with the outside environment is desired, due to limitations in visibility.) Hence, the admission of daylight to reduce artificial lighting, solar heat gain into the interiors and electricity generation capabilities have to be balanced and weighted in order to optimize the installation of semi-transparent BIPV windows.

1.4.2 Research Objectives

It is believed that an integrated modelling solution that represents the three energy-related functions of BIPV will generate much needed performance data and aid the use of BIPV for optimum building performance. Hence, the main aim of this study is to assess the overall energy benefits of semi-transparent BIPV in order to enhance architects' ability to better design glazing and increase integration of semi-transparent BIPV into building facades for tropical climates. The research objectives are set out as follows:

1) To measure and evaluate semi-transparent BIPV's electrical, thermal and optical properties in the laboratory under conditions representative of tropical climatic to assess energy performance in tropical climatic conditions;
2) To assess semi-transparent BIPV's energy performance when integrated in high-rise office buildings in a tropical climate;
3) To develop an energy index that considers the multi-functional characteristics (electricity generation, thermal and optical efficiencies) of semi-transparent BIPV;
4) To establish long term environmental and financial performance of semi-transparent BIPV in Singapore's tropical conditions; and,
5) To develop a simplified graphical representation of semi-transparent BIPV long term performance for building that considers lifetime energy, carbon and cost.

1.4.3 Research Hypothesis

Through the process of literature review (see chapter 2) and formulation of research objectives, the following hypotheses are developed:

1) Photovoltaic can increase the energy efficiency of high-rise buildings. Energy efficiency is critical in achieving zero-energy buildings or even positive-energy buildings;
2) BIPV application need not be limited to rooftop areas but can be extended to façade with more area for adoption;
3) Lifetime environmental and economic performance of semi-transparent BIPV windows can achieve benefits that are higher than its resource cost; and,
4) Semi-transparent BIPV plays a significant role in façade due to its energy generating and conservation capabilities, which requires proper design and optimization to maximise its benefits.

1.4.4 Potential Contribution

Upon the fulfilment of the above objectives, the proposed research is expected to achieve several potential contributions:

1) The study contributes to the knowledge in performance of solar buildings in the tropics that focus on alternative energy sources and making building systems as energy efficient as possible;

2) It empowers architects to design more sustainable buildings by providing a means that considers the overall electricity benefits of semi-transparent BIPV to increase buildings' energy efficiency;
3) It establishes a method to holistically represent the overall energy benefits of semi-transparent BIPV which also accounts for its life cycle resource use.
4) It provides a simplified graphical illustration that can be used by building designers at preliminary design stage to facilitate BIPV application to high-rise buildings.

The above contributions will not only enhance building designer's abilities in producing more energy efficient design but also encourage building owners to adopt solar energy as a renewable and clean source of energy by highlighting long term costs and benefits which are not currently considered in the development decisions.

1.5 Organisation of Thesis

In total, this thesis consists of eight chapters. A brief description of each chapter is outlined as follows:

1. The current chapter (chapter 1) serves as an introductory chapter which discusses the background information related to the topic. The statement and research objectives including the research hypotheses and potential contribution are established in this chapter. The main content of the thesis is also outlined.

2. Chapter 2 provides a review of pertinent literature along with a discussion and identification of the knowledge gap. First, the importance and preference for daylighting with regards to window fenestration are discussed, with reference to both occupants' preference and energy efficiency. Thereafter, a quick summary of photovoltaic technology and how semi-transparent building-integrated photovoltaic can be considered as an alternative window facade material is presented. Different aspects of photovoltaic integration in building design relating to the systems, benefits and performance are also reviewed. As buildings are usually designed to last for many years, the importance of life cycle assessment for semi-transparent building-integrated photovoltaic is also emphasized. Based on the literature review, the up-to-date research areas and their limitations are discussed and a knowledge gap is identified for this research.
3. Chapter 3 presents the main research methodology for this thesis. The overall research approach is described, which consists of physical measurements, building energy simulations and life cycle assessments including both environmental and economic performance. These three components will serve to provide information to form a decision support tool for building owners and designers to assist them in making decisions on integrating semi-transparent photovoltaic windows in high rise buildings.
4. The experiments to establish performance parameters and measurement results of the semi-transparent photovoltaic modules are explained and discussed in this chapter. Electrical measurements are

presented first, followed by the thermal measurements which include both U-value and SHGC properties. Lastly, the optical experiments which measure the modules' visible light transmission are documented.

5. Chapter 5 describes the development of the Net Electrical Benefit (NEB), a holistic multifunctional index, which is one of the main contributions of this thesis. The building simulations used to develop this index is documented and the results are presented.
6. Building on the simulation results, a life cycle assessment is performed in chapter 6. First, a quick review of current research work performed relating to building-integrated photovoltaic is presented. Subsequently, a quantification of life cycle resource use is performed using both primary and secondary data, before their environmental and economic performances are established and discussed. The last section of this chapter considers alternative scenarios which are used as a sensitivity analysis to examine probable situations and their implication on the results.
7. Chapter 7 documents a graphical representation of BIPV long term performance that is developed to aid architects and building designers in making decisions pertaining to the choice of semi-transparent BIPV modules for window application. The decision matrix consists of several criteria which are based on the semi-transparent BIPV performance results generated in the previous chapters.
8. Finally, chapter 8 concludes the thesis and summarises the key findings and recommendations. The major contributions and

significance of the study are also highlighted. In addition, the study's limitations and recommendations for future research are also stated.

CHAPTER 2 LITERATURE REVIEW

In this chapter, pertinent literature on various topics related to the research is reviewed. The chapter starts by describing the benefits of daylighting and its influence on the building energy use. Windows, a major component of a building's fenestration, are also discussed similarly in detail. The basics of photovoltaic technology are explained followed by a brief introduction to building-integrated photovoltaic and its benefits. An overview of the BIPV with respect to building energy consumption is presented. In addition, a literature review focusing on current technological developments and applications in this field is also provided.

2.1 Daylighting

Daylighting is the practice of placing windows or other openings and reflective surfaces so that natural light can provide effective internal lighting during the day (ASHRAE, 2009). Daylighting is known to affect visual performance, lighting quality, health, human performance and energy efficiency. In terms of energy efficiency, daylighting can facilitate substantial energy conservation by reducing the need for artificial. It is estimated that, lighting and its associated cooling costs can constitute up to 40% of a non-residential building's energy usage (ASHRAE, 2009).

With globalisation and rapid development, the construction of high-rise commercial buildings has brought about new fenestration systems that can achieve substantial energy conservation. With proper fenestration design, daylighting can be an important energy-saving tool. However, if it is inappropriately designed, it can have a drastic effect by allowing heat gain and turn into an energy-wasting component. According to the National Fenestration Rating Council (NFRC, 2005) and ASHRAE (2009), the benefits of daylighting can be summarised into the following three categories: health and well-being, energy efficiency and sustainable design . The principle of daylighting design is to maximise the utilisation of available outdoor illuminance without imposing excessive cooling loads or causing glare.

2.1.1 Daylighting and Occupant Performance

Daylighting for buildings' interior has been researched upon, with many studies adopting a survey-based approach since the 1960s. In 1965, a study was conducted in the U.K. to identify people's attitudes towards windows and lighting. Eighty-nine percent of the respondents felt that an exterior view was critical and 69% responded that their eyes preferred daylight to artificial lighting (Wells, 1965). Cuttle (1983) also conducted surveys in England and New Zealand where a large number of respondents (99%) believed that offices should have openable windows and (86%) considered daylighting to be their preferred source of lighting. Their reasons were that working in daylight results in less stress and discomfort as compared to artificial lighting. Similarly in a survey of occupants of an office building in United States, it was found that more than half of the occupants believed daylight was better for psychological comfort, office appearance and appeal, general health and visual comfort (Heerwagen and Heerwagen, 1986).

In Canada, Veitch et al. (1993) reported that 65–78% of surveyed occupants endorsed that natural light is superior. In its extended study, it was also found that office workers and university students believed that daylight is superior to other light sources and more than half of them reported that the best places to work were those that were illuminated by natural light (Veitch and Gifford, 1996).

Hence, based on the literature, it can be concluded that windows are an essential component of many buildings. This is due to a very strong preference for daylight in workplaces and the belief that daylight supports better health (Galasiu and Veitch, 2006).

2.1.2 Daylighting and Building Energy

Many literatures have shown that daylighting not only increases occupants' comfort but also reduces the buildings' energy consumption. A large number of such studies employed simulations and physical measurements indicating that substantial energy savings can be achieved by using different daylighting strategies.

Rutten (1991), using then-existing knowledge and calculation methods such as daylight factor, provided a conservative estimate which indicated potential savings of 46% of the artificial lighting electricity costs in Dutch buildings. In a simulation study, Szerman (1993) showed that the use of classical windows can result in 77% of lighting energy savings and 14% of total building energy savings. A range of 20–40% of lighting consumption savings was measured at seven different office test sites located in Europe (Embrechts and Van Bellegem, 1997). Within the tropics, it has been demonstrated by Zain-Ahmed et al. (2002) that a maximum of 10% energy savings could be achieved in a typical Malaysian building.

Going further, Bodart and De Herde (2002) evaluated the daylighting impacts based on an integrated approach to consider the thermal aspects of lighting loads involved. They demonstrated that daylighting itself can reduce 50–80% of the artificial lighting energy consumption. Also, building primary energy savings of up to 40% globally can be achieved in typical office buildings, through the combination of reduced lighting consumption and internal lighting load.

Comparative studies were also conducted to evaluate the difference within various daylighting control systems. Lee and Selkowitz (2006) discovered that there is a large variation of 20–59% with regards to measured lighting energy savings of two daylighting control systems. Moreover, additional energy savings due to reduced solar gains and lighting heat gains were not quantified and this could be assumed to increase the total operational cost savings.

It was found in another study on a deep-plan commercial office building that consisted of three lighting control systems, occupancy sensors would have saved 35%, light sensors (daylight harvesting) 20% and individual dimming 11% (Galasiu et al., 2007). Combining these systems, they saved 42–47% in lighting energy as compared to full power during office hours.

The above literature had common consensus that daylighting can have a positive impact on overall building energy consumption. However, due to varying building parameters such as windows size, floor area, orientation, types of systems adopted and most importantly, the location's climate and weather profile, the reduction could vary from building to building. In addition, the authors have highlighted the disadvantages of solar heat gain or thermal loss that can have a negative impact on daylighting. As such, a compromise between daylighting and its related thermal issues has to be achieved and balanced in order to determine an optimum building energy balance.

2.2 Fenestration

Fenestration is an architectural term that refers to the arrangement, proportion and design of window, skylight and door systems in a building (ASHRAE, 2009). Fenestration can serve as a physical and visual connection to the outdoors, providing a means to admit solar radiation for daylighting and heat gain into a space. In this thesis, fenestration shall be discussed exclusively in the context of a window as the other forms of fenestration are not considered.

The multiple benefits of incorporating windows into buildings include, amongst others (Dogrusoy and Tureyen, 2007):

1) constructing visual communication between the interior and exterior,
2) providing relaxation and refreshment,
3) allowing daylight into the room and providing natural ventilation,

4) eliminating boredom and monotony,
5) improving the emotional state of occupants, and
6) facilitating motivation in office environments.

Although very much preferred by occupants, the design of windows has to be seriously considered. Windows can affect the building energy use through thermal heat transfer, solar heat gain, air leakage and daylighting. Hence with proper design and installation, windows can minimise heating/cooling loads and electrical lighting costs.

2.2.1 Windows and Building Energy Consumption

Over the years, many studies have been conducted to estimate the windows' potential for energy savings in various climatic zones and the results reported vary. With more advanced computational simulation tools available in the market, optimization of window size/type to increase energy savings has been explored.

Al-Homoud (1997) showed that optimisation techniques could aid building designers to achieve building designs with optimum thermal performance. He concluded that, even with daylightings' potential to save energy disregarded, the optimum design for a large office building in six different cities could achieve 6.6–22.4% savings from thermal performance improvements. Similarly, another study on the impact of optimal window size and building aspect ratio on heating/cooling loads revealed that a south-facing WWR of

25% was the optimum for hot climates in Turkey (Inanici and Demirbilek, 2000).

In a study of multi-storey office buildings in Singapore, Wong et al. (2005a) investigated the effects of using double-glazed façade with ventilation compared with single glazed façade on the energy consumption, thermal comfort and condensation. Simulation results indicated that double-glazed facades with natural ventilation are able to minimise energy consumption and enhance thermal comfort.

An evaluation of various energy conservation measures via simulation was conducted in Saudi Arabia’s hot and humid climate and a 7% reduction in energy consumption was achieved in summer by adopting an efficient glazing system. It is recommended that low-emissivity double-glazed windows be used for large buildings in hot climates if energy efficiency was to be achieved. More energy-efficient windows can not only improve energy consumption but also the indoor comfort level (Iqbal and Al-Homoud, 2007).

Stegou-Sagia et al. (2007) studied the impact of glazing selection on building’s energy consumption in Greece. Their simulation results, based on Greece’s climate, indicated that adopting less glazing area and installing grey tinted glazing can reduce total annual energy consumption by 6.6–9.5% and 13.3–14.8% respectively, as compared to clear glazing. The study concluded that although glazing plays an important role in buildings by providing exterior view and daylight, it can also increase energy consumption due to its poor insulation value. They also highlighted the importance of daylighting in commercial buildings as it is common practice to have the artificial lights on during the whole day. Hence, energy conservation can be achieved through careful building design.

2.2.2 Window Properties

As discussed above, windows play a key role in building energy consumption. Their effects on the energy use are mainly determined by several window parameters which include thermal and optical properties. According to ASHRAE (2009), these properties are: (1) U-value (U-factor), (2) Solar Heat Gain Coefficient (SHGC) and (3) Visible Light Transmittance (VLT). These three parameters (combined with 2 other optional ratings, i.e. air leakage and condensation resistance), are also compulsory for the National Fenestration Rating Council (NFRC) energy performance label ratings of windows. In building energy simulation programs that consider fenestration such as *EnergyPlus* and *COMFEN*, these three parameters are considered in order to determine the window effects on the building interior's lighting and thermal conditions (Selkowitz, 2012, DOE, 2010, Hitchcock et al., 2008).

<u>U-value (U-factor)</u>

U-value, also known as U-factor, determines the steady-state heat transfer caused by indoor and outdoor temperature difference and is used to measure thermal transmittance. It represents the heat transfer rate through a window and expresses how much energy is transferred. The U-value can either represent the glazing itself or the entire window, including the frame and spacer material. The U-value for single glass is:

$$U = \frac{1}{1/h_o + 1/h_i + L/k}$$

where,

h_o, h_i	=	outdoor and indoor respective glass surface heat transfer coefficients, W/(m^2.K)
L	=	glass thickness, m
K	=	thermal conductivity, W/(m^2.K)

The overall U-value for an entire window can be estimated using area-weighted U-values for each contribution by:

$$U_o = \frac{U_g A_g + U_f A_f}{A_g + A_f}$$

where,

U_g, U_f	=	U-values of glass and frame respectively, W/(m^2.K)
A_f, A_g	=	surface area of glass and frame respectively, m^2

A window with a lower U-value will represent a lower amount of heat loss and is better at insulating a building, thus being more energy efficient. Hence, the U-value is important for cold climates where insulation is important to reduce heat loss.

Solar Heat Gain Coefficient (SHGC)

According to ASHRAE (2009), SHGC determines the steady-state heat transfer caused by solar radiation and consists of two components. First, is the directly transmitted solar radiation which is governed by the solar transmittance of the glazing system. The second is the inward flowing fraction of solar radiation absorbed through the entire window construction. SHGC can be used to measure the amount of solar heat gain through the fenestration and is expressed as a number between 0 and 1. The mathematical equation that represents the components of SHGC on a simple pane of glass is given as:

$$SHGC = T + NA$$

where,

T	=	solar transmittance, [-]
A	=	solar absorptance, [-]
N	=	inward-flowing fraction of the absorbed radiation, [-].

The SHGC is needed to determine the solar heat gain through a window's glazing system and should be included along with U-value and other instantaneous performance properties in any manufacturer's description of a window's energy performance. Since a higher SHGC value relates to increased heat transmission, it can be used for cooling load calculations. Glazing systems with lower SHGCs are more effective in reducing undesired heat gain as compared with higher SHGCs. As such, in hot climates SHGC is critical for buildings and are sometimes given higher priority than U-value for windows.

Visible Light Transmission (VLT)

The third important property of windows is the visible light transmittance, which is a value between 0 and 1. Along with fenestration area, visible transmission is directly related to daylighting and represents the solar radiation transmitted through the fenestration weighted with respect to the response of the human eye. Within the solar spectrum, there are three important categories of light energy: ultraviolet (UV), visible and infrared (IR). The light energy that affects the visible transmittance of a fenestration is the visible category which consists of wavelengths from about 390 to 780 nm (ISO, 2003a).

The transmittance *(T)*, reflectance *(R)* and absorptance *(A)* of a layer are formally defined as the fractions of incident flux that transmit, reflect and are absorbed by the layer respectively. Their sum, as shown below, equals unity.

$$T_{vis} + R_{vis} + A_{vis} = 1$$

The optical properties of glazing systems that contain multiple glazing layers are affected by the inter-reflections between the layers and optical properties of the individual layers. The overall properties also depend on the position in which individual glazing layers are placed in relation to each other. Hence, it is important to expand the glazing system to consider the individual layers before applying them to the overall properties of the system.

Glazing systems with high visible transmission values can provide good vision with ample natural light but if left uncontrolled, excessive glare can be a problem for indoor occupants. In order to maximise daylighting and minimise glare issues, mitigation methods such as blinds and curtains can be adopted. The visible transmission can significantly improve both energy savings and occupants comfort.

Light-to-Solar-Gain Ratio

In most applications, it is important to have high visible transmittance. While in temperate climates, good solar heat gain is important for offsetting wintertime heating costs, in tropical climates, low solar heat gain is good for offsetting cooling costs. However in the tropics, it is often difficult to have both high visible transmittance and low solar heat gain. A common rule of thumb is to select a glazing unit having a visible transmittance greater than its solar heat gain coefficient. To illustrate this concept and balance the different demands for both properties, a T_{vis} vs. SHGC chart or light-to-solar-gain (LSG) ratio can be used. The LSG ratio is defined by ASHRAE (2009) as:

$$LSG = \frac{VT}{SHGC}$$

where,

VT = visible solar transmittance, [-]

SHGC = solar heat gain coefficient, [-].

The LSG plot of 37 glazing specimens (Figure 2:1) used by Gueymard and DuPont (2009) to highlight the importance in characterising spectral selectivity and performance of glazing systems shows a large scatter.

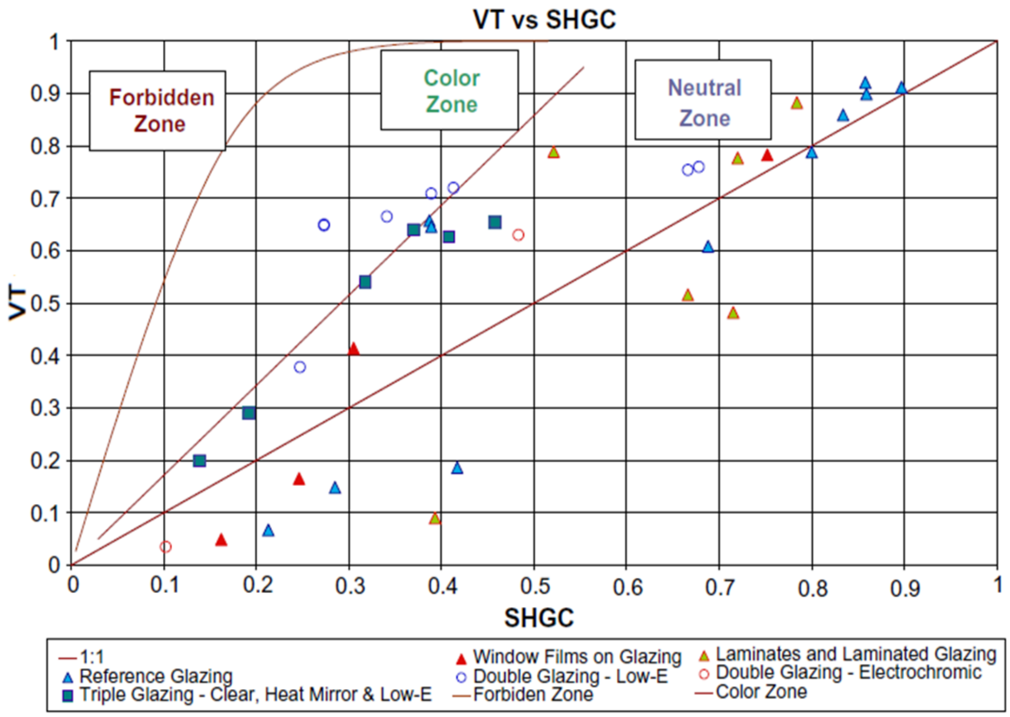


Figure 2:1 – LSG plot of 37 glazing specimens
Source: (Gueymard and DuPont, 2009, pp. 945)

The "neutral zone" contains glazings that do not have the edges of the visible spectrum stripped off and therefore do not have a coloured appearance. The "forbidden zone" is a region where it is impossible to devise a glazing with a transmittance greater than the indicated curve for a given SHGC value. Any glazing within the "colour zone" will impart a decidedly coloured appearance to the transmitted light (McCluney and Gueymard, 1993).

Generally, a high value of LSG is desired for buildings in hot climates in order to maximize daylight admission with minimal heat gain. This is also applicable to internal-load-dominated buildings, even in cool or cold climates, as solar gain reflection is often desired for such buildings. For buildings without strong internal cooling loads in cold climates, an LSG value less than 1.0 is generally appropriate (ASHRAE, 2009).

Various solar technologies that can be used in buildings to improve energy performance were briefly discussed earlier (see section 1.3). The photovoltaic technology being the most suitable for high-rise buildings in urban conditions, this is explored further.

2.3 Photovoltaic Technology

Solar energy can be directly converted into electricity with the help of a solar cell. Assemblies of these cells are used to make solar panels or modules, which are in-turn, combined to form photovoltaic arrays. The field of technology and research related to the application of electricity-producing solar cells is called photovoltaic.

2.3.1 Photovoltaic Basics

Solar cell is an electronic device which converts solar energy directly into electrical energy through the photovoltaic effect. When the light falls on the device, the light photons of certain wavelengths are absorbed by a semiconducting material and electrical charge carriers are generated. These carriers flow through a junction to produce an electrical current in the circuit. This current depends on the incident photon intensity and the nature of the semiconductors that constitute the junction device. Silicon, being the most abundant semi-conductor material available on earth, contributes to the bulk of commercial solar cells. Today, it is used in single-crystalline, polycrystalline and amorphous nature for the fabrication of solar cells (Reddy, 2010).

2.3.2 Photovoltaic Performance

The most common method of assessing photovoltaic performance is the photovoltaic efficiency under standard reporting conditions. International standards, such as American Standard for Testing of Materials (ASTM) and International Electro-technical Commission (IEC) standards, have been adopted to rate the performance of photovoltaic cells and modules in terms of their efficiency with respect to standard reporting conditions (IEC, 2007). The PV conversion efficiency (η) can be calculated from:

$$\eta = \frac{P_{max}}{E_{tot} \times A} \times 100\%$$

where,

η	=	PV conversion efficiency, [%]
P_{max}	=	maximum or peak power, [W]
E_{tot}	=	total incident irradiance, [W/m^2]
A	=	device area, [m^2].

The maximum or peak power, P_{max}, can be determined from measurements of the cell or module I – V (current – voltage) behaviour, along with other important parameters (IEC, 2007). The critical parameters on the I – V curve are the open-circuit voltage (V_{OC}), the short-circuit current (I_{SC}) and the maximum power point (P_{max}). These critical parameters are illustrated on a typical $I - V$ curve in Figure 2:2. The current and voltage that corresponds to P_{max} are also known as maximum-power current (I_{MP}) and maximum-power voltage (V_{MP}).

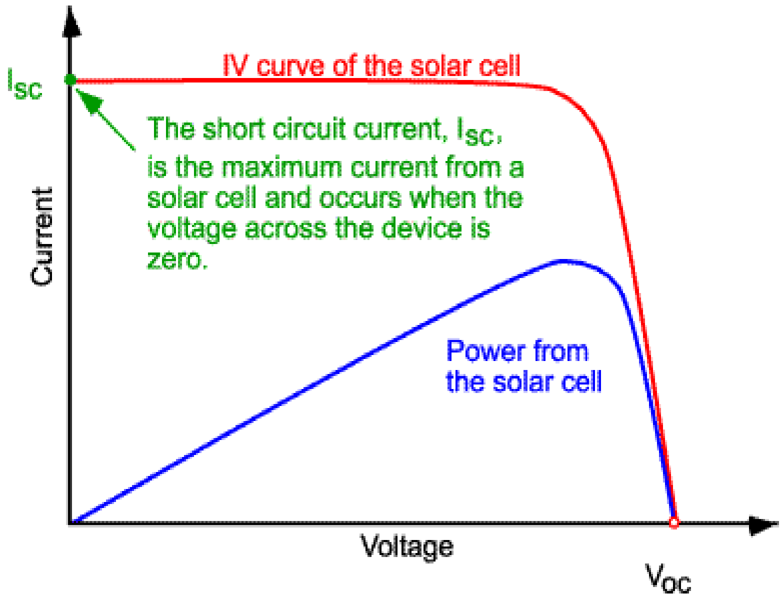


Figure 2:2 – Typical photovoltaic $I - V$ Curve
(Source: www.pveducation.org)

2.3.3 *Photovoltaic Technologies*

The development of solar cells is classified into three generations. Currently, the first generation (mono-crystalline silicon) and 2nd generation (thin-film solar cells) are the two basics classes of photovoltaic modules sold (Luque and Hegedus, 2011). The third generation, mainly dye-sensitised and organic solar cells, are generally in research stage and hence not widely commercialised.

First-generation technology consists of single-junction silicon wafers-based solar cells which includes single-crystal and multi-crystalline silicon (Luque and Hegedus, 2011). In 2007, first-generation solar cells accounted for more than 85% of commercial production. The efficiency of this technology is in the range of 16–22% (Prasad and Snow, 2005). It is well-known that 50% of the cost of these cells is the cost of 200–250 µm thick silicon wafers (Norton et al., 2011). Although research into this generation is currently on-going, they are still too expensive for competitive commercial production. It is likely that the cost reduction trend will reach its limit before the first-generation technology reaches full cost competitiveness.

The second-generation technology, also known as thin-film technology, includes amorphous silicon, poly-crystalline silicon, copper indium gallium selenide and cadmium telluride (Luque and Hegedus, 2011). This technology aims to reduce the cost by eliminating silicon wafers but maintain the efficiency of the first-generation photovoltaic systems. The technology uses only 1–10 µm if active material and absorbs the solar spectrum much more efficiently. These modules show efficiencies of 5–11% (Pagliaro et al., 2010). Although expansion of second-generation technology is slower than expected, it has the potential to reduce the cost of photovoltaic systems in large-scale production.

The last and third-generation of solar cells are the dye-sensitised and organic solar cells. The advantages of these cells over the conventional cells are the low cost production potential due to lower cost of materials, low cost processing and low process temperature (Luque and Hegedus, 2011). However, their efficiencies are also comparatively low, in the range of 3–10%.

2.3.4 Photovoltaic Systems

Although a photovoltaic module consisting of many cells is able to generate electricity, it cannot be used solely and has to rely on a system to produce usable energy output. A photovoltaic system consists of:

a) Photovoltaic array, comprising of modules,
b) Charge controller, to regulate the power from the photovoltaic array,
c) Power storage system, consisting of deep cycle batteries,
d) Inverter, to convert the D.C. power from the array to A.C power,
e) Cables, sensors, physical structure, and
f) Backup power supply or linking to utility grid, if needed. (Prasad and Snow, 2005)

Although the efficiency of the individual solar cells and photovoltaic module is critical in increasing the overall effectiveness of the system, the remaining components known as the Balance of System (BOS) are as important in ensuring that maximum efficiency is obtained and the entire system is functional.

2.4 Building-Integrated Photovoltaic (BIPV)

As discussed in section 1.3, solar photovoltaic is one of the few options to produce electricity with no emission of harmful gas and noise in urban areas. Cities have unique and significant potential to exploit solar electricity due to their large centralised energy demand and physical structure that can support power generation. BIPV is an energy concept in which photovoltaic modules form an integral component of a building. Thus, BIPV can be considered both as a building element and as an electricity generator from sunlight.

2.4.1 BIPV Systems

BIPV systems are installed as stand-alone or grid-connected systems. The types of systems utilised can consist of (a) sloping roof systems, (b) flat roof systems, (c) façade systems wherein the modules replace large glass surfaces and (d) integrated systems as façade accessories in which the modules are arranged as shading or solar protection systems. First-generation (mono or poly crystalline) cells are usually integrated with roof covering, together with standard roof tiles (see Figure 2:3). They have also been utilised as facades, replacing traditional glass as windows, by having gaps among the silicon wafers to allow direct sunlight to pass through. As seen in Figure 2:4, these solar cells are typically opaque, unique shadows are formed in the spaces of the building interior, which are ever-changing throughout the entire day.

Figure 2:3 – Example of rooftop application of opaque photovoltaic modules
Source: (Pagliaro et al., 2010, pp. 61)

Figure 2:4 – Example of skylight application of spaced-out opaque wafer modules
Source: (Petter Jelle et al., 2012, pp. 72)

In recent years, the introduction of semi-transparent photovoltaic modules such as thin-film and dye-sensitised solar cells has helped to provide homogeneous daylighting of interior spaces. These semi-transparent cells are highly suited for shading elements, facades and roof windows. They are also available to replace windows and glazing elements in warm facades and roof elements.

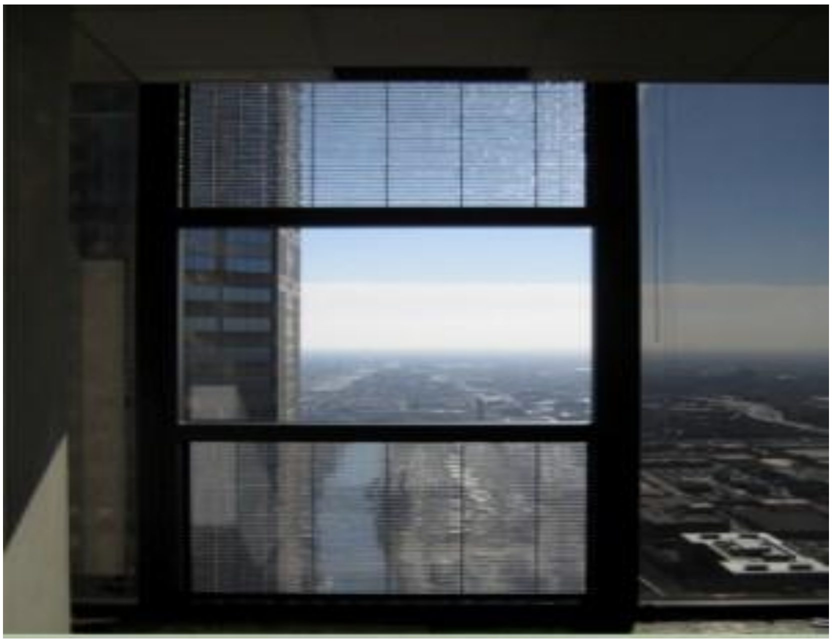


Figure 2:5 – Indoor view of a semi-transparent BIPV window
Source: http://www.solarchoice.net.au/blog/solar-pv-windows-bipv-building-integrated-photovoltaics-technology-by-pythagoras-solar/

2.4.2 Benefits of BIPV

Identifying the potential of BIPV is critical to the construction industry as it can severely affect the decision-making process. While some of the advantages can be quantified in monetary terms, there are others which are very subjective and different stakeholders might place differing values on them. The broad categories of these benefits are: (1) electrical, (2) environmental, (3) architectural/visual and (4) socioeconomic. These benefits are summarised in Table 2:1.

Table 2:1 – Summary of benefits which can add value to BIPV systems

Category	Potential Values
Electrical	kWh generated; kW capacity value; peak generation and load matching value, reduction in demand for utility electricity; power in times of emergency; grid support for rural lines; reduced transmission and distribution losses; improved grid reliability and resilience; voltage control; smoothing load fluctuation; filtering harmonics and reactive power compensation
Environmental	Significant net energy generator over lifetime; reduced air emissions of particulates, heavy metals, CO_2, NO_x, SO_x resulting in lower greenhouse gases, reduced acid rain and lower smog levels; reduced power station land/ water use; reduced impact on urban development; less nuclear safety risks
Architectural	Substitute building component; multi-functional potential for insulation, water proofing, fire protection, wind protection, acoustic control, daylighting, shading, thermal collection and dissipation; aesthetic appeal through colour, transparency, non-reflective surfaces; reduced embodied energy of the building; reflection of electromagnetic waves; reduced building maintenance and roof replacements
Socio-economic	New industries, products and markets; local employment for installation and servicing; local choice, resource use and control; potential for solar breeders; short construction lead-times; modularity improves demand matching; resource diversification; reduced fuel imports; reduced price volatility; deferment of large capital outlays for central generation plant or transmission and distribution line upgrades; urban renewal; rural development; lower externalities (environmental impact, social dislocation, infrastructure requirements) than fossil fuels and nuclear; reduced risk of nuclear accidents; symbol for sustainable development and associated education; potential for international cooperation, collaboration and long-term aid to developing countries

Source: "Added Value of PV Power systems", Report IEA PVPS T1-09:2001, pp. 21

2.4.3 Factors Affecting the Electrical Performance of BIPV modules

As electricity generation heavily depends on a module's exposure to sunlight, adverse conditions such as shading can result in loss of energy output (Norton et al., 2011). Photovoltaic modules are an interconnection of individual solar cells in series to achieve higher voltages. However, even if only one cell is shaded, electrical mismatching can occur resulting in a lower overall current and power output. The exposed cells will force more current through the shaded ones, resulting in a temperature increase of the shaded cells (known as "hot-spots"). In extreme cases, the voltage across the shaded cells can increase beyond the so-called cell breakdown voltage causing the cells to fail (Kovach and Schmid, 1996).

The prevailing standards for the performance measurement of PV modules generally follow the IEC standards (IEC 61215 and 61646). The testing is performed under Standard Test Conditions (STC): irradiance of 1,000 W/m^2, solar spectrum of AM 1.5G and a module temperature of 25°C (IEC, 2007). In actual, BIPV applications, there are several conditions that can affect the performance output of the systems. Higher module temperatures, shading and exposure to diffuse irradiance (rather than direct beam radiation as in the STCs) are often experienced by BIPV systems (Norton et al., 2011). In addition, previous studies, conducted in both sub-tropical and tropical climates such as Hong Kong and Singapore, have also shown that BIPV modules can reach peak temperatures of between 44–50°C during the day (Ye et al., 2013, Chow et al., 2009, Fung and Yang, 2008). Temperatures above the 25°C stipulated in the STCs can result in significant reduction in performance and efficiency (Mondol et al., 2007, Sugiura et al., 2003, Kato et al., 2002, Iliceto and Vigotti, 1998).

The performance of modules installed on-site can differ by up to 25–30% compared to a system under ideal conditions, due mainly to shading losses derived from the difference of insolation on shaded and unshaded parts of a photovoltaic array (Omer et al., 2003, Decker and Jahn, 1997, Gross et al., 1997). Shading loss may be attributed to the diffuse component of irradiance being different on different modules (Gonzalez, 1986) or obstruction by other arrays or nearby urban features and objects such as trees or structures or the building's own fittings (Clarke et al., 2008, Reinders et al., 1999, Alonso et al., 1997). In general, performance of BIPV modules can be influenced by parameters such as shading and system configuration that hinders direct irradiance (Yoon et al., 2011, Roman et al., 2008, Yoo et al., 1998).

2.4.4 Multifunctional Performance of BIPV Windows

Building-Integrated Photovoltaic (BIPV) windows have been proposed by many as an innovative and emerging glazing technology for use in the construction industry (Chow et al., 2010, Norton et al., 2011, Wong et al., 2008). When fully integrated through proper design, BIPV windows have the capability to displace conventional building façade materials while retaining their traditional functional roles and also providing the additional benefit of electricity generation. The effects of integrating photovoltaic glazing systems however have to be analysed from three main aspects: thermal and optical performance and electricity production.

Current research includes studies which have considered the design and use of semi-transparent BIPV windows through experimental and modelling approaches. With respect to total building energy consumption, Li et al. (2009) reported research findings on semi-transparent BIPV applied on buildings' facades. Li et al. (2009) and Miyazaki et al. (2005) studied the thermal, visual and electrical properties along with the financial aspects of a semi-transparent photovoltaic facade. Physical field measurements were conducted to determine the module's critical parameters before a generic high-rise office building was modelled as a case study using Hong Kong's recorded weather data. It concluded that the annual electricity benefit amounted to 12% of the annual building electricity expenditure. With that result, the simple payback period was estimated to be approximately 15 years. Miyazaki et al. (2005) undertook a simulation study to find the optimum transmittance of semi-transparent solar cell and to estimate possible energy savings of office buildings by considering the heating and cooling loads, daylighting and electricity production. A double-glazed semi-transparent amorphous silicon solar module was adopted for the study which was performed under the climatic conditions of Tokyo, Japan. They reported that the minimum electricity consumption in the building was achieved with 40% solar cell transmittance and 50% Window-to-Wall Ratio (WWR) and the energy savings achieved was 54%.

The impacts of integrating semi-transparent PV, in terms of electricity production and reduction of cooling load in Middle Eastern (Radhi, 2010, Bahaj et al., 2008) and sub-tropical (Chow et al., 2010) climates have been explored and discussed previously. Radhi (2010) performed an energy simulation of façade-integrated photovoltaic systems applied to a commercial building in United Arab Emirates. He found that the interaction between photovoltaic modules and the thermal performance of buildings in addition to the photovoltaic output made a significant difference. He also observed that the reduction in the building operational energy was in the range of 1.1–2.2% and this was largely due to the reduction in heat gain and cooling load. Bahaj et al. (2008) investigated the implications of emerging glazing technologies including semi-transparent thin-film photovoltaic, for energy control of highly glazed buildings in Middle Eastern climates, where it is largely tropical and cooling energy demand dominated. The thermal simulations conducted estimated that the current thin-film technology could reduce a room's cooling load by 31% and the future photovoltaic technology could possibly enable a façade to supply the air-conditioning load entirely and provide surplus energy for other uses.

An experimental study using a test chamber in Hong Kong undertaken by Chow et al. (2010) evaluated the energy performance of four different configurations of photovoltaic glazing systems: single glazing, double glazing, natural ventilating and force-ventilating, with single absorptive glazing being used as the standard benchmark. The results showed that photovoltaic glazing with 10% transmittance can effectively reduce direct solar transmission and excessive glare. On air-conditioning demands, the reduction in power consumption was 26% and 82% for single-pane and forced-ventilation cases, respectively.

In another study conducted in Hong Kong, Fung and Yang (2008) investigated the semi-transparent BIPV's thermal performance. Semi-transparent photovoltaic modules which maintain transparent gaps between opaque solar cells were studied and they introduced and verified a model to predict the thermal performance of such glazing through a calorimeter box. Using a parametric analysis the solar cell ratio, efficiency and module thickness were studied. They found that solar heat gain is a major component of the total heat gain, which was significantly affected by the area of the opaque solar cell.

Currently, research on the multi-functional effect of semi-transparent BIPV on the total energy balance is limited. Taking a life cycle approach examining the operational benefits as well as resource costs associated with BIPV for optimum application of such technology is critical. It is crucial to consider all the life cycle stages and potential effects in each stage in order to ensure that the environmental performance of the BIPV is optimised across its life cycle (Crawford, 2011). PV technology is considered “clean” and has no environmental effects as it is directly generating electricity from solar energy. However, during its life cycle, it actually consumes a large amount of energy and emits some Greenhouse Gas (GHG) during some stages such as solar cell manufacturing process, module assembly, balance of system (BOS) production, transportation, system installation and system disposal or recycling (Peng et al., 2013). Hence to accurately investigate the performance of BIPV systems, life cycle assessment should also be conducted to evaluate their impacts during its entire life cycle. This is discussed in the next section.

2.4.5 Implications of BIPV application

BIPV’s application could also result in negative impacts. One such implication is the urban heat island effect which is an environmental issue. It is a phenomenon where air temperatures in built cities are higher than suburban rural areas (Wong and Yu, 2005). This is mainly due to the absorption of solar radiation by mass building elements during daytime, which is subsequently re-radiated to the surroundings at night thereby increasing ambient temperatures.

To date, only a few literature presents findings relating to BIPV's effects on urban heat island effect. On large scale deployment of opaque solar photovoltaic arrays, Taha (2012) and Genchi et al. (2003) indicated that there is no negative impacts on air temperature and urban heat island in cities such as Los Angeles and Tokyo. On a building scale, Tian et al. (2007) examined the effects of opaque PV roof and façade on the building surface temperature and surrounding air temperatures. He reported that although the building surface temperatures changes significantly, there is little effect on the urban air temperature in the microclimate of Tianjin, China.

Second is the effect on thermal comfort of buildings where BIPV systems are installed. Occupants sitting near windows often experience thermal discomfort. Thermal comfort in perimeter zones can be affected by climatic conditions, indoor temperature, mean radiant temperature (Bessoudo et al., 2007). In warm climates, the temperature of photovoltaic modules can reach in excess of 45°C (Tina et al., 2013, Ye et al., 2013). Tina et al. (2013) also studied the thermal sensation of Italian occupants sitting or standing near BIPV systems and reported that it corresponded to a slightly uncomfortable but acceptable condition.

2.5 Life Cycle Assessment

Buildings often last 30–50 years or even longer and key decisions relating to their energy performance need to be 'future-proofed' against long-term economic and environmental changes (Georgiadou et al., 2012, Crawford, 2011). As such, a major implication arising from adopting a long-term view in designing for energy efficient buildings is the need to adopt a full life cycle perspective in order to minimise the impact of building solutions over their long lifetime (Hacking, 2009).

Life cycle assessment (LCA) is a tool for systematically analysing environmental performance of products or processes over their entire life cycle, including raw material extraction, manufacturing, use, and end-of-life disposal and recycling. Hence, LCA is often considered a "cradle-to-grave" approach in evaluating environmental impacts (Joshi, 1999, Ciambrone, 1997)

International Organisation for Standards (ISO 14040 and 14044) provides a generic framework for LCA (ISO, 2006a, ISO, 2006b) as shown in Figure 2:6. The goal and scope definition describes the underlying question (objective of the study), the system being considered, its boundaries and the definition of a functional unit. The flows of materials, resources and pollutants, are recorded in the inventory analysis. These elementary flows are characterized and aggregated, for different environmental problems, in the impact assessment stage and conclusions are drawn in the interpretation stage. Therefore, LCA is a structured and comprehensive method of quantifying material- and energy-flows and their associated emissions in the life cycle of products that can include goods or services.

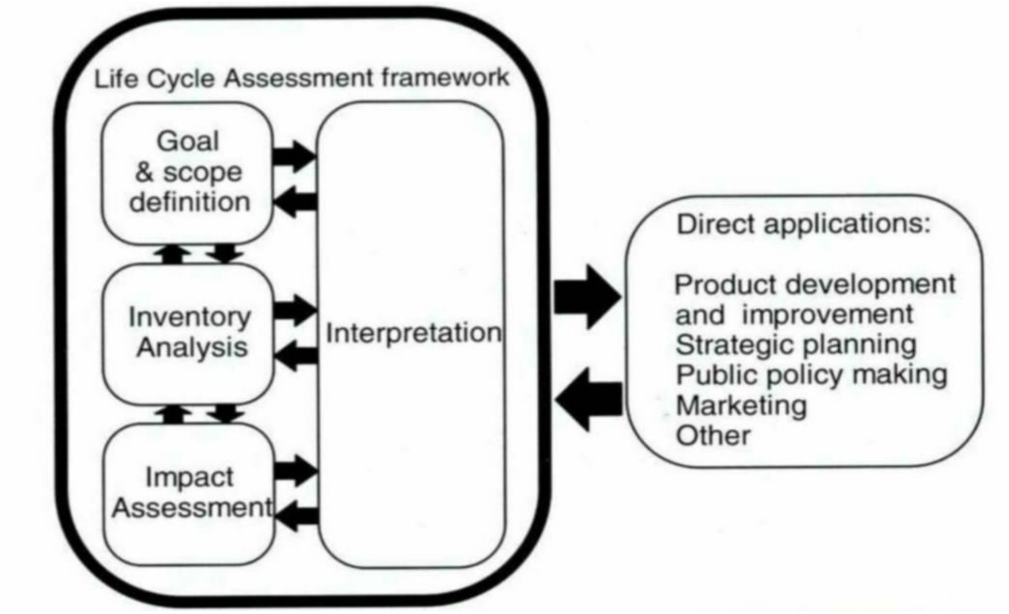


Figure 2:6 – Life-cycle assessment framework

Source: (ISO, 2006a), ISO 14040: Environmental management: life cycle assessment : principles and framework = Management environnmental : analyse du cycle de vie : principes et cadre, pp. 8

Although the LCA concept appears to be simple and straightforward, the processes involved are highly data-intensive exercises, requiring combining data from multiple, disparate, often proprietary sources, resulting in high costs, uncertain quality and significant time investment (Joshi, 1999). Users of LCAs often limit the boundary of analysis as a way to make the system easier to assess, and in most inventories, detailed assessment is made of resource uses, environmental releases from the main production processes, and important contributions from suppliers of inputs into the main processes (Singh et al., 2011). However, decisions about the cut-off criteria for exclusion of certain processes and inputs and how to minimise the resulting error are difficult to make scientifically. Such decisions may compromise research and objectivity and the reliability of results. In fact, the majority of variations observed in comparative studies have been shown to arise from differences in system boundaries which results in significant scepticism about LCA results (Suh et al., 2003). Although due to the many assumptions and variation LCA data are not absolute values, it provides a tool for quantification of environmental impacts through the life cycle of the product.

As identified by Singh et al. (2011), a review of recent literature suggests a rising interest in incorporating LCA in building construction decision-making and such applications can be for building materials selection or construction systems and process evaluation. The objective of LCA studies in building materials is to enable selection of environmentally preferred materials and products by identifying sources of the most significant environmental impacts. As for construction and process, the evaluation involves more than simple aggregation of individual product and material assessments. Efforts attempting to assess complete buildings, systems and construction processes have often identified life cycle phases with the most environmental impacts and have provided a basis for overall building system assessment.

2.5.1 LCA for BIPV

Although the generic framework of LCA has long been established, it was only recently that a methodology guideline specifically for LCA of photovoltaic electricity was introduced and published (Fthenakis et al., 2011). Guidance includes, photovoltaic-specific parameters used as inputs in LCA, choices and assumptions in the life cycle inventory data analysis and implementation of modelling approaches. The integration of semi-transparent BIPV in any building to promote sustainability needs to be based on both financial and environmental implications including minimizing GHG emissions and energy consumption (Georgiadou et al., 2012).

Energy-conscious design should consider the potential energy-related life cycle impacts of semi-transparent BIPV. Depending on the goal and scope, the system boundary considered could be either “cradle to cradle” or “cradle to grave”. The main design criteria within life cycle energy assessment include embodied energy, operational energy assessment and deconstruction. Embodied energy is the energy used to extract, process, manufacture and transport the finished material to the site. The embodied energy of semi-transparent BIPV has been studied previously (Kim et al., 2012, Perez and Fthenakis, 2011).

The recommended specific indicators of life cycle performance are greenhouse gas emissions and (GHG) and cumulative energy demand (CED). GHG emissions during the life cycle stages of photovoltaic systems are estimated as an equivalent of CO_2 (denoted as $kgCO_2eq$) using an integrated 100-year time horizon from the global warming potential factors published by the Intergovernmental Panel on Climate Change (IPCC) (Forster et al., 2007). The CED describes the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or service. The energy sources in the CED indicator result include fossil, nuclear, biomass, hydro, primary forest, wind and solar. The impact indicators can be further processed into GHG emissions intensity of photovoltaic electricity, energy payback time (EPBT) and energy return on energy investment (EROEI). EPBT, measured in years, can be calculated relative to the average grid electricity currently used in any country. EROEI, expressed as energy generation per unit of energy input, denotes the units of energy for each unit invested in the production process.

There have been many LCA studies on photovoltaic systems. In a recent LCA review of five common photovoltaic system technologies (mono-Si, multi-Si, a-Si, CdTe thin-film and CIS thin-film), Peng et al. (2013) discussed them in terms of energy requirement, energy payback time (EPBT) and greenhouse gas (GHG) emission rate during whole life cycle. It was concluded that mono-Si photovoltaic system demonstrates the worst environmental performance due to its high energy intensity during the manufacturing and production processes. It was also determined that in general, the EPBT of mono-Si photovoltaic systems ranged from 1.7 to 2.7 years with GHG emissions rate between 29–45 gCO_2eq/kWh. The EPBT and GHG emission rate of thin-film photovoltaic systems were within 0.75–3.5 years and 10.5–50 gCO_2eq/kWh, respectively. This finding encourages the adoption of semi-transparent BIPV as mono-Si photovoltaic modules are opaque in nature whereas thin-film technology allows the modules to be semi-transparent.

In a study of roof-mounted BIPV in the UK, Hammond et al. (2012) used an integrated approach to evaluate the environmental and economic feasibility of a 2.1kWp system, with mono-Si modules. He estimated the EPBT to be 4.5 years with an EROEI of 4.6 considering a 25 years BIPV system lifetime. The study also estimated a carbon payback period of 4 years and a “carbon gain ratio” of 5:1. However, the prevailing market conditions were not conducive for BIPV system to break even in economic terms, which clearly demonstrated the importance of government support schemes to promote uptake of BIPV in the UK. In the US, Keoleian and Lewis (2003) evaluated BIPV energy and environmental performance relative to conventional grid electricity and building materials. They concluded that for a 2 kWp roof-mounted BIPV installation using thin-film modules, the EPBTs are between 3.39–5.52 years for 15 selected cities. They also observed shorter EPBT values for cities with higher insolation.

In sub-tropical Hong Kong, a 22 kWp roof-mounted BIPV system with mono-Si modules was analysed in terms of energy and emissions payback time (Lu and Yang, 2010). The results showed that the EPBT of the BIPV system was 7.3 years and the GHG payback time was 5.2 years, with respect to fuel mix of local power stations. The research further extended to discuss the EPBTs for different orientations, ranging from 7.1 years (for optimal orientation) to 20.0 years for a west-facing vertical BIPV façade. Lim et al. (2008) performed a study on the environmental benefits and technical impacts of installing roof-mounted BIPV systems in Malaysia. Using a 1 kWp BIPV system with three different PV technologies (mono-Si, multi-Si and thin-film), he examined the energy performance and implications of installing at various locations in Malaysia. He estimated that the EPBT values were 3.2–4.4, 2.2–3.0 and 1.9–2.6 years for mono-Si, multi-Si and thin-film modules, respectively. It was also highlighted that the high embodied energy of Malaysian BIPV systems were due to the logistics of importing components which also resulted in higher costs.

A couple of studies have considered façade integration of BIPV with different technologies. Oliver and Jackson (2001) examined the energy costs of supplying electricity in Europe and included the use of an avoided cost technique to illustrate the benefit of adopting BIPVs. The façade mounted multi-Si modules were estimated to require 2.9 MJ/kWh as embodied energy. The EPBT and EROEI were 5.5 years and 4.5 respectively. When the embodied energy of conventional glass cladding system was deducted from the BIPV as an avoided burden, the BIPV net embodied energy value was reduced to 2.6MJ/kWh. With the net BIPV embodied energy, the EPBT was reduced to 4.8 years while EROEI increased to 5.2.

In the US, Perez and Fthenakis (2011) investigated the actual performance of a 11.3 kWp BIPV mono-Si façade system and its environmental footprint was extrapolated to other façade systems by means of performance ratio and avoided building materials. They reported the system's EPBT and EROEI to be 3.81 years and 7.2 respectively. The GHG emissions rate was 60.5 gCO_2eq/kWh.

2.6 Life Cycle Cost Assessment

View over a 30-year period, initial costs can account for approximately just 2% of the total, while operations and maintenance costs equal 6%, and personnel costs equal 92% (Romm, 1994). Recent studies have also shown that green building measures implemented during construction or renovation can result in significant building operational savings and hence, building-related costs are best revealed and understood when they are analysed over the life span of a building (USGBC, 1996).

One of the barriers to the widespread adoption of PV systems is their high capital cost compared to conventional sources. Building owners are often price-sensitive and if they are not convinced that BIPV systems can actually make economic sense, the impact made by the PV market will be rather modest (Cavallaro, 2010). However, their decisions are often based on initial cost that does not consider maintenance and replacement costs in use or the effect of future increases in electricity prices. A way to change the current scenario will be to consider the long-term energy costs including the savings in electricity (Silva et al., 2010).

Life cycle cost analysis (LCCA) is an economic application based on the LCA concept to determine the cost implications of building materials over their lifetime (Kirk and Dell'Isola, 1995). However, unlike LCA, which considers time as stable, and assess the system impacts based on current knowledge, LCCA includes the ability of money to accrue interest and grow in value over time. Parallel with the ISO LCA framework, it provides valuable information for evaluating an investment, as the solution with the lower life cycle cost is the one that delivers the greater value (Kneifel, 2010). This means that although upfront costs may be higher for a building solution, the life cycle cost may be lower due to reduced running costs, maintenance costs or replacement costs. In particular, when assessing energy conservation or renewable energy projects which increase the initial capital costs, LCCA can determine whether or not these projects are economically justified from the investor’s viewpoint, based on reduced energy costs and other cost implications over the project life or the investor's time horizon (Fuller and Petersen, 1996).

Several studies have attempted to evaluate BIPV economically, in order to assess the viability of solar photovoltaic application in buildings. In New Delhi (India), a LCCA evaluated that the unit cost of electricity for roof-mounted BIPV systems were approximately 20% lower than stand-alone photovoltaic systems (Chel et al., 2009). The effects of carbon credit to reduce unit cost of electricity from the systems were evaluated to be a further 20% which paved the way for a discussion on such schemes as one of the policy issues for promotion of renewable energy systems.

Oliver and Jackson (2001) compared the cost of electricity supply from a BIPV cladding system and a conventional electricity supply mix in Europe. Using an avoided cost technique that considered the avoided economic costs associated with a conventional glass cladding system, the unit electricity costs for a BIPV system decreased by over 50%. As the investigated BIPV system was significantly more expensive than conventional sources, government subsidies or policies had to be placed to ensure its viability due to their potential to supply electricity that uses significantly less primary energy than conventional electricity mixes.

In the UK, Hammond et al. (2012) concluded that BIPV systems were not expected to break even over its assumed 25-year lifetime under present market conditions. Under normal base case conditions, the investigated roof-tiled BIPV systems' payback was estimated to be between 26 to 54 years, depending on the range of capital costs and electricity output. When evaluated with new feed-in tariffs, the situation improved significantly to 15 years, which demonstrated the importance of the new government tariffs support scheme to the future uptake of BIPV, along with the need for technical innovation and application in the next generation of photovoltaic technologies.

2.7 PV Integration during Building Design

2.7.1 Early design stage decision

The integration of renewable energy systems, such as BIPV, into a building design should be addressed during the initial conceptual design stage and not considered as a subsequent add-on (Attia et al., 2012). During this stage, architects constantly explore design directions and decisions taken during this stage can determine the success or failure of any BIPV implementation. Furthermore, 20% of all design decisions taken during the early design phases, subsequently influence 80% of all design decisions (Donn, 2009). In an economic study undertaken by Hawken et al. (1999), he concluded that the first 1% is critical because all the important mistakes are often made on the first day of the design process. This is because although upfront design and construction costs may represent only a fraction of the life cycle costs, when just 1% of a project's capital investment cost is spend up, up to 70% of its life cycle cost may have already been committed (Romm, 1994).

PV integration into architecture and the construction industry is an important issue in promoting its use to improve energy efficiency of the building stock. One of the major barriers to overcome is the reluctance of building designers and owners to integrate BIPV in design and construction of buildings (Schoen et al., 1998). Active involvement of architects has been highlighted as essential for the success of PV in buildings and informative collaboration between architects and PV professionals is the key. Photovoltaic can only be included in building projects if architects and developers have sufficient knowledge about the technologies and possess the appropriate design tools to assist them.

2.7.2 Current Stage of Design and Informative Tools

In order to support decision-making during the early design phases, it is essential to include informative conceptual tools that reflect the issues pertaining to the design of BIPV. Despite its importance, most existing informative tools are exclusively serving certain geographical contexts and heating-dominated environments and are not applicable to the tropics (Attia and De Herde, 2011). Also, most of the existing PV tools are simulation software that cater more towards engineers (Attia and De Herde, 2010). These tools are aimed at systems sizing and electricity generation prediction. Although scientific studies involving BIPV have been on the rise in the first decade of this century, they are mainly theoretical/experimental, development and feasibility studies (Quesada et al., 2012). The information available fails in the sense that it is presented neither in a format useful to support design decisions nor include information carriers (such as cost) which determine design decisions.

Decision support tools are required to ensure that PV is considered from the start of the building design process, where the first decisions have a major impact on the possibilities to include them (Schoen et al., 1998). For semi-transparent BIPV, there is also a need to understand parameters that can affect the overall building energy consumption such as reduction/increase of cooling load and admission of daylight. The absence of such holistic design criteria and information in established decision-making tools will inhibit a robust and future-oriented decision-making process at the critical early design stages (UNPD, 2007, Ravetz, 2000).

2.8 Discussion and Identification of Knowledge Gap

In order to promote the optimum use of BIPV systems to further enhance the energy efficient capabilities of buildings, there is a need for knowledge on energy performance that can assist the selection and application of BIPV in the early stages of building design. They should encompass information that not only includes the performance of the BIPV system itself, but also its implications and impacts on the building. Catering to professionals such as architects and building owners, they can include information on long-term economic and environmental impacts, especially since cost is often a deciding factor. Currently, the lack of information on lifetime BIPV performance in tropical settings and LCA-based data severely inhibits the development of any suitable tool in a form that designers can easily comprehend.

The research therefore intends to bridge these gaps and provide a comprehensive understanding in order to quantify the simultaneous effects of solar heat gain reduction, daylighting provision and energy production during application of semi-transparent BIPV windows in the tropics. Current measurements of photovoltaic technology performed under international laboratory standards may not reflect the true conditions during actual building application. In actual façade installations in high density urban areas and tropical conditions, BIPV windows are subjected to shading and also higher temperatures which have not been determined and included in the international standards. As such, performance measurements are preliminary and only reflect the “factory-fitted” quality of BIPV. To ensure that BIPV windows perform to its expected level, they have to undergo performance tests under realistic building conditions. This information could then be translated and integrated into a graphical performance index that can assist architects and designers to evaluate semi-transparent BIPV window’s performance after building integration in early design stages.

The information can then be translated to consider lifetime environmental and economic performances which provide building designers with additional first-hand information on semi-transparent BIPV’s energy efficiency to increase and enhance widespread adoption. With multiple benefits that semi-transparent BIPV offers, it can also be used as a comparison to evaluate and identify the ideal semi-transparent BIPV technology of choice, depending on the criteria of the user.

2.9 Summary

Fenestration is an important component of any buildings as it not only affects the energy efficiency of the buildings, but also serves to satisfy the preference of its occupants. Relating to energy consumption, windows can affect building energy use in many ways. First, artificial lighting can be reduced significantly by the use of natural sunlight which is also generally more preferred by occupants. Second, the thermal properties can affect the indoor cooling/heating load of the building. In hot and humid climates, good heat insulation is necessary to prevent excessive heat gain, as compared to cold climates where the use of sunlight to warm up the interiors is preferred.

Adopting semi-transparent BIPV windows can result in the multi-functional capabilities of windows. Not only do they affect daylighting and heat gain/loss, the semi-transparent BIPV window is also able to generate photovoltaic electricity as a form of renewable energy for on-site use. The urban areas where there are generally more tall buildings, increased façade area and relatively little roof space support the adoption of photovoltaic for windows. As both photovoltaic systems and buildings are long term and capital-intensive investments, their viability should consider their life cycle environmental and economic performance. By evaluating them over their life time, decisions to adopt them can be encouraged and appropriate government policies can also be formulated. To promote the application of BIPV systems, design and informative graphs that can be easily adopted in early stages of building design to aid in decision-making should be available. These tools can aid architects and buildings designers to compare and adopt alternative designs, as well as assist them in convincing building owners in the systems' economic viability.

From the background information along with the identification of knowledge gap as discussed thus far, the next chapter formulates this research study's research methodology.

CHAPTER 3 RESEARCH METHODOLOGY

The previous chapter established the current knowledge and identified a knowledge gap. Here in this chapter, the research methodology of the research study is presented. First, research approach is discussed to provide an overview of the research work. Thereafter, the individual stages of research are explained.

3.1 Research Approach

In order to bridge the knowledge gap in semi-transparent BIPV performance in tropical climatic conditions, a research approach as shown in Figure 3:1 is adopted for this study. It included:

- Experimental investigations of photovoltaic modules in real building conditions to establish their performance parameters,
- Computer simulations of energy performance of office building with semi-transparent PV windows, using Singapore office operational practices and performance parameters established,
- Life cycle assessment of environmental (and cost) performance of semi-transparent BIPV windows based on current PV manufacturing practices, module importations to Singapore and energy performance in office buildings established by computer simulations, and
- Integration of results from the above investigations in a multi-criterion graphical tool that facilitates selection of semi-transparent BIPV windows for multi-storey buildings.

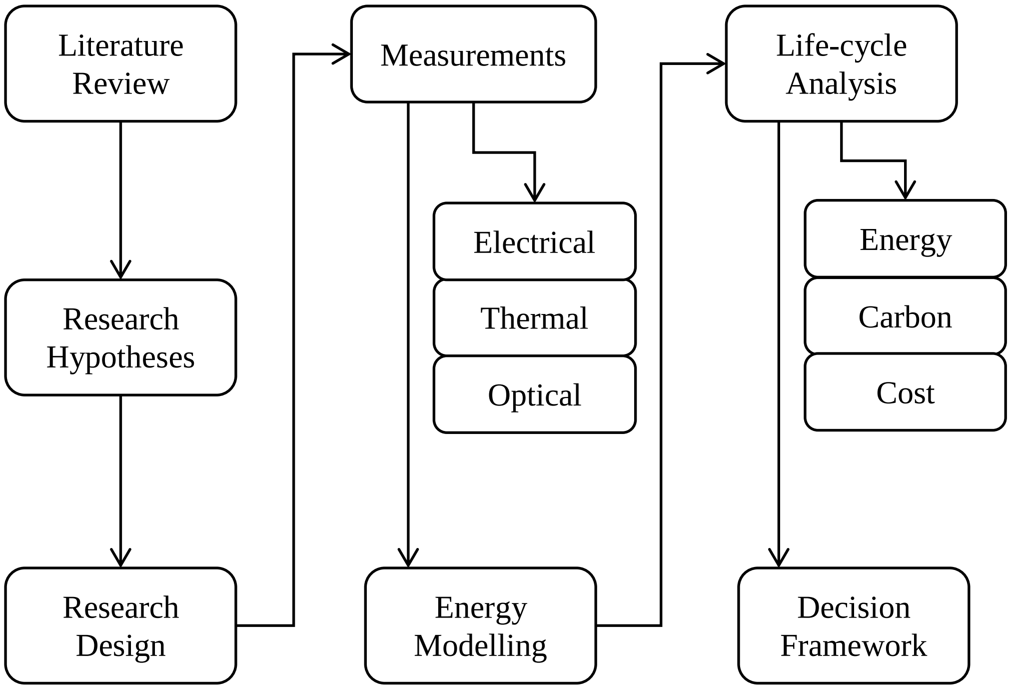


Figure 3:1 – Overview of research approach

The properties of semi-transparent BIPV considered include thermal, optical and electrical properties which have been previously discussed in chapter 2. Thermal measurements included both SHGC and U-value, which are glazing properties, often used to determine thermal effectiveness of traditional glazing systems. Optical measurements were aimed at obtaining the semi-transparent BIPV modules' VLT to evaluate their ability to allow daylight into building interiors in order to reduce the need for artificial lighting. It should also be noted that semi-transparent photovoltaic modules have much lower VLT as increasing it will generally reduce its efficiency. Electrical measurements were performed by placing the modules under conditions such as higher cell temperatures and diffuse lighting which are more realistic during real-life applications in the tropics.

Thermal and optical measurements were required as these properties were not readily available in the manufacturer's data sheets. For those modules that these data were available, a consistent standard was not adopted to establish these along with insufficient information provided on the conditions (summer or winter) used.

The experiments to measure the relevant BIPV properties were performed at the laboratories of Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS) and adhered to relevant international standards (see chapter 4). Measuring all the modules under uniform standards and conditions, ensures that these data were reliable to be adopted for subsequent building energy simulations.

These essential parameters thus established were then used for building energy studies where parametric simulations were conducted. The impacts on the building's cooling energy and required artificial lighting, together with the PV electricity generation, are combined to obtain an index that is capable of quantifying the overall energy benefit of semi-transparent BIPV applications, relative to solid walls and traditional glazing. Parametric studies to vary the orientations and Wall-to-window ratio (WWR) were also performed to identify the best WWR for the various orientations (see chapter 5 for further details).

The third stage included a life-cycle assessment on energy, carbon and costs relating to the adopting semi-transparent BIPV systems in Singapore. First, the annual energy benefits from chapter 5 were adjusted to illustrate the total life cycle energy benefits. Second, data on input-flow processes were obtained from existing literature and *eco-invent* (v2.1) database and modified to cater for local use. Environmental performance evaluation considered both energy and carbon. Third, costs relating to adopting semi-transparent BIPV systems were obtained from local contractors and photovoltaic system integrators. The economic analysis also included local government policies where subsidies are available for the implementation of solar technologies. The economic performance assessed the payback periods after considering the current electricity tariffs. Sensitivity analysis for both environmental and economic performance to consider impacts of relocating module manufacturing locations, shading from nearby buildings and future increase in electricity tariffs were also included. The detailed life cycle assessment is documented in chapter 6.

Lastly, all the findings were then consolidated to develop a performance-based framework. The indicators within the tool include GHG emissions, EPBT, EROEI, capital cost, payback time and VLT. The decision-making tool is in the form of a radar chart acting as a selection matrix and serves to include environmental, economic and occupant preference aspects. This acts as a tool to assist building designers, such as architects in their early building design decisions pertaining to semi-transparent BIPV window application. Users can make their decisions based on their criteria or emphasis on environmental or economic performance. If occupant preference and aesthetic considerations are important, the inclusion of VLT can also assist in picking a choice.

3.2 Selection of BIPV Modules

For this research, ten commercially-available BIPV modules were acquired. They include both single and double-glazed units and consist of different constructions and technologies. Most are made of thin-film solar technologies: amorphous silicon (a-Si), micromorph silicon (µc-Si) and copper indium gallium selenide (CIGS); except for two modules which are of organic (plastic) and poly-crystalline wafer-based silicon (poly-Si). The manufacturers' data sheets for all the modules except the last are compiled in Appendix A. The last module was a laboratory reference module for the electrical measurements (see section 4.1) and hence a manufacture data sheet was not available. The modules' descriptions and specifications are shown in Table 3:1.

Table 3:1 – Module data and specifications of semi-transparent BIPV modules under investigation

Module	Manufacturer (module type)	Module area (m^2)	Maximum Power (W)	Photovoltaic Technology	Construction Assembly	Appearance
A	Hanwa Makmax (KN-50)	0.931	72	a-Si	Single Glass Laminate	Standard
B	Hanwa Makmax (KN-42)	0.93	42	a-Si	Single Glass Laminate	Standard
C	Auria Solar (Micromorph)	1.43	80	µc-Si	Single Glass Laminate	Red
D	Auria Solar (Micromorph)	1.43	45	µc-Si	Single Glass Laminate	Golden
E	Auria Solar (Micromorph)	1.43	60	µc-Si	Single Glass Laminate	Dark blue
F	Solyndra (SL-001-150)	1.97	150	CIGS	Cylindrical Glass Tube	Standard
G	Schott Solar (Voltarlux ASI-ISO-E1.2)	0.843	40.4	a-Si	Double-Glazed Unit	Standard
H	Konarka (KT-800)	0.54	8.3	Organic (plastic)	Flexible Laminate	Golden
I	Spear Technology Alliance (SSM-42S0533Air)	0.931	50	a-Si	Double glazed unit	Standard
J	SERIS RND Reference Module	1.65	170	poly-Si	Glass Tedlar	Blue

Note: a-Si = amorphous silicon; µc-Si = micromorph silicon; CIGS = copper indium gallium selenide

3.3 Measurement Designs

This section provides a brief summary on the measurements conducted to determine the BIPV module performance parameters in tropical conditions experienced in Singapore. Electrical measurements were first performed to study the photovoltaic power output of modules under higher temperatures, different shading patterns and direct/diffuse irradiance. In addition, thermal properties (SHGC and U-value) and optical properties (VLT) of the modules were tested.

3.3.1 Electrical Measurements

Experiments were performed to study the photovoltaic electricity generating capabilities of the semi-transparent BIPV modules by replicating realistic building conditions (see section 4.1 for details) such as higher cell temperatures, exposure to non-uniform irradiance (partial shading) and exposure to diffuse light conditions. The measurements were conducted at SERIS's PV Module and Performance Analysis (PVPA) facility located off-campus at International Business Park's I-Quest building. The testing and analysis facilities and procedures followed in PVPA are in accordance with the following standards:

1) IEC 60904-1:2006 Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics;
2) IEC 61646:2008 Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval; and,

3) IEC 61215:2005 Crystalline silicon terrestrial photovoltaic (PV) modules – design qualification and type approval.

Equipment and Instrumentation

The equipment and instrumentation used in the electrical measurements are tabulated and summarised in Table 3:2. The entire system was designed and installed by PASAN ® Measurement System.

Table 3:2 – Equipment and instrumentation used at SERIS PVPA facility

<table>
<tr><th>Equipment/ Instrument</th><th>Model</th><th>Accuracy/ Standard</th></tr>
<tr><td>Solar Simulator</td><td rowspan="2">SUNSIM 3B</td><td rowspan="2">Irradiance Non-uniformity (≤1.0%)
Pulse instability (≤ 1.0%)
Spectral Distribution (≤1.0%)
Overall IEC Standard = Class A</td></tr>
<tr><td>Data Acquisition Unit</td></tr>
<tr><td>PC with Operating Software</td><td>Custom-built with pre-installed software</td><td>Standard PC</td></tr>
<tr><td>PV mount in temperature-controlled chamber</td><td>Custom-built</td><td>25°C–85°C</td></tr>
</table>

Experimental Layout

A schematic section of the laboratory setup is shown in Figure 3:2. Mounting structures for photovoltaic modules were housed within a chamber where the ambient temperatures can be controlled. The semi-transparent BIPV modules were mounted in the sample holder within 5° normal to the centre line of the solar flasher's beam. They were then connected to a control unit consisting of an electric load and the data logger, which was co-located at an adjacent space. Temperature in the controlled chamber could be used to adjust the module temperature, which was measured through thermocouples mounted evenly at the back of the PV module.

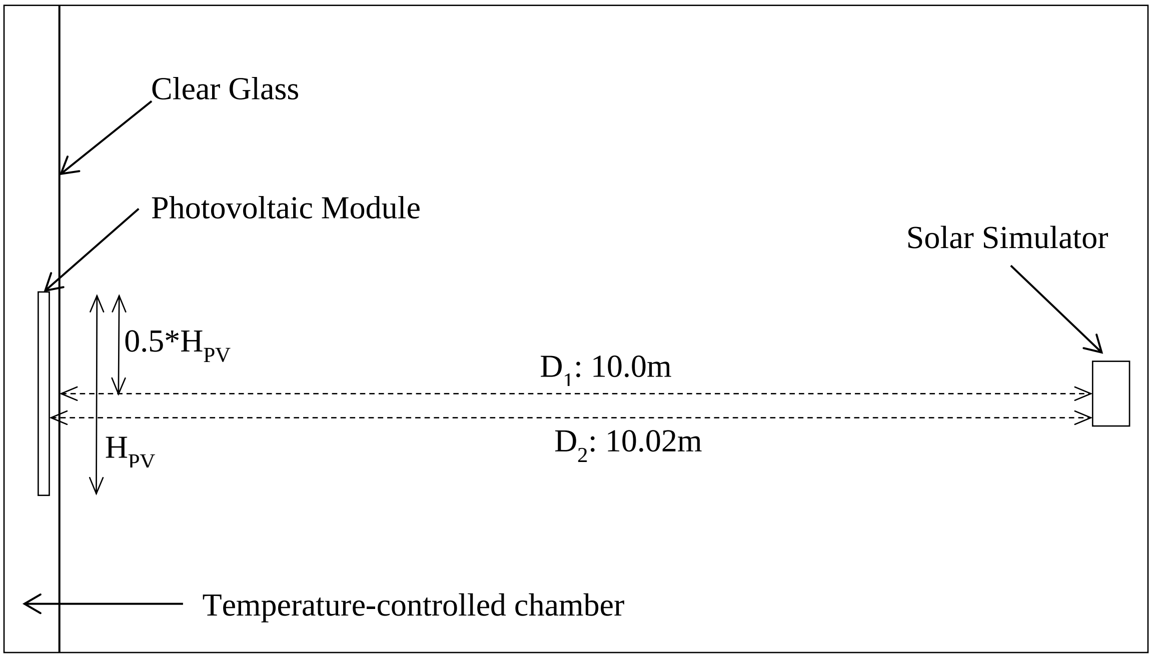


Figure 3:2 – Schematic diagram of laboratory setup for electrical measurements

Note: H_{PV} – Photovoltaic module height, D_1 – Distance between solar simulator and chamber glass, D_2 – Distance between solar simulator and PV module

3.3.2 Thermal Measurements

Thermal measurements, for both U-value and SHGC, were performed with the calorimetric hot box laboratory set up at SERIS (for details refer to section 4.2). There are three major equipment in the thermal laboratory: a solar simulator, an automated XZ scanner and a guarded hot box. These equipment are remotely controlled by a software developed within the LabVIEW environment. The laboratory equipment and measurement procedures are in accordance and comply with the following standards:

1) ISO 8990 Thermal Insulation – Determination of Steady-State Thermal Transmission Properties – Calibrated and Guarded Hot Box;
2) ASTM C1363 Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus;
3) ASTM C1199 Standard Test Method for Measuring Steady-State Thermal Transmittance of Fenestration Systems using Hot Box Methods;
4) ASTM E1423 Standard Practice for Determining Steady-State Thermal Transmittance of Fenestration Systems;
5) NFRC 102 Procedure for Measuring the Steady-State Thermal Transmittance of Fenestration Systems; and,
6) NFRC 201 Procedure for Interim Standard Test Method for Measuring the Solar Heat Gain Coefficient of Fenestration Systems using Calorimetric Hot Box Methods.

Equipment and Instrumentation

The equipment and instrumentation used in the thermal measurements are tabulated in Table 3:3.

Table 3:3 – Equipment and instrumentation for SERIS thermal laboratory

Equipment/ Instrument	**Model**	**Accuracy/ Standard**
Solar Simulator	ARRIMAX 18 kW HMI Lamp Lighting System	AAA
Automated XZ Scanner	Kipp&Zonen CMP11 Pyranometer	AAA
Guarded Hot Box	Custom-Designed and Local-Built Consisting of Metering Box, Guarding Box and Climate Box	-

Experimental Layout

Full-scale measurements were conducted in the thermal chamber located at Level 4, Block E3A, SERIS, NUS. The thermal laboratory is co-located with an adjacent control room where measurement procedures are controlled and data collected is processed and stored. The configuration and layout of the thermal laboratory is illustrated in Figure 3:3.

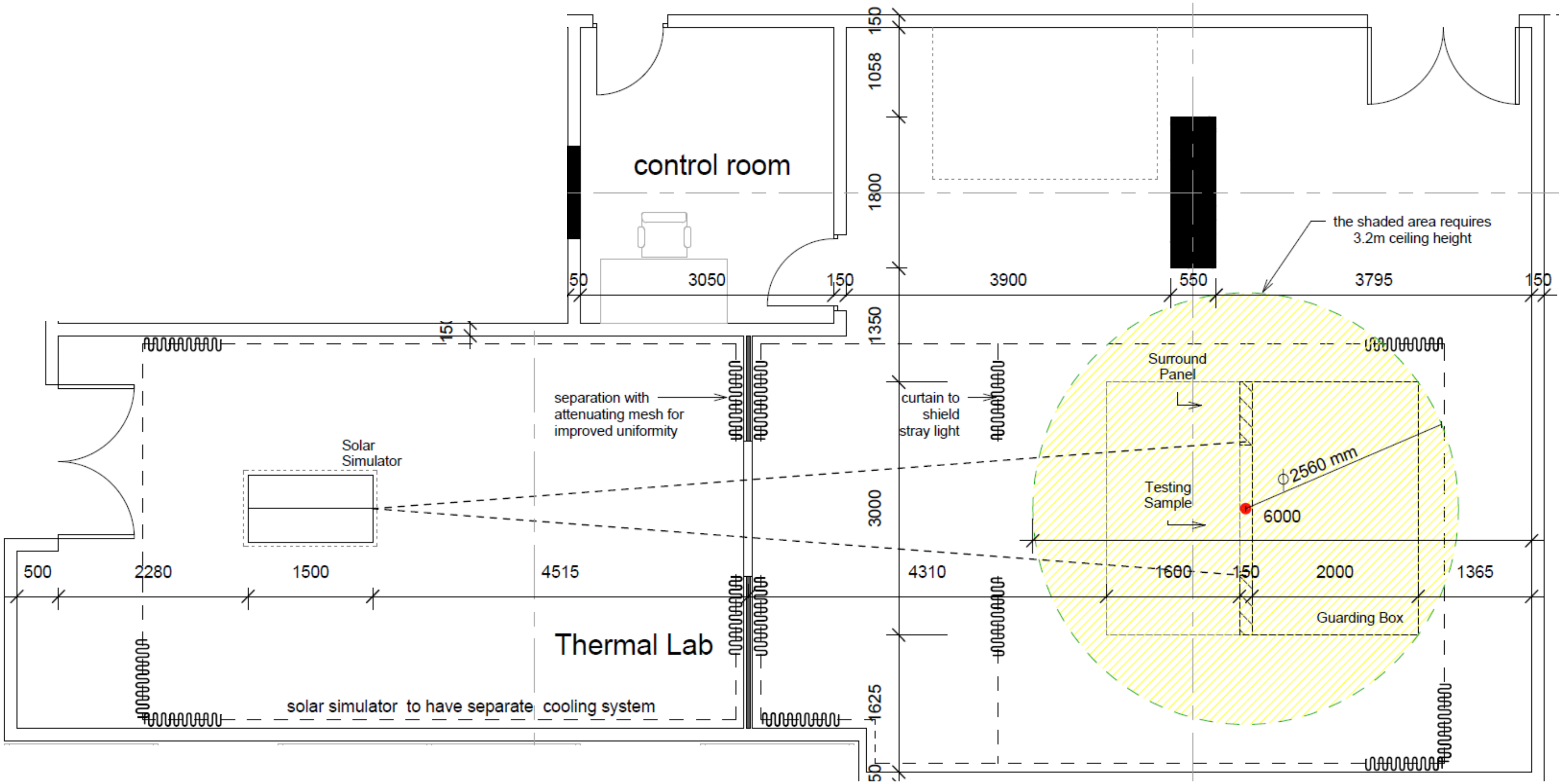


Figure 3:3 – Layout of SERIS thermal laboratory

3.3.3 Optical Measurements

The purpose of the optical measurements was to capture the visible light transmittance of the semi-transparent BIPV modules which were used in the building energy simulations to determine the artificial lighting requirements (see chapter 5). An integrating sphere was used for the measurements which took place in SERIS's gonio-photometer laboratory. The test method is in line with the following standards:

1) ASTM E1175 Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials using a Large Diameter Integrating Sphere; and,
2) ASTM E903 Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials using Integrating Spheres.

The equipment and instrumentation used for the optical measurements are shown in Table 3:4.

Table 3:4 – Equipment and instrumentation of SERIS integrating sphere

Equipment/ Instrument	**Model**	**Accuracy/ Standard**
Integrating Sphere	IFT Rosenheim 1.25m diameter	DIN 5063-3*
Illumination Equipment (Light Source)	24V/ 250W Halide Lamp, Projector with Parallel Beam Illumination	Standard Illumination A
Detector	Radio/ Photometer 211	Lux meter Class A

*DIN 5063-3 Radiometric and photometric properties of materials: methods of measurement for photometric and spectral radiometric characteristics

3.4 Building Energy Simulations

Simulations were performed to estimate the impacts of semi-transparent BIPV application, on building energy consumption. Singapore's typical meteorological year data was used to determine a commercial buildings' energy use on artificial lighting, cooling electricity usage and photovoltaic electricity generated when installed with semi-transparent BIPV modules. The inputs of the BIPV modules' were based on the electrical, thermal and optical measurements performed. Different orientations and WWR (10–100%) were also included as part of the parametric simulation study.

EnergyPlus was chosen as the simulation software as it is capable of modelling the multi-functional role of semi-transparent BIPV. *EnergyPlus* is a building simulation software developed by the United States Department of Energy which includes various program modules that enable the simulation of cooling-heating loads, daylighting and photovoltaic systems. It is capable of calculating hourly heating and cooling loads of buildings by the heat balance method. It takes into account all heat balances on outdoor and indoor surfaces and transient heat conduction through the building fabric. It is more accurate than the weighting factor method, which is used in precedent thermal loads calculation software such as DOE-2, because it allows the variation of properties with time steps (Strand et al., 1999). Simulation results of *EnergyPlus* have also been validated through analytical, comparative and empirical tests (Witte et al., 2001; Olsen et al., 2003). While *EnergyPlus* is able to handle simulations such as controllable window blinds, electrochromic glazing, layer-by-layer heat balances that allow proper assignment of solar energy absorbed by window panes, it includes a performance library for numerous commercially available windows.

The most restricting limitation of *EnergyPlus* is the lack of a graphical user interface. The lack of a complete, simple but flexible interface inhibits a smooth and convenient user input (Maile et al., 2007). To overcome this limitation, an *EnergyPlus* plugin for Google's *SketchUp* is used to first draw the building geometry before adding on the rest of the building systems (Ellis et al., 2008). The other limitation is the building model warm-up period. The engine simulates the first day multiple times (as determined by user) until either a tolerance is met or a certain number of attempts has passed. Although this is a reasonable approach for design simulation, insufficient model warm-up can lead to errors in simulation (Maile, 2010). As such, the simulation study included the maximum period of 25 days and the building model's thermal mass was also investigated to ensure that it did not affect the accuracy of the simulations (see section 5.4). The detailed modelling procedures and results are discussed in chapter 5.

3.5 Life Cycle Assessment

Results from the parametric analyses (see chapter 5) were adopted and used for conducting a LCA study to determine the semi-transparent BIPV systems' long term performance. From the simulation study, the 90% WWR was considered to be the most practical and optimized performance. The annual simulation results were used to determine the 25-year life time energy benefit to determine the environmental and economic performance in terms of energy, carbon and costs.

The IEA framework for BIPV LCA assessment (see section 2.6) was used with *eco-invent* (v2.1) database (Jungbluth et al., 2009; Frischknecht et al., 2007) along with secondary database form literature to determine the life cycle energy requirements of semi-transparent BIPV systems (including modules, BOS and installation). *Eco-*invent is the leading supplier of consistent and transparent life cycle inventory data of renown quality and their databases have often been updated regularly (Frischknecht et al., 2007, Jungbluth, 2005). The information obtained from the database were also modified to account the investigated modules' construction types, BIPV system capacity, manufacturing countries' electricity mix and transportation required. Local contractors and photovoltaic system integrators were also contacted to obtain cost-related information on installing typical BIPV systems.

Two widely-used specific indicators, as recommended by Fthenakis et al. (2011), used in this study are: greenhouse gas emissions (GHG) and cumulative energy demand (CED). They are chosen because they can be used easily to evaluate sustainability and environmental performance of photovoltaic systems (Peng et al., 2013).The GHG emissions during the life cycle stages of the BIPV system were estimated as an equivalent of CO_2 (denoted as $kgCO_2eq$) using an integrated 100-year time horizon with the global warming potential factors published by the Intergovernmental Panel on Climate Change (Foster et al., 2007). The CED describes the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or service, in terms of primary energy. The energy sources included in the CED indicator results are fossil, nuclear, biomass, hydro, primary forest, wind and solar.

The impact indicators were also further processed into energy payback time (EPBT) and energy return on energy investment (EROEI). EPBT, measured in years, was calculated and evaluated for both CED and GHG avoided relative to the average electricity mix used in Singapore. EROEI, expressed as energy production per energy unit of input, would denote the units of energy for each unit invested in the production process.

For life cycle cost assessment, the electricity saved would be converted into costs saved using current electricity tariffs to determine the payback period and return on investment. The costs involved in supplying and installing the semi-transparent BIPV system were collected from local PV distributors, system integrators and construction contractors involved in glazing works. The costs in an LCCA can be expressed in different ways (real costs, nominal costs and discounted costs) depending on the purpose of analysis (Bennett, 1999). Real costs are the costs measured in terms of resources or in terms of each other and not affected by time-related effects (such as inflation) as compared to nominal and discounted costs (Stone, 1980). Since LCCA is mainly used to compare options, the constant price approach using real costs is used.

Sensitivity analyses were also performed on the environmental and costs assessments by considering alternative manufacturing locations, effects of nearby buildings and various degrees of increase in future electricity prices. The detailed life cycle analyses of energy, carbon emissions and costs are discussed in chapter 6.

3.6 Semi-Transparent BIPV Decision Support Tool

After identifying the overall energy benefits and analysing the environmental and economic performance of the selected semi-transparent BIPV modules when integrated as windows in office buildings in Singapore in a life cycle perspective, a design tool is developed in the form of a radar chart. The results established in the previous stages of the study provide the basis for the development of this chart. The decision-making process to select the desired modules can be based on a range of factors. Depending on the criteria and preference of the building designer or architect, the decision support tool can assist by providing essential and easy-to-understand relative performance within the group of PV modules and clear double-glazed windows.

3.7 Summary

This chapter presented the overall research methodology for this study. The research approach used adopted physical measurements, simulation of building energy use and a life cycle study to determine the impacts of semi-transparent BIPV windows on buildings in Singapore.

Physical measurements, conducted within SERIS's facilities, were used to investigate the electrical, thermal and optical properties of the semi-transparent BIPV modules. For electrical measurements, the power generating capability of the modules was determined under higher cell temperatures, different shadings and direct/diffuse irradiance. The thermal and optical properties studied were the U-value, SHGC and VLT. The obtained properties were subsequently used as input parameters of the building energy simulation, which determined the overall impacts of semi-transparent BIPV on artificial lighting, cooling energy and photovoltaic generation. Parametric analyses considering different orientations and WWRs were also included.

From the simulation study, the lifetime energy benefits of the semi-transparent BIPV modules were determined and used in a life cycle analysis that investigated their environmental and economic performance which considered long-term energy, emissions and costs. Last but not least, a semi-transparent BIPV decision support tool is developed based on the results to assist building designers in adopting such technologies.

CHAPTER 4 SEMI-TRANSPARENT BIPV MEASUREMENTS

In the previous chapters, literature covering long-term adoption of semi-transparent BIPV windows has been reviewed, and the research methodology for this study has been established. This chapter presents the electrical, thermal, and optical measurement processes and results.

4.1 Electrical Measurements

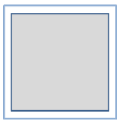
As discussed in Chapter 2, performances of BIPV systems are often affected by conditions such as partial shading, higher module temperatures and diffuse irradiance. However, they are not reflected in the current test conditions used in the laboratories to determine performance characteristics of BIPV modules. As such, electrical measurements were conducted to determine semi-transparent BIPV modules' performance under a set of more realistic conditions that BIPV are often exposed to in the tropics than existing standards. This chapter presents the conditions adopted for the performance measurements and the results of the experiments.

4.1.1 BIPV Test Conditions

Shadings in the building context can be divided into near and far shadings. Near shadings refers to objects that create hard and contoured shadows, such as elements protruding from the building (antennas, chimneys, latches, etc.) or objects on the module surface, e.g. leaves and birds' droppings. Far shading refers to nearby buildings or trees that can partially-block direct sunlight and create a shadow with less discrete edges. Realistic building applications often result in indirect sunlight, partial or even complete shading on BIPV modules. Good planning would avoid these sub-optimal situations; however, in the urban context it may not be always possible. Buildings in these situations, particularly when they need to meet certain energy generation target, may end up with substantial fractions of the photovoltaic modules in sub-optimal conditions. As such, it is highly relevant to test the performance of BIPV modules under these conditions.

The conditions adopted for the electrical measurements are shown in Table 4:1. They include effects of near and far shadings, which result in zero and diffuse irradiance. The module temperatures were all maintained at 50°C to reflect the average daytime temperatures of photovoltaic modules measured in Singapore which ranged from 35–65°C (Ye et al., 2013). The shading effect investigated also looked at both longitudinal and cross shadings, which refer to the direction of the cell strings. The first measurement set was with 50% opaque shading parallel and cross-directional to the cell strings with module temperature maintained at 50°C and standard directional irradiance of 1000 W/m^2 from the flasher. The second measurement set was performed separately with 300 W/m^2 of direct and diffuse irradiance.

Table 4:1 – Description and illustration of electrical measurement conditions

Test Set	**Description of Conditions**	**Illustrations**
1	Shading Orientation Effect • Transmission at 0% • Module temperature at 50°C • Coverage at 50% • Orientation at both parallel and cross	50P  50C 
2	Indirect Irradiance Effect • Module temperature at 50°C • Coverage at 100% • Direct and Indirect Irradiance	direct  diffuse 

Note: P – parallel; C – cross-directional

Creation of diffuse light and shadings

To identify a suitable representation of the lower diffuse irradiance and various shading conditions, non-standard measurement conditions were designed. In order to create diffuse light, a translucent woven silk fabric was mounted on the glass wall facing the flasher. It was selected for its ability to scatter all directional light into diffuse light due to its fine and evenly woven pattern. The solar transmission of the selected fabric was measured with a pyranometer to be around 30% with homogeneous reduction of the transmission light spectrum across the 350–1200 nm range, measured with a Lambda 950 UV-VIS-NIR spectrophotometer. The optical scatter of the fabric, i.e. its ability to create diffuse light, was assessed with a gonio-photometer.

Figure 4:1 shows the reflection and transmission pattern of the fabric when illuminated with directional light. With it, diffuse irradiance of 300 W/m^2 incident on the photovoltaic module would be produced. To create partial full shadows, opaque standard cardboards of 2mm thickness were adopted. Similar to the fabric, the opaque cardboards were also mounted on the temperature chamber's clear glass.

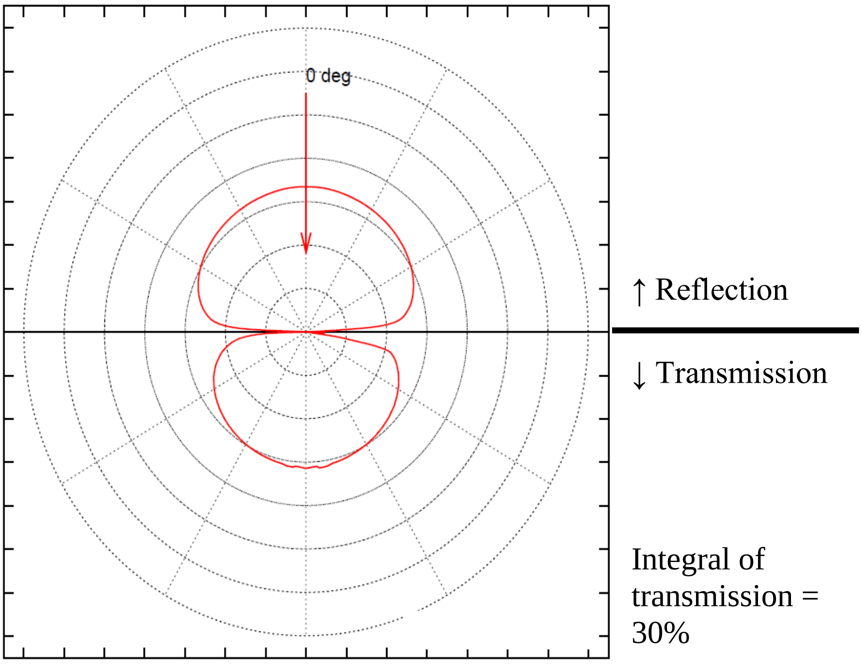


Figure 4:1 – Polar plot of translucent fabric's optical scatter

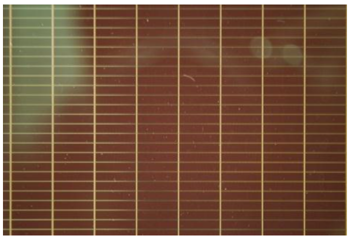
4.1.2 Photovoltaic Modules for Building Integration

To analyse the electrical performance of BIPV modules, five modules of different photovoltaic technologies and constructions were tested. The thin-film photovoltaic technologies included a-Si, μc-Si, copper-indium-gallium-diselenide (CIGS) and organic plastic. The list of selected photovoltaic modules (which is a sub-set of those listed in the Table 3:1) and their STC-rated performance specifications are shown in Table 4:2 with their images and dimensions shown in Figure 4:2.

Table 4:2 – Specifications of photovoltaic modules tested for electrical measurements

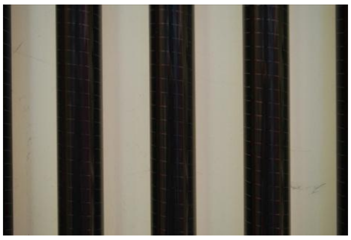
Module	**A**	**F**	**G**	**H**	**J**
Manufacturer (module type)	Taiyo Kogyo (Hanwa KN-50)	Solyndra (SL-001-150)	Schott Voltarlux (T-ISO E1.2)	Konarka (KT-800)	SERIS RND Reference Module
Module area (m^2)	0.93	1.97	0.64	0.54	1.65
Module efficiency (%)	7.6	7.63	6.31	1.54	10.3
Maximum-point voltage (V)	77.3	70.5	64.2	8.0	35.3
Maximum-point current (A)	0.96	2.15	0.63	1.03	4.8
Open-circuit voltage (V)	97.64	96.0	82.7	11.1	43.7
Short-circuit current (A)	1.12	2.50	0.72	1.29	5.14
Maximum power output (W)	72	150	40.4	8.3	170
Photovoltaic technology	a-Si	CIGS	a-Si	Plastic	multi-Si
Construction assembly	Single Glass Laminate	Cylindrical Glass Tube	Double-Glazed Unit	Flexible Laminate	Glass Tedlar

Module A



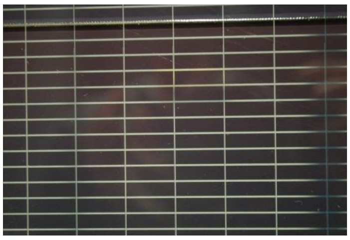
Cell size: 9mm x 2mm

Module F



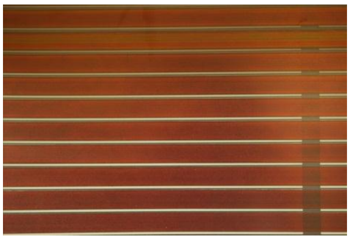
Cell size: 1080mm x 6mm

Module G



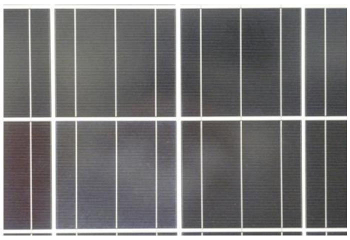
Cell size: 16mm x 5mm

Module H



Cell size: 200mm x 12mm

Module J



Cell size: 150mm x 150mm

Figure 4:2 – Close-up of the photovoltaic modules tested for electrical measurements

4.1.3 Measurement Results and Discussion

The results for the shading orientation effect (test set 1 in Table 4:1) on the five tested modules are shown in Table 4:3. The results indicated that shading orientation with respect to the cell strings has very different impacts on the power production for all the modules. While a certain fraction of the power is still generated with the parallel shading, cross shading produces little or almost no power.

Table 4:3 – Results of electrical measurements investigating effects of shading orientation

Module	Coverage	P_{MAX} (W)
A	50P	31.38
	50C	0.44
F	50P	32.76
	50C	1.00
G	50P	20.11
	50C	0.18
H	50P	3.37
	50C	0.05
J	50P	57.86
	50C	1.00

Note: P – parallel shading, C – cross shading

The results of measurements investigating the effects of irradiance are compiled and illustrated in Table 4:4 . The results show that the photovoltaic modules tested generally prefer diffuse to direct irradiance due to the higher power generated for all five modules. To show the comparative difference between the powers generated, Figure 4:3 shows the percentage increase in measured power generation (or efficiency) of diffuse as compared to direct light for the modules.

Table 4:4 – Results of electrical measurements investigating effects of irradiance

Module	Irradiance (300 W/m^2)	P_{MAX} (W)	Efficiency (%)
A	direct	19.04	6.82
	diffuse	21.93	7.86
F	direct	18.03	3.05
	diffuse	25.48	4.31
G	direct	11.28	5.88
	diffuse	13.46	7.01
H	direct	2.00	1.23
	diffuse	2.56	1.58
J	direct	58.70	11.86
	diffuse	65.41	13.21

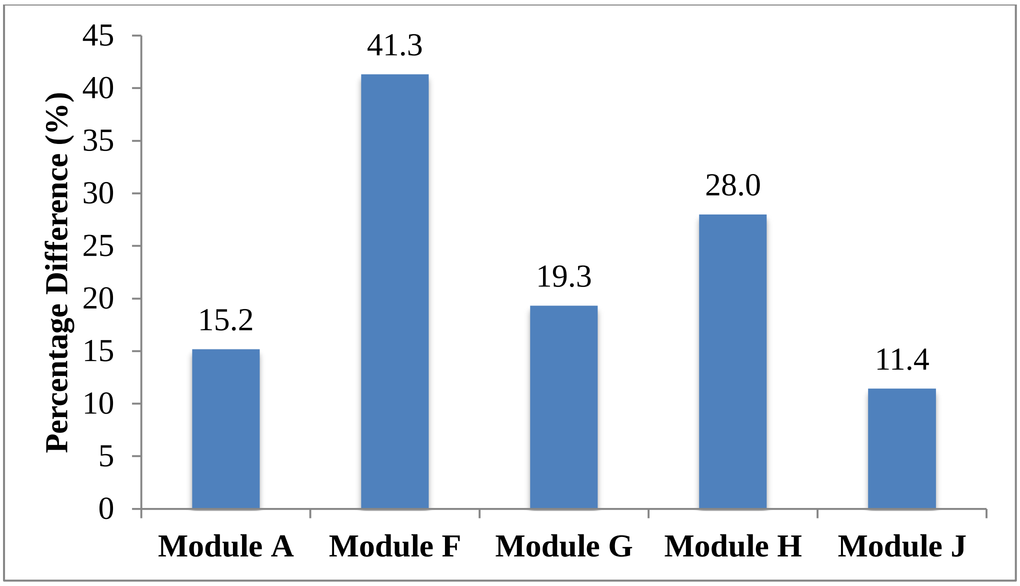


Figure 4:3 – Percentage difference of direct and diffuse irradiance

All the photovoltaic modules produced more power when the irradiance (300 W/m^2) is diffuse. This effect is larger for the thin-film modules and the least for the multi-Si module. The percentage difference ranges from 15.2–41.3% for the thin-film modules as compared to the 11.4% obtained for the multi-Si module (module J). The reason for module F having excessively higher percentage increase as compared to modules A and G was due to the cylindrical glass tube assembly which allows it to capture more directional light as compared to the commonly-used flat plate modules. The organic plastic module showed approximately 28% increase for diffuse irradiance. The results further strengthen existing literature (Jardine et al., 2001) which indicated that thin-film technologies marks an increase in efficiency under overcast skies (diffuse irradiance) as compared to crystalline silicon, even at higher operating temperatures and lower irradiance levels.

4.2 Thermal Measurements

The thermal experiments were designed to determine the U-value and SHGC of the semi-transparent BIPV modules under the laboratory setting previously discussed in section 3.3. The calorimetric hot box, which is a combined system for measuring U-value and SHGC, was adopted although the measurement modes and settings are slightly different. This section provides a detailed description of the calorimetric hot box under different measurement modes and also presents the measurement results.

For the thermal measurements, six semi-transparent modules were selected from Table 3:1. These six modules were selected as they are semi-transparent and are therefore suitable for building integration as window façade materials. The modules chosen are modules B, C, D, E, G and I. This selection spans across different photovoltaic technologies and different constructions (single and double-glazed).

4.2.1 U-Value Measurements

The schematic cross-section of the SERIS calorimetric hot box system in U-value measurement mode is shown in Figure 4:4. The system consists of four main components: a metering box surrounded by a guarding box on the indoor side, a climate box on the outdoor side, and a surround panel holding the test specimen sandwiched between the indoor and outdoor side boxes. Figure 4:5 and Figure 4:6 show the general views of the calorimetric hot box system.

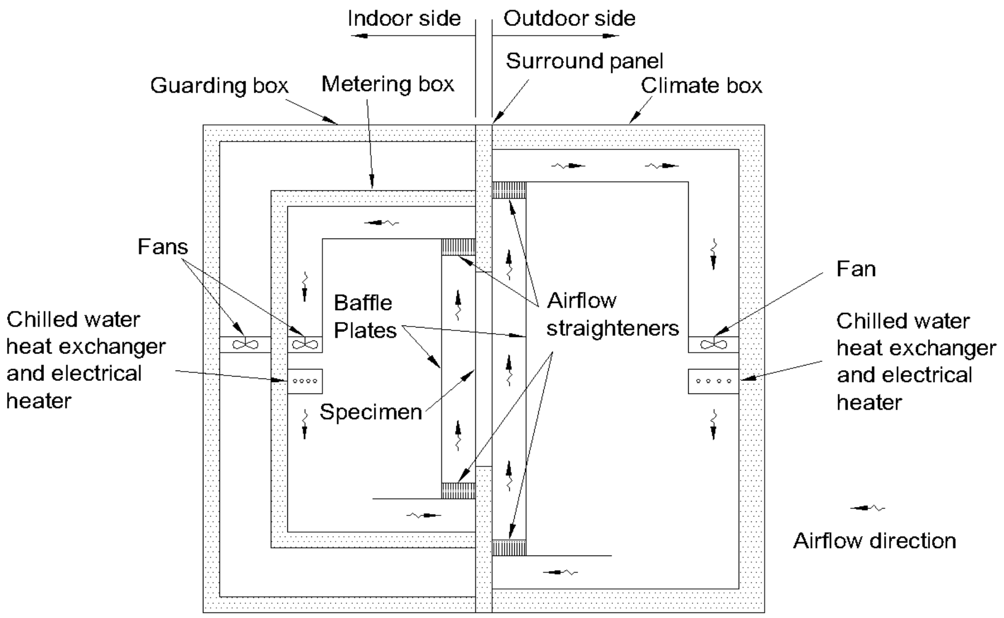


Figure 4:4 – Schematic of the SERIS calorimetric hot box

Note: shown are the main components, the metering and surrounding guarding box on the left hand side (representing the indoor side), the climate box on the right hand side (representing the outdoor side) and the surround panel holding the specimen sandwiched in between

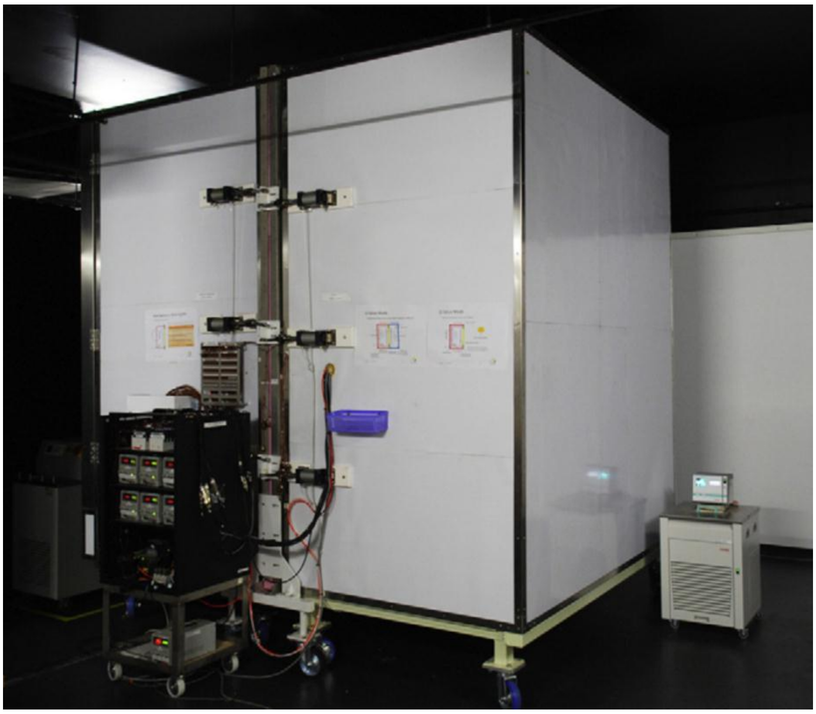


Figure 4:5 – General view of SERIS calorimetric hot box system in U-value measurement mode (closed).

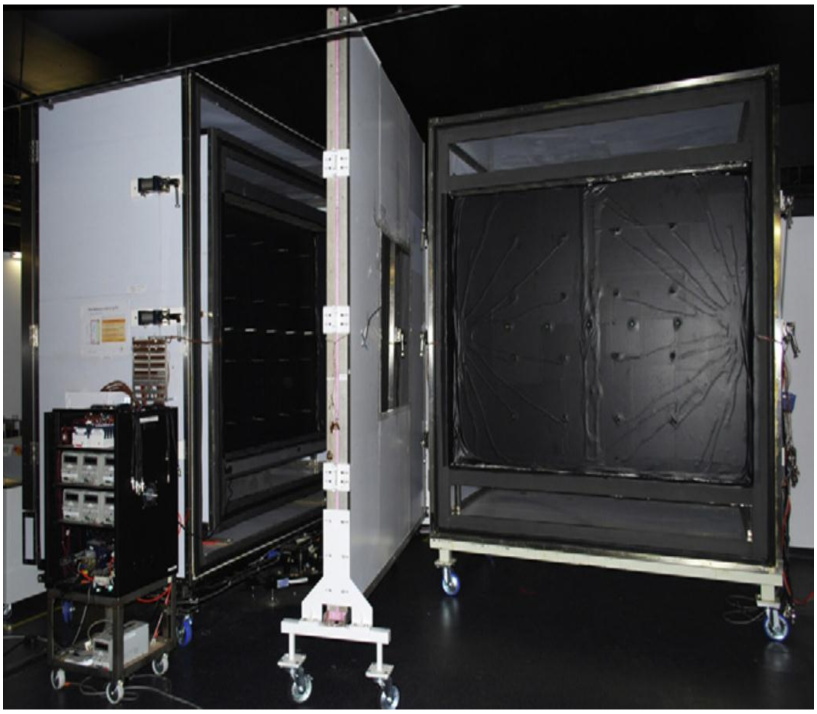


Figure 4:6 – General view of SERIS calorimetric hot box system (opened)
Note: the system is shown opened to provide a view of the surrounded metering box

4.2.1.1 Measurement Setup

Metering Box

The metering box is designed to measure specimen sizes of up to 1.5m (H) x 1.5m (W). The walls are made of 100mm thick extruded polystyrene (XPS) board with plywood and protective film as facing materials, resulting in an outer dimension of 2.2m (H) x 1.9m (W) x 1.0m (D). To monitor the heat loss through the walls, sensors are integrated in the walls using 112 T-type copper-constantan thermocouples. A baffle plate, made of a 6mm thick aluminium plate, installed parallel to the specimen forms an air curtain. The aluminium baffle plate along with other surfaces that are likely to exchange radiative heat with the specimens were covered with a layer of black wall paper with an emittance of 0.90. There are 16 DC-powered axial flow fans on the rear section of the metering box. This arrangement allows long airflow travelling distance between the air curtain and fans, thus improving the airflow uniformity.

Additionally, airflow straighteners made of bundles of 4mm diameter plastic straws and typically used in simple wind tunnel setups, were installed at both the inlet and outlet of the air curtain. It helped to reduce local turbulence level near inlet/outlet, where the air stream direction could change. To monitor the airflow velocity, five one-dimensional airflow velocity sensors (EE66, E+E Elektronik) were distributed along the horizontal centreline of the air curtain and airflow uniformity better than ±5% was achieved.

A heat exchanger was installed beneath the fans for cooling and a DC-powered electrical heater was located next to the heat exchanger. A high stability chiller (SC2500a, Julalo), with temperature stability better than ±0.1 °C in its bath, supplied chilled water. The chilled water flow rate was throttled by a manual ball valve so that the bath temperature could be controlled. For temperature control, chiller outputs, i.e. flow rate and bath temperature, were fixed and the electrical heater output was fine-tuned by a software proportional-integral-differential controller. The heater was powered by high stability linear DC power supply (GPS-3030DD, GW Instek). Overall, temperature stability of less than ±0.01 °C was achieved in all boxes.

The heat extraction by the chilled water loop was determined by measuring volumetric flow rate and temperature difference, as shown in Equation 1. A magnetic flow meter (Rosemount 8711, Emerson) was used for volumetric flow rate measurement and two 1/10 DIN RTD sensors used for the differential temperature measurement.

$$Q_c = C_p \rho \dot{V} \Delta T \qquad (1)$$

where,

C_p = specific heat of chilled water, [J/(kg.K)]

ρ = specific density of chilled water, [kg/m^3]

$\dot{V}$ = volumetric flow rate of chilled water, [m^3/s]

ΔT = temperature difference of metering box, [K].

The time rate of heat input to the metering box by electrical devices, including sensors, fans and heater, Q_e, was determined by computing the product of voltage (measured by NI 9227, National Instruments) supplied to each of the three electrical device groups (i.e. sensors, fans and heater), as shown in Equation 2.

$$Q_e = \sum_{i=1}^{3} V_i I_i \qquad (2)$$

where,

V_i = voltage supplied to the *i*th electrical device group, [V]

I_i = current supplied to the *i*th electrical device group, [A].

The metering box was instrumented with temperature sensors for both air and surface temperature monitoring. For air temperature measurement, 16 sensors (1/3 DIN RTD) housed in a stainless steel sheath with vent holes, were arranged uniformly as a 4 x 4 grid over the 1.5m x 1.5m effective measurement area in the air curtain between the baffle plate and the specimen. For surface temperature monitoring, 34 T-type thermocouples were attached to all surfaces with radiative heat exchange with the specimen.

Guarding Box

The metering box was surrounded by a guarding box, measuring 2.7m (H) x 2.4m (W) x 1.4m (D), for metering box wall heat loss control. The air layer thickness between the guarding and metering boxes were 150mm at the sides and 300mm at the back. The guarding box was constructed with the same materials used for the metering box. Copper tubes were attached to the side walls of the guarding box for cooling and heaters made of electrical resistance wires were installed near the cooling coils. The guarding box cooling loop shared a common chiller (SC2500a, Julalo) with the metering box heat exchanger. Seventeen DC-powered fans were available for air circulation. The temperature control mechanism was similar to that for the metering box. The guarding box was instrumented with a 1.10 DIN RTD sensor for air temperature monitoring.

Climate Box

The climate box was similar to the metering box in its construction, temperature/velocity sensor arrangements and temperature control mechanism. The size of the climate box was 2.7m (H) x 2.4m (W) x 1.4m (D). Five AC-powered axial flow fans were used for air circulation and forced ventilation to achieve up to 6 m/s air speed in the air curtain. Similarly, the airflow velocities were monitored by the five airflow velocity sensors (EE65, E+E Elektronik). The chilled water was supplied by a second chiller (FP51-SL, Julabo) with temperature stability better than ±0.05 °C in its bath.

Surround Panels

Surround panels were constructed for the various specimen sizes. The surround panels were made of 100mm thick XPS with plywood and white colour film as the facing materials. As indicated by ASTM (2009), the maximum specimen thickness was 100mm. Perimeter joints between the specimen and surround panel were sealed by tape to prevent air leakage. The static pressure between the metering and climate side air curtains, which was to be less than 10Pa, was monitored by a differential pressure transducer (Setra 264). The surround panel was clamped onto the guarding and climate boxes with pneumatic cylinders to ensure air tightness.

Thermocouples were installed in the interface between the XPS and plywood for surface temperature monitoring. Depending on the surround panel size, 10 –20 thermocouples were instrumented on each side. The time rate of heat flow through the surround panel metered area was calculated as shown in Equation 3:

$$Q_{sp} = \frac{k_{XPS}}{d_{sp}} A_{sp} (T_{sp,c} - T_{sp,m}) \quad (3)$$

where,

k_{XPS} = thermal conductivity of the XPS material, [W/(m.K)]

d_{sp} = thickness of surround panel core, [m]

A_{sp} = area of the surround panel within metered range, [m^2]

$T_{sp,c}$ = area-weighted average core material surface temperature at the climate side, [°C].

$T_{sp,m}$ = area-weighted average core material surface temperature at the metering side, °C

4.2.1.2 Calibration of Calorimetric Hot Box

When a steady state is attained in the metering box, the time rate of heat flow through the specimen, Q_s, can be determined from the heat balance:

$$Q_s = -(Q_c + Q_e + Q_{wl} + Q_{fl} + Q_{sp}) \qquad (4)$$

where,

Q_{wl} = time rate of metering box wall heat loss, [W]

Q_{fl} = time rate of surround panel flanking heat loss rate, [W].

Figure 4:7 shows schematic of the heat balance within the metering box. Conventionally, heat flow rate terms in Equation 4 can be either positive or negative. A positive value implies that thermal energy is supplied to the metering box and a negative value implies that thermal energy is removed from the metering box.

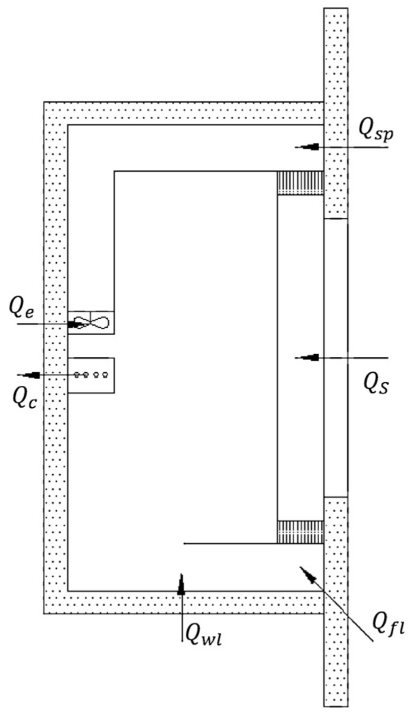


Figure 4:7 – Schematic of heat balance in the metering box

The U-value of the specimen can then be calculated as:

$$U = \frac{Q_s}{A_s(T_c - T_m)} \qquad (5)$$

where,

A_s = specimen surface area, [m^2]

T_c = area-weighted average climate side temperature, [°C]

T_m = area-weighted average metering side temperature, [°C].

As given in Equations 1–3, the heat transfer rate due to the chilled water loop, electrical devices and through the surround panel could be determined experimentally, but calibrations were required to determine the wall and flanking losses.

<u>Metering Box Wall Loss Calibration</u>

In the wall loss calibration, a characterisation panel was used to fill in the surround panel opening. It was constructed and instrumented in a similar way to a surround panel. The air temperatures were maintained equal in both the metering and climate box, so that the heat flows through the surround panel and characterisation panel were negligible. The flanking loss could also be ignored due to the negligible temperature gradient across the surround panel and characterisation panel. Based on heat balance, the time rate of wall loss was calculated as:

$$Q_{wl} = -(Q_c + Q_e + Q_{sp} + Q_{cp}) \qquad (6)$$

where,

Q_{cp} = time rate of heat flow through the characterisation panel, [W]

Surround Panel Flanking Loss Calibration

The objective of flanking loss calibration was to identify the additional heat transfer from the metering box to the climate box through the surround panel. The result obtained from the calibration consisted of two components. First is the additional complex heat flow around the contact point of the metering box opening and surround panel, which cannot be modelled by Equation 3. Second is the additional heat flow due to imperfect surround construction, e.g. seams between XPS boards. In a flanking loss calibration, the surround panel opening was filled with a characterisation panel as well and temperatures in all boxes were fixed as the actual temperatures in a U-value test. The rate of flanking loss was calculated as:

$$Q_{fl} = -(Q_c + Q_e + Q_{wl} + Q_{sp} + Q_{cp}) \qquad (7)$$

4.2.1.3 U-value Measurement Results

The U-value measurement results of the six selected semi-transparent BIPV modules are shown in Table 4:5. Each specimen's test took 12 hours to complete and the last five sets of hourly results were averaged to obtain the thermal transmittance.

Table 4:5 – U-value measurement results of semi-transparent BIPV modules

Module	Specimen	Construction	U-value [W/(m²K)]
B	Hanwa Makmax (KN-42)	Single glass laminate	5.076
C	Auria Solar (Micromorph – Red)	Single glass laminate	4.795
D	Auria Solar (Micromorph – Golden)	Single glass laminate	5.080
E	Auria Solar (Micromorph –Dark Blue)	Single glass laminate	5.096
G	Schott Solar (Voltarlux ASI-ISO-E1.2)	Double-glazed unit	1.674
I	Spear Technology Alliance (SSM-50SS0533Air)	Double-glazed unit	2.140

The single-glazed BIPV modules exhibit much lower U-values which were mostly expected. As compared to published data, they are generally lower than single glazing which exhibits U-values of between 5.1–5.9 W/(m^{2}K) (Chen and Wittkopf, 2012, ASHRAE, 2009, Gueymard and DuPont, 2009). A similar study on U-values of single-glazed semi-transparent amorphous silicon modules also reported approximately 4.5 W/(m^{2}K) as U-value (Wong et al., 2005b). The double-glazed BIPV modules' U-values were slightly different from the distributors' manufacturing data of 1.2 and 1.65 W/(m^{2}K) for modules G and I respectively. The difference could largely be attributed to the specifications provided in the data sheets being general in nature, and not specific to the product provided. The values achieved are also generally in line with modern conventional double-glazing units (Maurus et al., 2004). The results of the experimental setup were compared to and validated by computer simulations to ensure their accuracy (Chen and Wittkopf, 2012).

4.2.2 SHGC Measurements

The same calorimetric hot box system discussed in the previous section was used to measure the SHGC values of the same set of semi-transparent BIPV modules, although a slightly different configuration in instrument set-up was adopted. Figure 4:8 shows the schematic cross-section of the calorimetric hot box system in the SHGC measurement mode. Pictures of the main components are shown in Figure 4:9 and Figure 4:10. The same metering box, guarding box and surround pane used in the U-value measurement mode were re-used. However, on the outdoor side, the climate box was replaced by a solar simulator and an external air curtain.

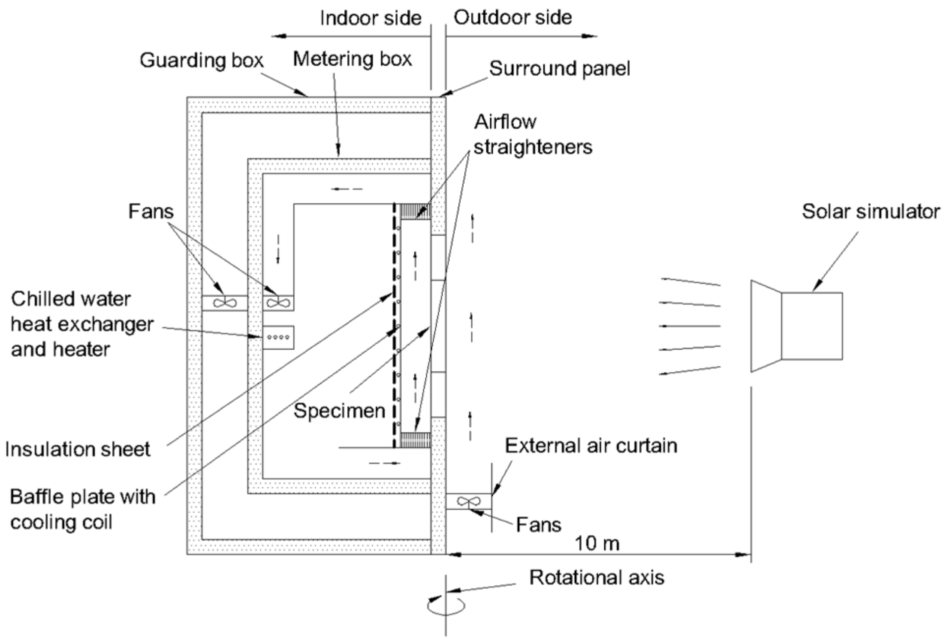


Figure 4:8 – Schematic section of SERIS calorimetric hot box system in SHGC measurement mode

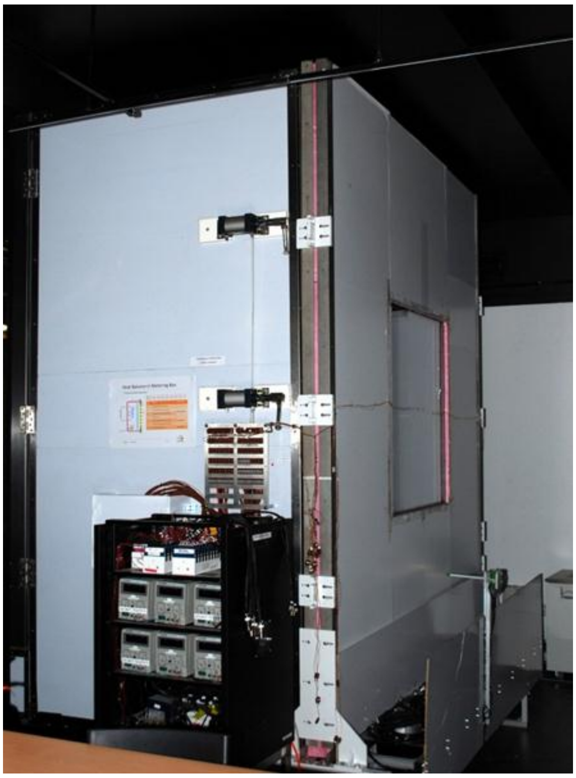


Figure 4:9 – General view of SERIS calorimetric hot box in SHGC measurement mode

Figure 4:10 – Front view of solar simulator used for SHGC measurements

4.2.2.1 Measurement Setup

Solar Simulator

The solar simulator performance is critical for indoor SHGC calorimetric measurements. Ideally, the solar simulator radiation should resemble standard sun radiation conditions used in the glazing or fenestration rating methods (ISO, 2003b, ISO, 2003a, NFRC, 2010a, NFRC, 2010c). Solar simulators, whether flash or steady-state type, are routinely used in photovoltaic cell or module characterization and other solar energy-related research applications. IEC 60904-9 (2007) defines the performance requirements of solar simulators in photovoltaic characterization. Solar simulators are classified as class A, B or C with regards to their spectrum mismatch, spatial non-uniformity and temporal instability. For SERIS's solar simulator, a single-lamp solution was identified as the most appropriate solution (ARRIMAX, ARRI 18/12 lamp system with 18 kW metal halide lamp HM 18000W/SE/GX51, Osram). In order to achieve a small divergence angle and improved uniformity the lamp system was located 10m away from the calorimeter specimen plane.

External Air Curtain

It was necessary to provide forced ventilation on the outdoor side of the specimens to regulate the outdoor side convective surface heat transfer. The external air curtain consisted of five AC-powered axial flow fans installed in a row. To streamline the airflow, two plywood boards were installed on the two sides of the baffle plates. Airflow velocities in the air curtain were monitored by a sensor (EE65, E+E Elektronik) and one 1/3 DIN resistance detector (RTD) sensor was mounted near the airflow velocity sensor for external air curtain temperature monitoring.

Environmental Conditions for Measurements

SHGC is dependent on environmental conditions, including temperatures, surface heat transfer coefficients and solar radiation on both indoor and outdoor sides. Table 4:6 summarizes the standard environmental conditions for the SHGC measurements as defined by NFRC (2010b).

Table 4:6 – Standard environmental conditions for SHGC measurements

Environmental Conditions	**NFRC 2013**	**SERIS Calorimetric Hot Box System**
Indoor Side	T_{in} = 24 °C h_{in} = 7.7 W/(m^{2}K) ± 5%	T_{in} = 24 °C h_{in} = 7.7 W/(m^{2}K) ± 5%
Outdoor Side	I_s > 680 W/m^2	T_{out} = 24 – 27 °C h_{out} = 18 W/(m^{2}K) ± 10% I_s > 500 W/m^2
Spectrum	Actual sun or solar simulator spectrum	Actual solar simulator spectrum

4.2.2.2 SHGC Measurement Procedures

In general, SHGC comprises of both the direct solar transmission through the glazing and the heat radiated inwards from the glazing as it heats up through absorption, referred to as the secondary heat gain. The secondary heat gain would be relatively small for clear glazing and larger for darker glazing due to relatively higher absorption. Semi-transparent BIPV can be considered special as some of the absorbed solar radiation is converted into electricity and hence would not contribute to the heat built up. This reduction will also correspond with higher photovoltaic efficiency. As such, all the semi-transparent BIPV modules were connected to an electrical load to simulate its actual SHGC performance while producing electricity.

After mounting and setting up semi-transparent BIPV modules and equipment, 2-3 hours have to be allowed before SHGC measurements could commence. This is the time required for heat fluxes to stabilize towards the required steady state condition inside the metering box. After attaining steady state, two measurements were taken at intervals of 30 minutes and averaged.

4.2.2.3 SHGC Measurement Results

The SHGC values of the six semi-transparent BIPV modules were measured and shown in Table 4:7. The results were subsequently used for building energy simulation purposes.

Table 4:7 – SHGC measurement results of semi-transparent BIPV modules

Module	**Specimen**	**Construction**	**SHGC [-]**
B	Hanwa Makmax (KN-42)	Single glass laminate	0.289
C	Auria Solar (Micromorph – Red)	Single glass laminate	0.413
D	Auria Solar (Micromorph – Golden)	Single glass laminate	0.298
E	Auria Solar (Micromorph –Dark Blue)	Single glass laminate	0.387
G	Schott Solar (Voltarlux ASI-ISO-E1.2)	Double-glazed unit	0.154
I	Spear Technology Alliance (SSM-50SS0533Air)	Double-glazed unit	0.123

The single-glazed modules have a SHGC range of 0.289–0.413 while the double-glazed modules’ range is 0.123–0.154. Only module G’s manufacturing data sheet indicated its SHGC (of 0.10) which is fairly close to the measured value. The measured SHGCs of the single-glazed BIPV windows are lower than coloured single glazing whose values lie between 0.5–0.8 (ASHRAE, 2009) and close to double low-e glazing values of 0.25–0.4 (Gueymard and DuPont, 2009). The double-glazed BIPV modules SHGCs are similar to triple-glazed low-e windows. Similar to the U-value measurements, the SHGC results were also validated through computer simulations to ensure their accuracy (Chen et al., 2012).

4.3 Optical Measurements

Optical measurements were designed to obtain the visible light transmittance (VLT) of the same set of six semi-transparent BIPV modules. They were performed using a large diameter integrating sphere in one of SERIS's in-house laboratories. This section discusses the detailed description of the large integrating sphere and measurement procedures, before presenting the measurement results.

4.3.1 Measurement Setup and Procedures

4.3.1.1 Measurement Setup

The large integrating sphere has two modes, one to measure transmittance and the other to measure reflectance. In this study, only the transmittance mode will be discussed as only the VLT was measured. Figure 4:11 shows the general view of the large integrating sphere's setup in SERIS. The light source was placed directly in front of the sample port at incidence angle. The photometer was connected to an electric reader where the detected reading would be displayed. During measurement, all the lights were switched off to ensure accurate reading.

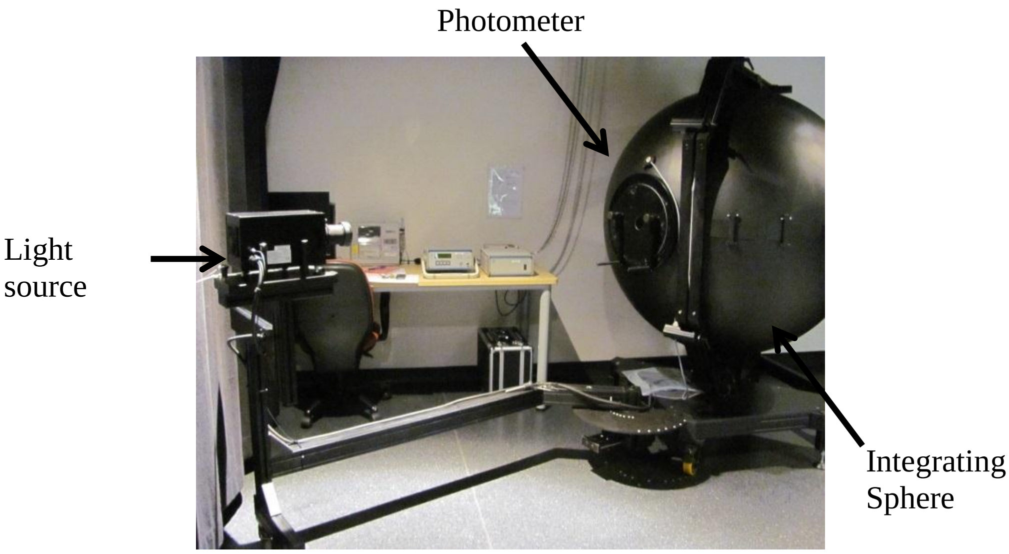


Figure 4:11 – Picture of integrating sphere in transmittance mode

4.3.1.2 Measurement Procedures

After the incident beam had warmed up for 45 minutes and stabilised, the first reading was recorded without a sample. Care was taken to ensure that the light spot size is appropriate for the chosen port size to ensure that illuminance from the light source was fully transmitted into the integrating sphere. The electronic reading was then recorded (E_0). To measure a specimen's VLT, it was first placed directly in front of the sample port, in between the light source and large integrating sphere (as shown in Figure 4:12) and the resulting signal was recorded again (E_x). The measurement sequence was repeated until the ratios are within 0.005 measurement units of each other.

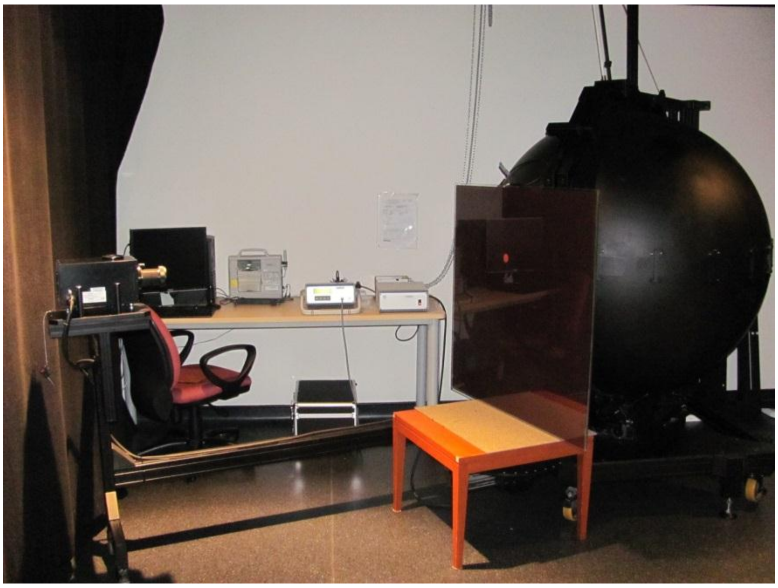


Figure 4:12 – View of semi-transparent BIPV module during VLT measurement using a large integrating sphere

All readings obtained were recorded using the IFT excel file (see Table 4:8). The VLT was calculated by dividing the readings with sample at port (E_x) with the initial readings (E_0). To ensure the accuracy of measurement results, separate recordings were performed on two different days. The average values were then used as the VLT of the individual semi-transparent BIPV modules.

Table 4:8 – IFT template excel file for recording of VLT

Protocol	Company:	National University of Singapore		
Date of test:	14th June 2012		Investigator:	Ng Poh Khai
Determination of the visible light transmittance				
Specimen	Module No.	E_x	E_0	$\tau = E_x/E_0$
Hanwa Makmax (KN42)	1			
Auria Solar Micromorph (Red)	2			
Auria Solar Micromorph (Golden)	3			
Auria Solar Micromorph (Dark-Blue)	4			
SCHOTT Voltarlux (ASI-T-ISO-E1.2)	5			
Spear Technology (SSM-42S0533Air)	6			

Note: E_x = sample at port; E_0 = port open; τ = visible light transmittance

4.3.2 *VLT Measurement Results*

The VLT of the six semi-transparent BIPV modules measured in two separate recordings are shown in Table 4:9. The results from the two rounds of measurement were averaged and subsequently used for building energy simulation purposes. The six semi-transparent BIPV modules display VLT of 1.84–9.17%. The standard-coloured modules (B, G and I) generally have a higher range, notwithstanding the difference in construction (single or double-glazed). The coloured modules (C, D and E) exhibit the lowest VLTs with module D (golden) being the poorest in VLT at 1.82%.

Table 4:9 – VLT measurement results of semi-transparent BIPV modules

No.	**Specimen**	**Round 1 [%]**	**Round 2 [%]**	**Avg. VLT [%]**
B	Hanwa Makmax (KN-42)	9.18	9.15	9.17
C	Auria Solar (Micromorph – Red)	5.16	5.22	5.19
D	Auria Solar (Micromorph – Golden)	1.82	1.85	1.84
E	Auria Solar (Micromorph – Dark Blue)	4.12	4.22	4.17
G	Schott Solar (Voltarlux ASI-ISO-E1.2)	6.89	6.92	6.91
I	Spear Technology Alliance (SSM-50SS0533Air)	7.33	7.35	7.34

4.4 LSG Ratio of Tested Semi-Transparent BIPV Modules

As discussed previously in section 2.2, the LSG ratio can be used as a simple index for evaluating the energy efficiency of window fenestration. By definition, it is the ratio of VLT divided by the SHGC value of the glazing material. From the thermal and optical measurements conducted, the LSG ratios of the six semi-transparent BIPV modules are also calculated and are shown in Table 4:10.

Table 4:10 – LSG ratio of semi-transparent BIPV modules

No.	Specimen	VLT [%]	SHGC	LSG Ratio
B	Hanwa Makmax (KN-42)	9.17	0.289	0.32
C	Auria Solar (Micromorph – Red)	5.19	0.413	0.13
D	Auria Solar (Micromorph – Golden)	1.84	0.298	0.06
E	Auria Solar (Micromorph – Dark Blue)	4.17	0.387	0.11
G	Schott Solar (Voltarlux ASI-ISO-E1.2)	6.91	0.154	0.45
I	Spear Technology Alliance (SSM-50SS0533Air)	7.34	0.123	0.60

All the values are below the 1:1 (ratio) line as indicated in Figure 2:1 and are close to the laminated glazing and window films on glazing. Although their LSG ratios might not seem ideal for window application in the tropics, their electricity generation capabilities should increase their overall energy efficiency.

4.5 Comparison of Measurement Results

The results of the thermal and optical measurements are summarized in Table 4:11. The values obtained from the manufacturers' brouchures (if any), are also indicated alongside. Only the VLT value of module I (7.34%) are similar, with the remaining not provided or differing significantly. As the measured results were obtained in a controlled, certified laboratory under standardised conditions, they were deemed to be reliable for subsequent building energy simulation use.

Table 4:11 – Thermal and Optical BIPV Modules Performance (Measured against Provided)

		U-value [W/m²K)]		SHGC [-]		VLT [%]	
Module	**Specimen**	**Measured**	**Provided**	**Measured**	**Provided**	**Measured**	**Provided**
B	Hanwa Makmax (KN-42)	5.076	N.A.	0.289	N.A.	9.17	10.6
C	Auria Solar (Micromorph – Red)	4.795	N.A.	0.413	N.A.	5.19	10-20
D	Auria Solar (Micromorph – Golden)	5.080	N.A.	0.298	N.A.	1.84	10-20
E	Auria Solar (Micromorph – Dark Blue)	5.096	N.A.	0.387	N.A.	4.17	10-20
G	Schott Solar (Voltarlux ASI-ISO-E1.2)	1.674	1.2	0.154	0.10	6.91	10.0
I	Spear Technology Alliance (SSM-50SS0533Air)	2.140	1.65	0.123	N.A.	7.34	7.34

4.6 Summary

This chapter established the electrical, thermal and optical properties of a range of semi-transparent BIPV modules. These properties are used for subsequent building energy simulations. Electrical measurements were conducted for modules of various technologies to examine their performance under different levels of shading and irradiance (direct and diffused). Thermal and optical measurements were performed for photovoltaic modules of various constructions to determine their U-value, SHGC and VLT. The U-values, SHGC and VLT measurements were conducted in controlled laboratory conditions and in accordance to international standards to ensure their accuracy. However, certain limitations still exists as outdoor measurements should be conducted to determine the actual performance relating to Singapore’s weather conditions. Nonetheless, the results were deemed suitable for this study as comparative studies were to be adopted instead of determining the exact performance.

These properties are used for building energy simulations to determine overall energy use relating to artificial lighting, cooling electricity and photovoltaic electricity generation. The details are discussed in the next chapter.

CHAPTER 5 IMPACTS OF SEMI-TRANSPARENT BIPV WINDOWS ON BUILDING ENERGY

As discussed in Chapter 2, there is a lack of research on multi-functional performance of semi-transparent BIPV facades as well as BIPV performance as compared with conventional glazing in tropical regions, where it is hot and humid whole-year round resulting in buildings being cooling-load dominated. In addition, many previous studies utilized theoretical modelling for semi-transparent BIPV modules which might not reflect the modules commercially available in the market. Performance data reported by manufacturers are normally established under laboratory conditions which might not represent the actual building conditions prevalent in tropical locations, leading to substantially different in-use performance from the predicted.

This chapter, reports the overall energy performance of semi-transparent BIPV modules evaluated over different WWRs and across the four main orientations in Singapore, through the consideration of increase/reduction in cooling loads, daylight utilization and production of electricity.

5.1 Profile of Singapore's Hot and Humid Climate

First, Singapore's solar radiation was analysed to understand the prevalent climatic conditions. The analysis used *EnergyPlus* weather data file which represents the typical meteorological year data commonly used with building energy performance software (Ng et al., 2012). The data comprise of hourly values over a typical year, usually obtained and averaged from long-term measurements. Figure 5:1 shows monthly horizontal radiation data along with diffuse and direct components. It can be seen that monthly solar radiation in Singapore is similar throughout the year and the diffuse component accounts for more than 60% of the global solar radiation. With such a high diffuse solar radiation component, vertical facades on various orientations could also receive sufficient sunlight to deem them suitable for BIPV applications.

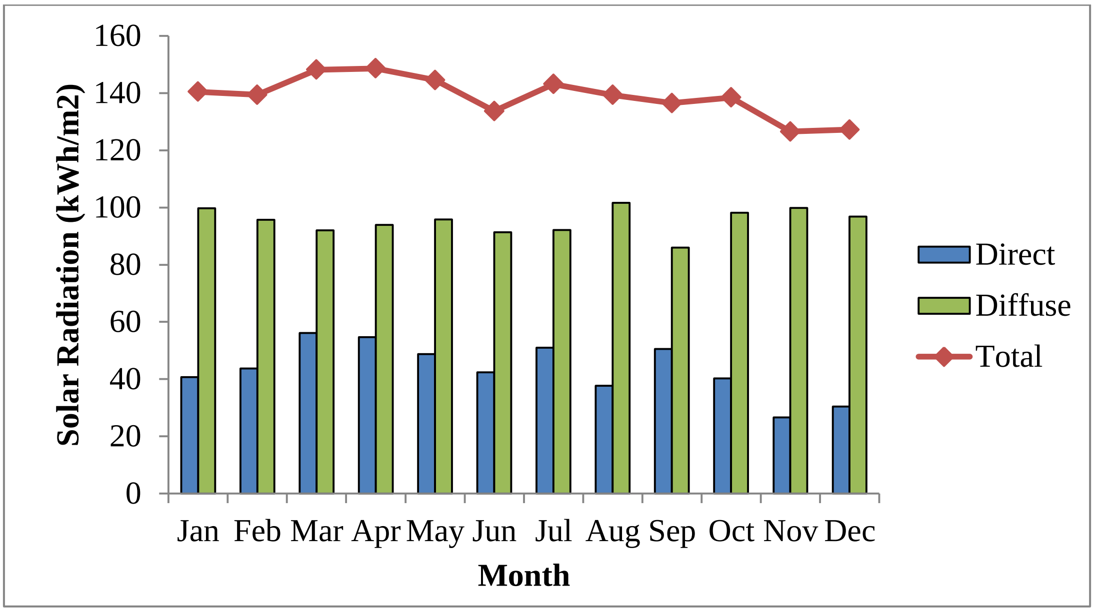


Figure 5:1 – Monthly solar radiation for Singapore (direct/diffuse/total)
Based on: ASHRAE International Weather for Energy Calculations (IWEC) data

The solar radiation received by the various orientations is shown in Figure 5:2. The East and West facades receive the highest solar radiation (approximately 670 kWh/m^2/yr). This is to be expected as the sun path of Singapore is generally overhead, from East to West. The North and South facades receive relatively lesser solar radiation, at roughly 530 kWh/m^2/yr. The diffuse component, which forms the majority of the vertical façade's solar radiation, is generally consistent on all orientations. This highlights the potential of implementing BIPV on all facades and not limited to only those that face the direct sun path.

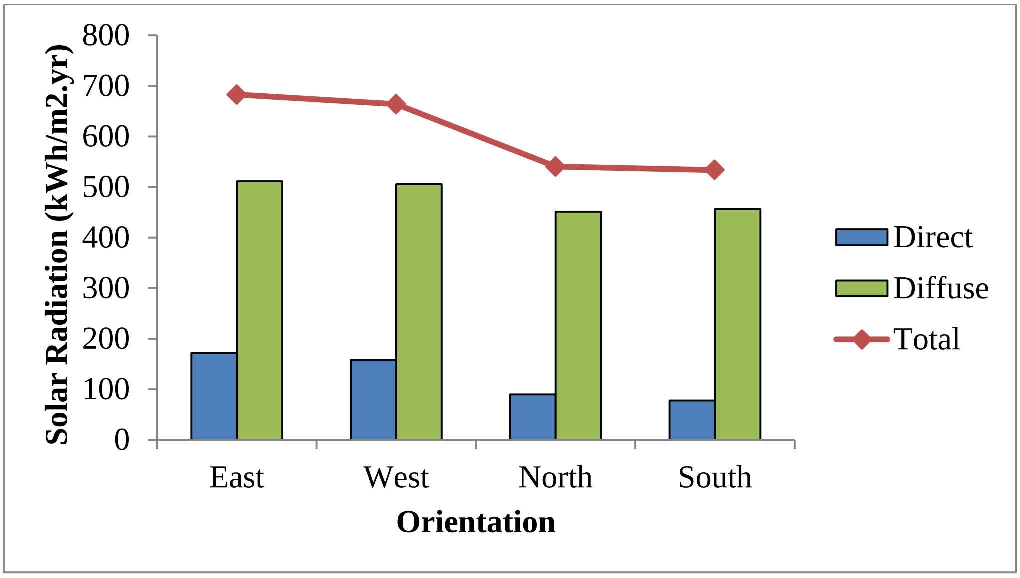


Figure 5:2 – Annual solar radiation for various orientations
Based on: ASHRAE International Weather data for Energy Calculations (IWEC)

5.2 Holistic Multi-Functional Index – Net Electrical Benefit

Due to the multi-functional role that semi-transparent BIPV adopts, there are several parameters that can affect and define its energy performance. Therefore, BIPV's investigation with respect to energy-related impacts should adopt a new performance index, aimed at producing a holistic view. To optimize and analyse the design for BIPV, the effects of electricity generation and building physical aspects should be evaluated. The multi-functional role will need to include both the positive and negative aspects for a complete assessment of semi-transparent BIPV windows. Positive elements are the photovoltaic electricity generation and electricity savings due to natural daylight while the increase in cooling electricity due to additional solar gains is the negative element. A further negative aspect would be the limited visual connection with the external environment. This however, was not considered in the multi-functional index (see chapter 7 for further discussion on this aspect).

To objectively assess these three factors of electricity, the Net Electricity Benefit (NEB) is defined. As shown in Equation 8, it is the sum of the lighting electricity savings and photovoltaic electricity production minus the increase/decrease in electricity consumption required for space conditioning (heating/cooling) as compared to a building with 0% WWR (i.e. solid walls).

$$NEB = L_{savings} - C_{electricity} + PV_{generation} \qquad [kWh/m^2] \qquad (8)$$

where,

$L_{savings}$ = artificial lighting savings through the utilisation of daylight;

$C_{electricity}$ = increase in electricity consumption required for space conditioning due to transmission of additional solar heat gain; and,

$PV_{generation}$ = photovoltaic window electricity generation output.

When the NEB is positive, the application of the semi-transparent BIPV windows would be justified as the energy savings, from daylight usage and generation, are higher than the increase in electricity consumption for space conditioning. In this manner, NEB is a simple index capable of assessing the overall electricity benefit of incorporating a semi-transparent BIPV window, relative to a selected reference (solid wall/other glazing).

5.3 Semi-Transparent BIPV Windows in Singapore Buildings

Six semi-transparent BIPV modules were deemed as suitable and chosen as the set of modules that are to be analysed through computer simulations in terms of energy performance of office buildings in Singapore when integrated as windows. As discussed in chapter 4, the modules were laboratory tested to determine the relevant thermal, optical and electrical properties essential for building energy simulations. However, modules F, H and J used for these measurements are not suitable for window application. This is because modules F and H are of inappropriate construction assemblies, being made of cylindrical glass tube and flexible laminate respectively (see Figure 4:2 for more details). Module J, being a poly-Si wafer-based module, also does not qualify due to its opaque nature. The modules' old identifier and new numbering are shown in Table 5:1.

The electrical measurements show that different photovoltaic technologies and module constructions result in varying increase when the modules are subjected to diffuse instead of direct irradiance. Modules 1 and 5 were tested in the electrical measurements as such the results recorded for the increase in efficiency are directly adopted. Module 6 is made from a-Si photovoltaic technology and as such, the average increase in the efficiency of similar technologies (modules 1 and 3) were used for adjustments. Modules 2, 3 and 4 are micromoprh modules, which use a combination of a-Si and crystalline silicon technologies (Bravi et al., 2011). Hence, the average of the a-Si and crystallaine modules (modules A, G and J) was adopted for the diffuse efficiency of these modules. As shown in section 5.1, north/south has an approximate direct:diffuse ratio of 85:15 while east/west's ratio is roughly 75:25. As such, the efficiency of a module facing a given orientation was adjusted accordingly taking into consideration the portion of direct and diffuse. The adjustment procedures are shown in Table 5:1. Thermal and optical measurements were conducted for the selected six modules (as discussed in chapter 4) and hence were used directly for the building energy simulations.

Table 5:1 – List if chosen BIPV modules and their adjustments of efficiencies for energy simulation

			(A)	(B)	(C) = (A)*(B)/100	(D) = (A)*0.25 + (C)*0.75	(E) = (A)*0.15 + (C)*0.85
New No.	**Old No.**	**BIPV modules**	**Rated Efficiency (%)**	**Percentage increase due to diffuse component (%)**	**Adjusted diffuse efficiency (%)**	**Adjusted efficiency for east/west (%)**	**Adjusted efficiency for north/south (%)**
1	**B**	Hanwa Makmax (KN-42)	7.60	15.20	8.76	8.47	8.58
2	**C**	Auria Solar (Micromorph – Red)	4.75	14.33	5.43	5.26	5.33
3	**D**	Auria Solar (Micromorph – Golden)	4.50	14.33	5.14	4.98	5.05
4	**E**	Auria Solar (Micromorph –Dark Blue)	5.59	14.33	6.39	6.19	6.27
5	**G**	Schott Solar (Voltarlux ASI-ISO-E1.2)	3.15	19.30	3.76	3.61	3.67
6	**I**	Spear Technology Alliance (SSM-50SS0533Air)	4.20	17.25	4.92	4.74	4.82

5.4 Performance Simulation

The purpose of the simulation was to compare the building energy use when installed with semi-transparent BIPV windows of different WWRs, as compared to an opaque wall. A hypothetical office building, with a square floor plan with facades facing the four main orientations, was set up within *EnergyPlus* simulation software (version 7.0) with the definition of the building geometry, location, internal loads, façade properties and orientation. An illustration of the simulation methodology is shown in Figure 5:3.

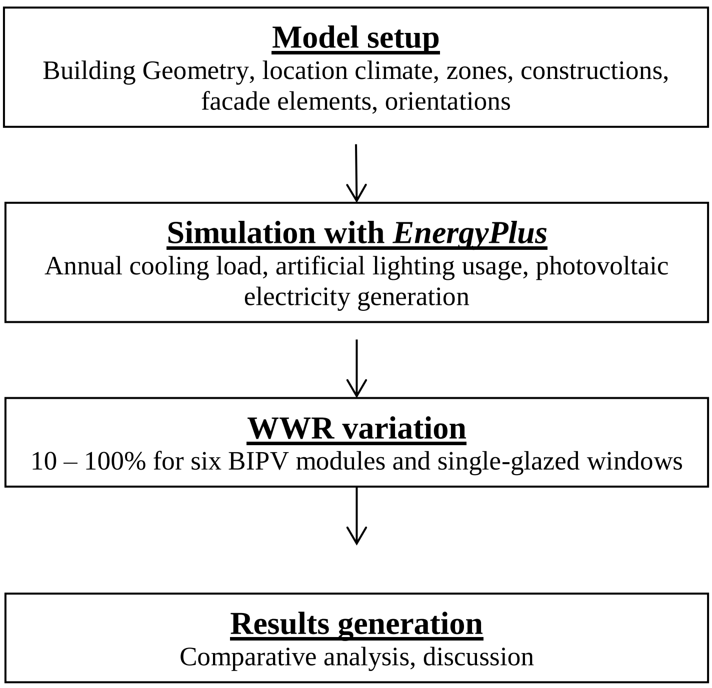


Figure 5:3 – Overview of simulation methodology

A standard mid-floor (30m (W) x 30m (B) x 3m (H) was modelled to reduce computational loads. The space was divided into five zones, consisting of four perimeter zones (200m^2 each), facing east, west, north, south and a core zone. The zones were separated by internal walls which were deemed adiabatic to prevent heat transfer in between so that each perimeter zone can be accurately analysed. The core zone was not considered during the simulations. The window aspect ratio was maintained at 1:10 for all window-to-wall ratios (WWRs), similar to the length-to-height ratio of the external buildings. Properties of the six semi-transparent BIPV modules as established by experiments and modified to suit Singapore climate (see section 5.3) were included in the model to be used for the windows. A central cooling system with a coefficient of performance (COP) of 3.37 was chosen for the building to comply with building legislation requirements in Singapore (SPRING, 2006). The COP was used to determine the electricity consumption of the cooling system from the cooling loads obtained. The plan view of the office is shown in Figure 5:4, while the building description, construction details and internal heat gains are shown in Table 5:2, Table 5:3 and Table 5:4, respectively. The building description values used adhered to the local building code of practice standards (SPRING, 1999, SPRING, 2006)

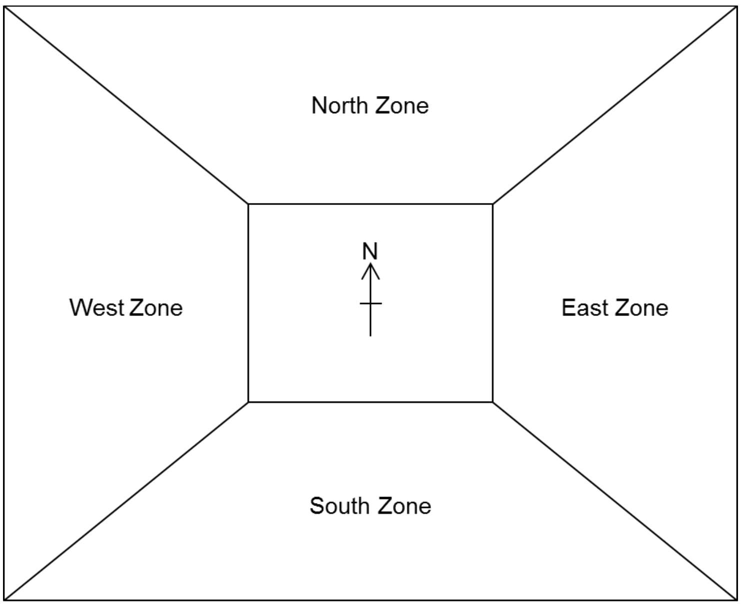


Figure 5:4 – Plan view of the simulated office building

Table 5:2 – Description of office building used for simulation

Parameters	
Total simulated area	800 m^2
Floor-to-ceiling height	3.0 m
Window aspect ratio (height: length)	1:10
Window-to-wall ratio (WWR)	10–100 %
Illuminance setpoint	500 lux
HVAC temperature setpoint	22 °C
Occupancy	0.2 person/m^2
Lighting	10 W/m^2
Equipment	8 W/m2
Infiltration rate	0.1 air changes per hour
Ventilation rate	3.0 $m^3/(s.m^2)$
Operational hours	0900–1800 hrs (weekdays only)

Table 5:3 – Construction details of the office building used for simulation

Layers (outer to inner)	**Thermal conductivity [W/(m·K)]**	**Density [kg/m^3]**	**Specific heat [J/(kg·K)]**
Exterior wall			
200 mm heavyweight concrete	1.95	2240	900
50 mm insulation board	0.03	43	1210
Air space	(Thermal resistance = 0.15 m^2·K/W)		
19 mm gypsum board	0.16	800	1090
Ground floor			
200 mm heavyweight concrete	1.95	2240	900
Roof			
100 mm heavyweight concrete	0.53	1280	840
Air space	(Thermal resistance = 0.15 m^2·K/W)		
Acoustic tile	0.06	368	590

Table 5:4 – Hourly variations office building model's internal heat gains

	Occupants [%]	**Lighting [%]**	**Electric Equipment [%]**
0 h – 8 h	0	0	0
8 h – 9 h	0	30	40
9 h – 10 h	90	90	90
10 h – 12h	95	90	90
12 h – 13 h	50	90	80
13 h – 17 h	95	90	90
17 h – 18 h	30	50	50
18 h – 24 h	0	0	0

Daylighting controls were also adopted to simulate the reduction of artificial lighting required. Artificial lighting will also be used when daylight itself was insufficient in meeting the required illuminance setpoint of 500 lux. Two daylight reference points were set in each zone which will act as photocells that control the overhead electric lighting. The positions (as seen in Figure 5:5) of the reference points in each zone are placed evenly between the façade and interior core wall, and also spread evenly across the length of the façade. Their height is set at 0.8m, which is the typical desk height. The fraction of the zone controlled by each reference point was divided evenly (i.e. 50%)

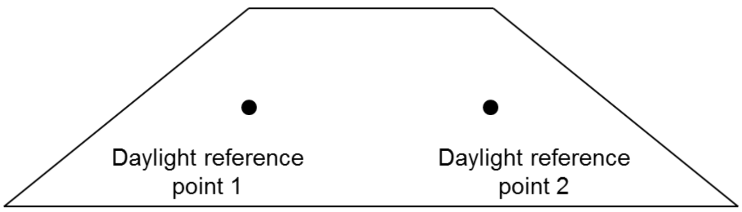


Figure 5:5 – Positions of daylighting reference points in a typical zone

Continuous dimming was chosen as the type of lighting control where the overhead lights dim continuously and linearly as the daylight illuminance increase. The lights stay on at the minimum point even with further increase in the daylight illuminance. The lowest power the lighting system can dim down to, expressed as a fraction of the maximum input power is 30%. Figure 5:6 illustrates the continuous dimming relationship of the lighting control.

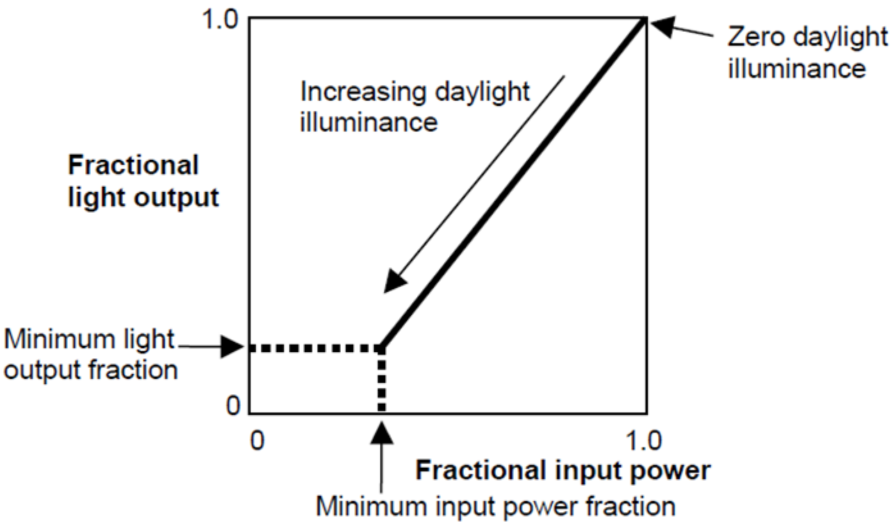


Figure 5:6 – Illustration of continuous dimming relationship for simulated building

The thermal accumulation in high mass buildings can dictate the degree of temperature swing of interior zones. It can also increase the degree of diurnal temperature if there is storage of excessive solar radiation (Mithraratne and Vale, 2006). To mitigate this, *EnergyPlus* ran the first day of weather data several times, known as warm-up period, to generate the initial conditions for heat conduction associated with the thermal mass of the walls. The maximum number of warm-up days was set at 25 days and within this period the convergence tolerance should be achieved. However, depending on the thermal mass level of the office building construction, the thermal accumulation in the building mass may not be sufficiently accounted for. This could result in errors in predicting the building cooling load, which is dependent on the thermal massiveness (Mithraratne and Vale, 2006). In order to ensure that the building's thermal mass do not affect the accuracy of the simulations, the same annual weather data was repeated over a consecutive three-year period. The building configuration adopted for this simulation was 50% WWR for all orientations and the window type was the BIPV module 1 (Hanwa). As shown in Figure 5:7, the predicted total building loads for the second and third years differed from the first year's results by less than 0.14%. As such, it was deemed that the thermal massiveness of the building was already sufficiently accounted for in the first year of simulation.

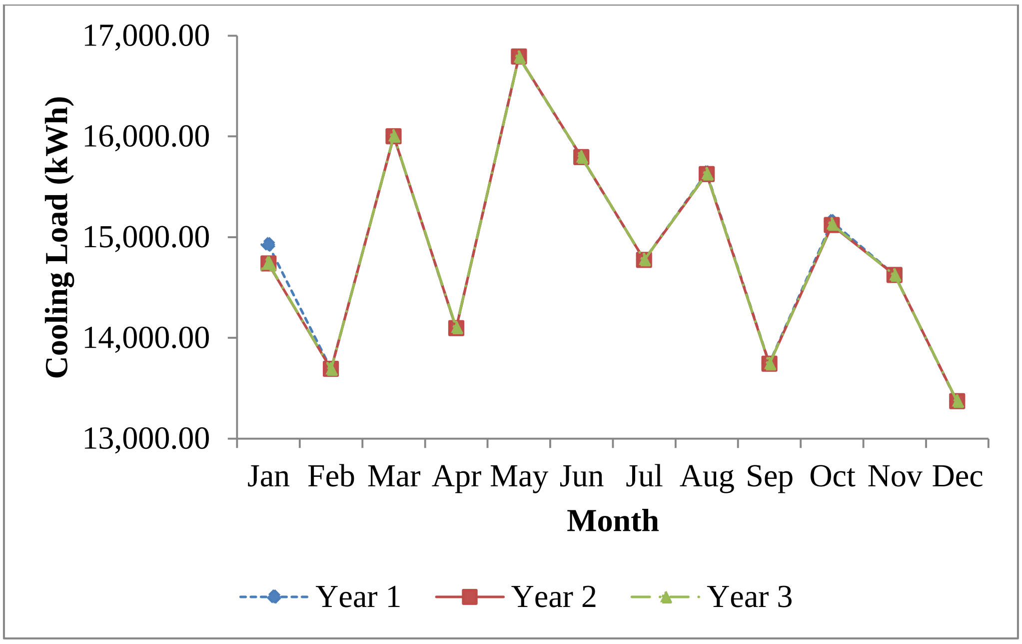


Figure 5:7 – Long term predicted total building cooling load (over a period of 3 consecutive years)

The model thus established was used to evaluate the impact of integrating semi-transparent BIPV windows on the energy consumption resulting from artificial lighting usage, space conditioning (cooling) energy usage and photovoltaic energy generation. Parametric analyses on the WWR and orientations for six-semi-transparent BIPV modules were conducted to investigate their effect on the overall performance of the building based on their annual NEB (in kWh per unit floor area). The WWR was varied from 10 to 100% (at 10% intervals) for the four main orientations (east, west, north and south). A sample *EnergyPlus* input file containing the building model with 50% WWR is shown in Appendix B.

5.5 Results and Discussion

5.5.1 Parametric Analyses on WWR and Orientations

The overall annual NEB as a function of WWR for the six semi-transparent BIPV modules for east, west, north and south orientations are shown in Figure 5:8, Figure 5:9, Figure 5:10 and Figure 5:11 respectively. NEB performance of modules 1, 5 and 6 is very similar being positive throughout all WWR and across all four orientations relative to opaque walls. The NEBs vary from 1.79 to 23.26 kWh/m^2/yr and increase steadily with the increase in WWR. Performances of modules 2, 3 and 4, however, are very different. As the WWR increases, their NEBs decrease before increasing slowly after 60% WWR. Out of these 3 modules, only module 2 manages to obtain a positive NEB which is only achieved at high WWRs (70–100%). Module 2’s NEB range from -1.69 to 4.30 kWh/m^2/yr, while for modules 3 and 4 they are lower at -6.31 to -0.87 kWh/m^2/yr and -4.69 to -0.81 kWh/m^2/yr respectively.

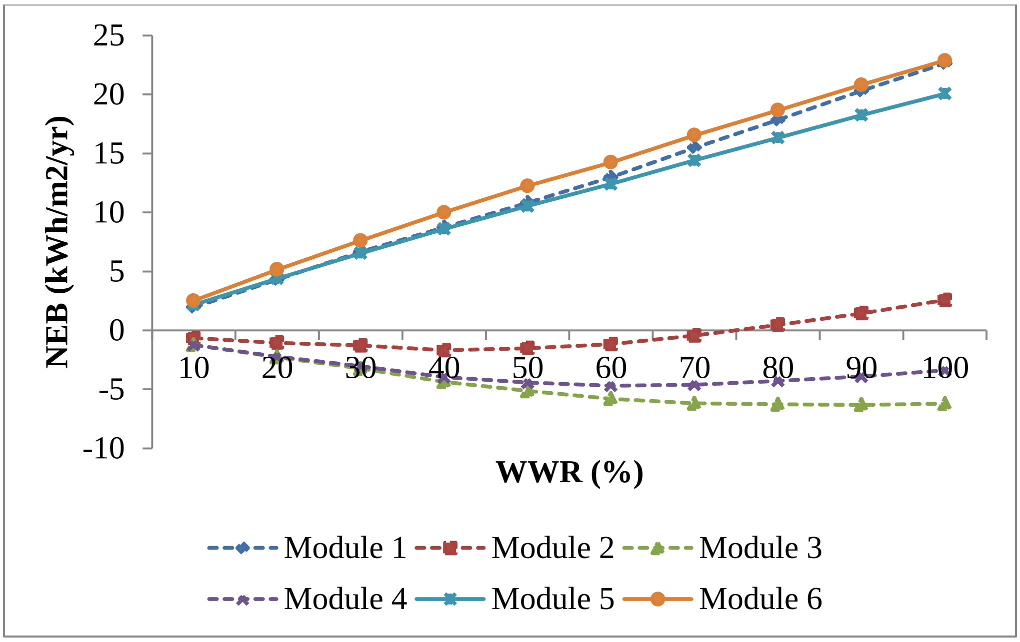


Figure 5:8 – Effects of WWR on NEB for various modules on east façade orientation

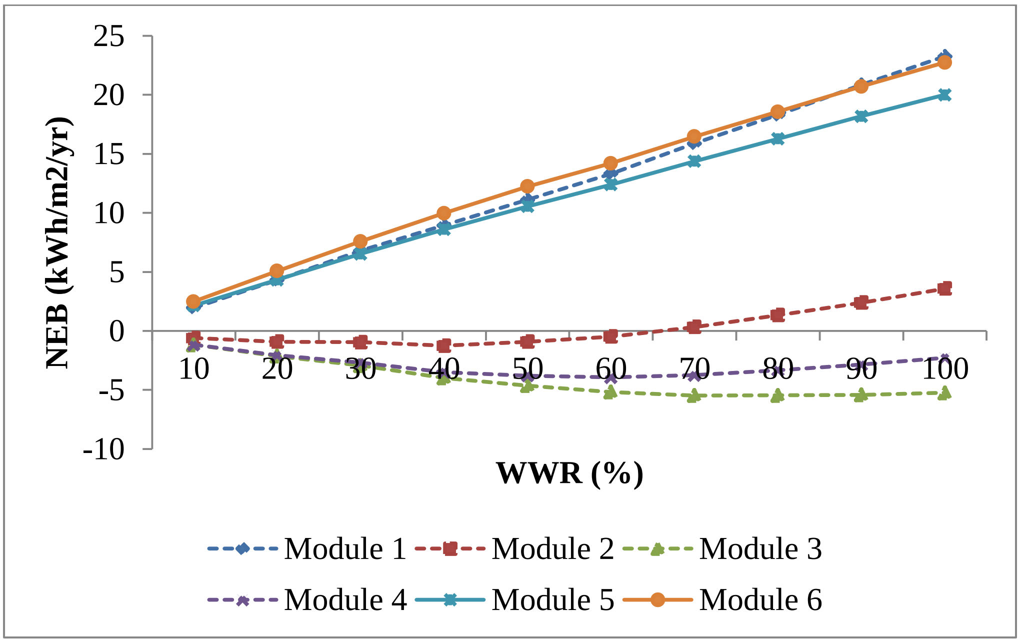


Figure 5:9 – Effects of WWR on NEB for various modules on west façade orientation

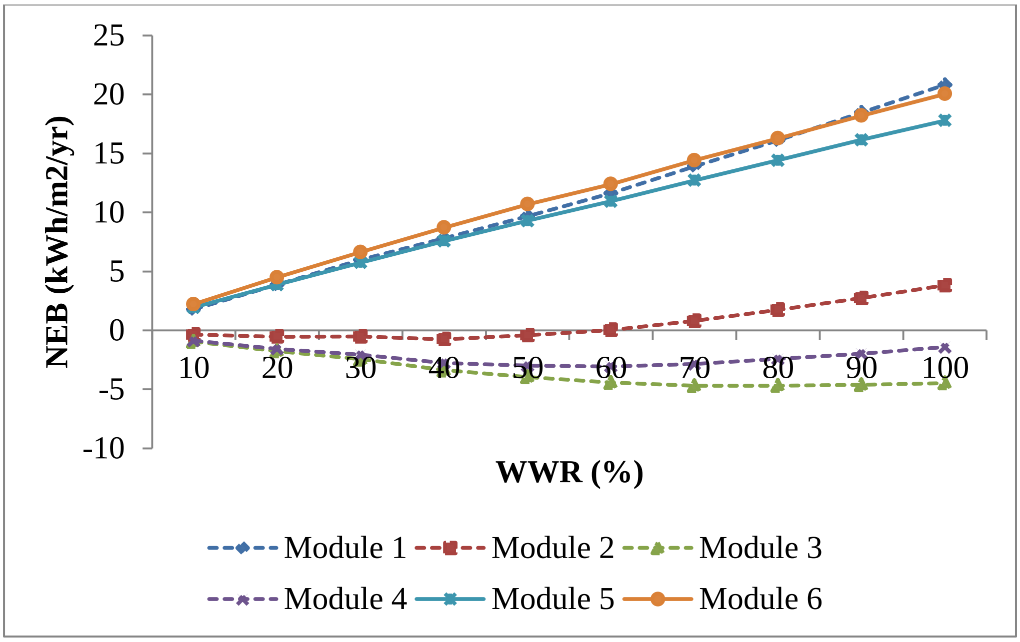


Figure 5:10 – Effects of WWR on NEB for various modules on north façade orientation

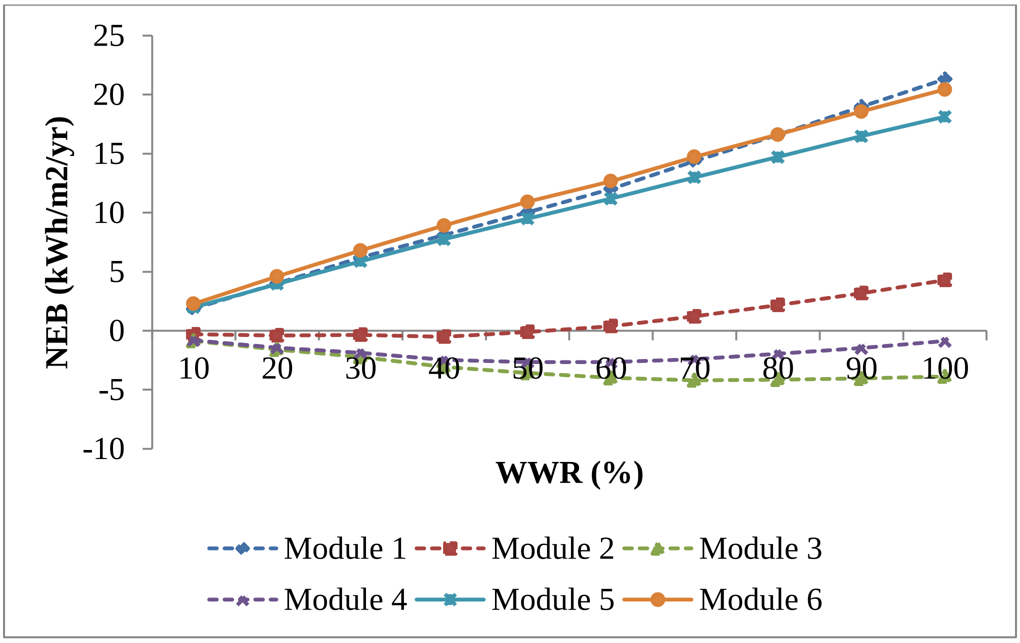


Figure 5:11 – Effects of WWR on NEB for various modules on south façade orientation

The results indicate that the NEBs of BIPV relative to opaque walls can be very different and dependent on the WWR adopted. Double-glazed BIPVs (modules 5 and 6) show good performance due to their better thermal performances, even though they have slightly lower photovoltaic efficiencies. Good thermal performance for facades is important for tropical areas like Singapore which have high outdoor temperature and solar heat gain. Single-glazed BIPVs (modules 1 – 4) have higher U-values and SHGCs which allow heat gain and results in higher cooling energy loads. However, module 1 with similar performance to the double-glazed window indicates that higher photovoltaic efficiency and/or VLT can offset the increase in thermal gains. To further understand the impacts of the individual positive elements (reduction in artificial lighting and PV electricity generation), their respective percentages of contribution to the total positive elements are tabulated from the simulation results and shown in Table 5:5. It can be seen that PV electricity generation is the main positive component for NEB ranging from 69.1–88.5% for all modules across various orientations. For this reason, module 1 can out-perform all other single-glazed BIPVs as its photovoltaic efficiency is the highest.

Table 5:5 – Breakdown of positive impacts of semi-transparent BIPV modules

	Reduction in artificial lighting [%]		**PV electricity generation [%]**	
	Minimum	**Maximum**	**Minimum**	**Maximum**
Single-Glazed BIPV				
Module 1	21.7	27.6	72.4	78.3
Module 2	18.7	22.6	77.4	81.3
Module 3	12.6	15.6	84.4	87.4
Module 4	19.7	23.9	76.1	80.3
Double-glazed BIPV				
Module 5	25.2	30.6	69.4	74.8
Module 6	27.4	33.1	66.9	72.6

The results also suggest that, in Singapore it is possible to integrate semi-transparent BIPV modules on facades that do not face the sun path. As seen from Figure 5:10 and

Figure 5:11, the modules 1, 5 and 6 generate positive NEBs for all WWRs on north/south orientations relative to opaque walls where diffuse sunlight contributes approximately 70% of skylight received. Module 2 is also able to achieve positive NEB when the WWR is 60% or more. Furthermore, diffuse sunlight is known to be 'cooler' than direct sunlight which reduces the solar heat gain in the zones and in turn, decreases the amount of cooling required and also the size of the air-conditioning system. This finding strongly supports extensive semi-transparent BIPV adoption across all orientations in tropical Singapore's high-rise buildings.

5.6 Comparison of BIPV windows against conventional glazing

In real-life applications, design decisions to convert opaque walls to windows are rarely considered. Often, aesthetic decisions pertaining to façade design are firmed, before alternatives for materials and systems are considered. As such, the approach should be considering the difference in energy performance in adopting semi-transparent BIPV modules on areas where windows are already established. Then the selection should consider the relative benefit of using semi-transparent BIPV rather than common glazing types. This section compares the performance of the six BIPV modules acting as semi-transparent windows against that of conventional glazing.

Additional simulations and comparative analyses were performed to explore the performance of semi-transparent BIPVs against three energy efficient window glazing systems (double, low-e and tinted low-e), in terms of total electricity consumption. This comparison was limited to buildings with highly glazed facades, and therefore only WWRs of 70–100% were considered. The properties of common window glazing types which were used for comparison are shown in Table 5:6.

Table 5:6 – Properties of traditional and current window glazing types

Layers (outer to inner)	**Solar transmittance**	**Visible transmittance**	**Thermal conductivity [W/(m·K)]**
Double glazing			
12 mm clear glass	0.653	0.841	0.9
6 mm air gap	-	-	-
6 mm clear glass	0.775	0.881	0.9
Double low-e glazing			
6mm low-e glass	0.60	0.84	0.9
6mm air gap	-	-	-
6mm clear glass	0.775	0.881	0.9
Double low-e tinted glazing			
6mm low-e tinted glass	0.36	0.5	0.9
6 mm air gap	-	-	-
6 mm clear glass	0.775	0.881	0.9

Based on: *EnergyPlus* (version 7.0) window construction database

The total annual electricity consumption of nine window types (six semi-transparent BIPV modules and the three glazing systems) for highly-glazed facades (WWR of 70% or more) is compared and shown in Figure 5:12. Three commonly used window glazing types portray a consistent increase in annual electricity consumption of approximately 3 $kWh/m^2/yr$ for every 10% increase in WWR. In contrast to that, all the semi-transparent BIPV modules show a decrease in annual electrical consumption of 0.15–2.45 $kWh/m^2/yr$.

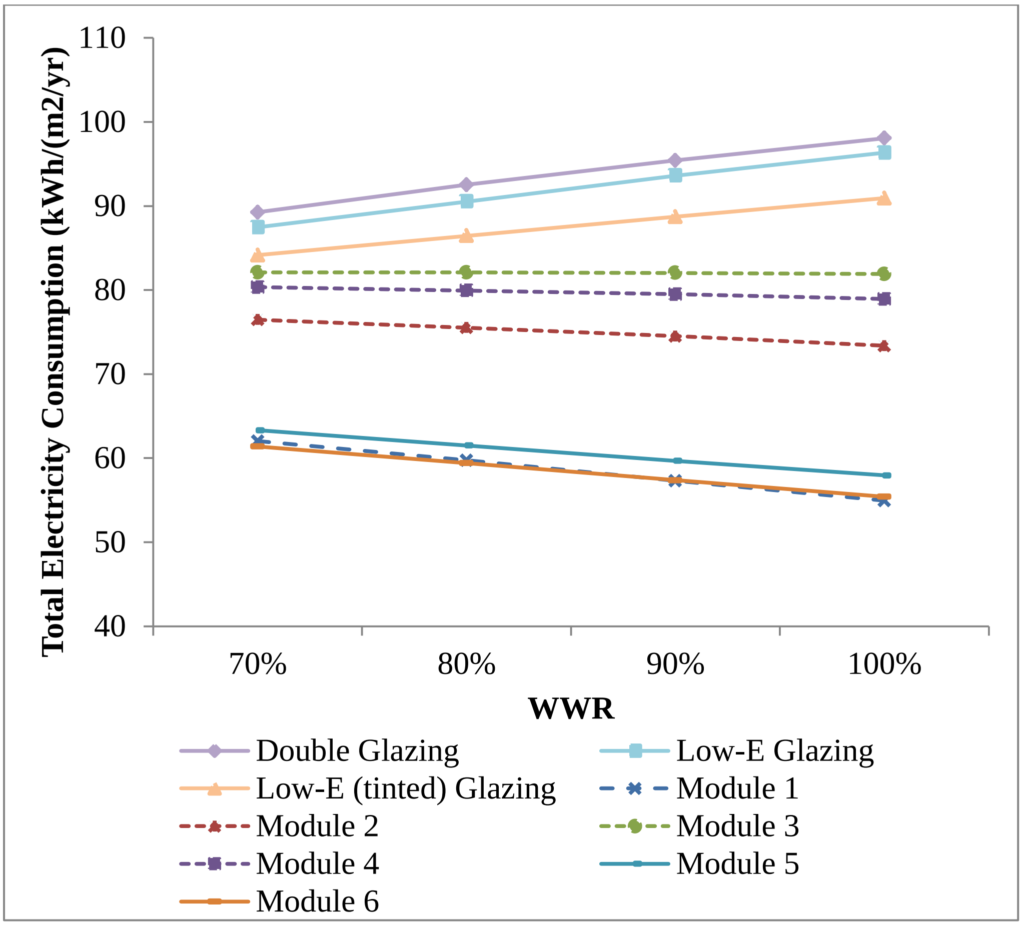


Figure 5:12 – Annual electricity consumption with nine window types (lighting, air-conditioning & PV electricity generation included)

5.7 Redefining "Net Electricity Benefit"

In the hot and humid climate of Singapore double-glazed windows are the de-facto standard for energy efficient buildings. In addition, recent government regulations also mandated that new or existing building works of at least 2,000 m^2 to be certified with the minimum score of Green Mark, which is the environmental sustainability standard for building works in Singapore (BCA, 2012). As such, the use of single-glazing for highly-glazed buildings will be minimized and replaced by double-glazed windows in time to come.

Architectural design decisions will also follow suit, whereby comparisons will be made against the new standard of double-glazing. Hence, the NEB as defined earlier, should encompass and reflect the difference in selecting a semi-transparent BIPV module as compared to double-glazed windows. This will assist design decisions directly, when information relating to the direct comparison of semi-transparent BIPV and double-glazed windows is at hand readily. Therefore, the NEB is hereby redefined as the net electricity benefit as compared to a double-glazed window, considering the increase/decrease in lighting and cooling electricity required and generation of photovoltaic electricity.

The redefined NEBs of the six semi-transparent BIPV windows for 70–100% WWR are shown in Figure 5:13. The single-glazed BIPV modules are highlighted in dotted lines for easy viewing and segregation. The performance of the six modules ranges from 7.43–40.72 kWh/m^2/yr and portraits a consistent increasing trend as the WWR increases from 70–100%. The double-glazed BIPV modules perform the best with their NEBs of 27.65–41.52 kWh/m^2/yr. Out of the four single-glazed modules, only module 1 is able to achieve similar electrical benefit. The remaining single-glazed BIPV modules of varying colours, though did not perform exceptionally well, still manage to obtain NEBs of 7.43–21.88 kWh/m^2/yr.

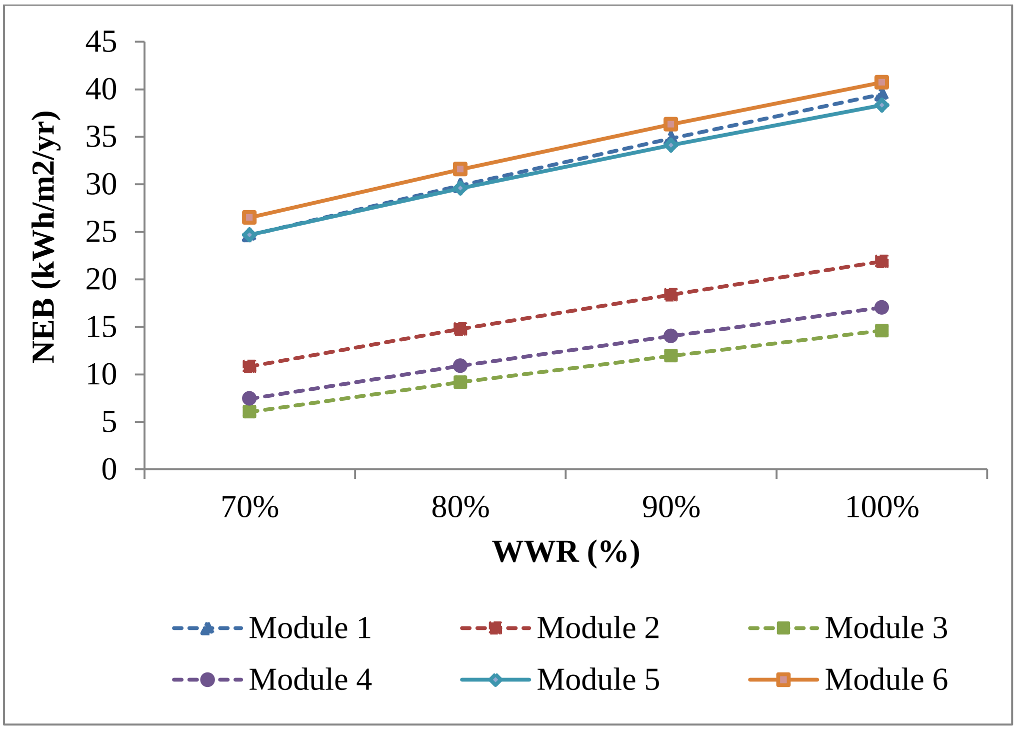


Figure 5:13 – NEB of the six semi-transparent BIPV windows (relative to double-glazing)

The potential percentage savings that may be achieved by adopting semi-transparent BIPV and other alternative window types as compared with commonly used double-glazing systems are shown in Figure 5:14. The low-e and tinted low-e glazing exhibit consistent savings of approximately 2.0 and 6.7% respectively compared with double glazing. The semi-transparent BIPV modules indicate a consistent increase in savings of between 6.79–41.52%. Although the double-glazed BIPV modules show the largest percentage savings, the results indicate that even the lower performing semi-transparent BIPVs with negative NEBs are relatively more energy efficient compared with current window technologies.

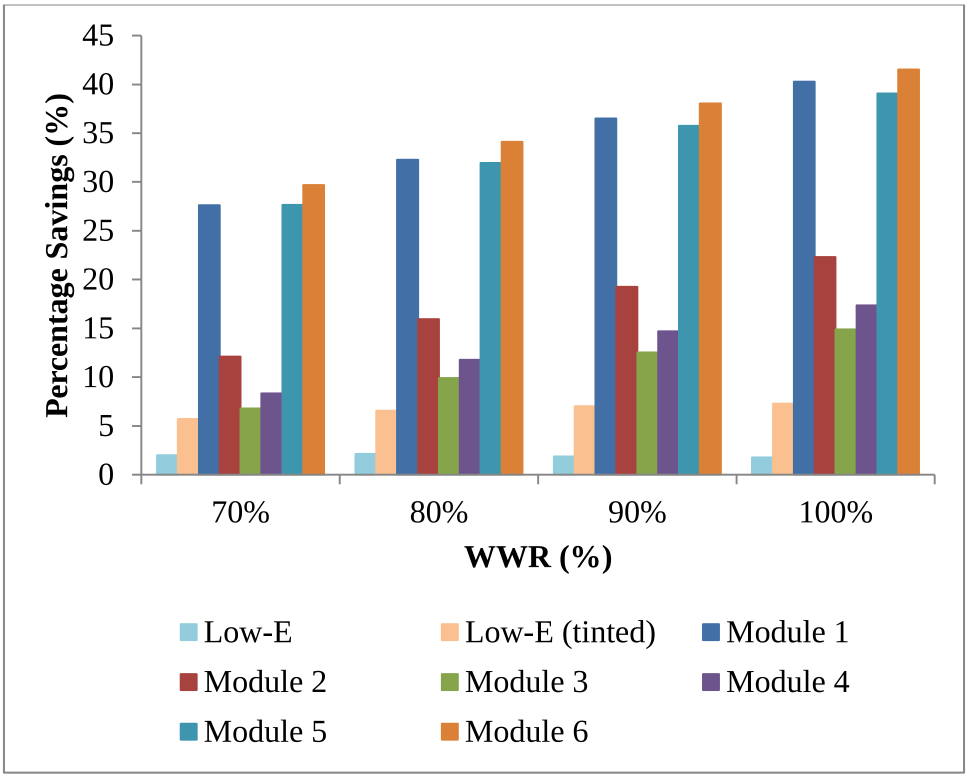


Figure 5:14 – Percentage of total NEB savings of alternative window types relative to double glazing

5.8 Summary

This chapter first demonstrated the theoretical energy-saving potential of semi-transparent BIPV windows in Singapore buildings. Data obtained through physical measurements were used for building energy simulations to determine the electrical benefits of applying semi-transparent BIPV windows as compared to a fully opaque wall. Parametric simulations were performed by varying both the orientation and WWRs for all the six investigated BIPV modules. Modules 1, 5 and 6 were able to achieve positive NEBs through the entire WWR range of 10–100%. Module 2 was only able to obtain positive NEB after 60% WWR while modules 3 and 4 were unable to achieve positive NEBs for any WWR or orientations.

Subsequently, the energy saving potential of semi-transparent BIPV windows in highly glazed buildings as compared to double-glazed windows was explored. The redefined NEB can assist building designers by providing them quantitative information on the electrical benefits of adopting different semi-transparent BIPV, as compared to using double-glazed windows. All the six investigated semi-transparent BIPV modules performed better than current energy efficient window adopting double-glazed low-e technologies. As compared to double-glazing, the modules obtain NEB of 7.43–40.72 kWh/m^2/yr which translates directly to 6.79–41.52% in building energy savings.

CHAPTER 6 LIFE CYCLE ASSESSMENT

6.1 Introduction

This chapter discusses the life cycle performance of the six selected semi-transparent BIPV modules. The analysis is conducted to evaluate its environmental and economic performance over its life time. Sensitivity of the results to alternative scenarios such as manufacturing modules in alternative regions, effects of nearby shading and future increase in electricity tariffs are also performed.

6.2 Life Cycle Assessment of BIPV

Although photovoltaic technology is widely recognised as the cleanest power generating technology and therefore BIPV should also be encouraged, some argue that it consumes additional energy during its life cycle, particularly in the manufacturing processes, which may be larger than its energy output in its life time. Therefore, in order to holistically examine the life cycle performance of any photovoltaic system, an LCA which considers resource investment as well as output should be used to measure its sustainability.

However, as discussed in section 2.5, LCA research that considers the multi-functional performance of semi-transparent BIPV facades (against traditional double-glazed windows) in tropical regions is lacking. In the hot and humid climate of tropics, high insolation received through the semi-transparent façade affects the building's interior lighting and solar heat gain in addition to the electricity generated by the photovoltaic. If the savings in building materials (BIPV modules replacing building envelope materials) and building space conditioning loads due to BIPV integration are taken into account, the life cycle performance could reveal higher potential (Lu and Yang, 2010). It is also imperative to examine the effects of transporting photovoltaic modules to countries where they are not produced locally, such as Singapore.

6.3 Life Cycle Energy Performance

As discussed in previous chapters, a holistic evaluation of semi-transparent BIPV windows' energy performance should include all its energy-related impacts on a building. In chapter 5, the term NEB was introduced, which represents all the contributory elements which are photovoltaic electricity generation, electricity savings due to natural sunlight and the difference in cooling electricity. From the simulation results in chapter 5, the energy performance was estimated based on the application of BIPV in a highly-glazed Singapore office building with a WWR of 90%. Although these results indicate that WWR of 100% is able to achieve an even higher NEB, 90% was chosen as more realistic where the framing and trunking are assumed to occupy 10% of the WWR. Hence, the functional unit of assessment is $81m^2$ (90% of the 30m x 3m building façade) of semi-transparent BIPV window system. The annual simulation results are used to determine the 25-year life cycle energy performance of the semi-transparent BIPV systems. Fthenakis et al. (2011) note that all photovoltaic modules degrade over time which reduces its electricity efficiency and therefore recommended using a linear degradation reaching 80% of the initial efficiency at the end of the lifetime.

The breakdown of the energy simulation results for the six BIPV modules are tabulated in Table 6:1. As the energy performances of East and West (as well as North and South) are very similar due to the sky conditions in Singapore, they are averaged and presented together (i.e. as EW and NS). The modules being semi-transparent, artificial lighting requirement is increased relative to clear double-glazed windows used as the base case.

Table 6:1 – Annual and life cycle energy performance as compared to double-glazed window

	Orientation	**Lighting (kWh/yr)**	**Cooling (kWh/yr)**	**PV generation (kWh/yr)**	**Annual NEB (kWh/yr)**	**Life cycle NEB (GWh)**
Module 1	East / West	-1218	3871	5297	7951	185.5
	North / South	-1364	3061	4511	6207	143.9
Module 2	East / West	-1862	2341	3897	4376	99.6
	North / South	-1981	1848	3318	3185	71.3
Module 3	East / West	-2464	3280	2193	3009	69.8
	North / South	-2508	2529	1867	1888	42.5
Module 4	East / West	-2043	2541	2926	3424	78.3
	North / South	-2140	1991	2491	2342	52.3
Module 5	East / West	-1622	6014	3309	7702	184.3
	North / South	-1773	4868	2817	5912	140.8
Module 6	East / West	-1547	6638	3138	8229	197.9
	North / South	-1703	5374	2671	6342	151.9

6.4 Life Cycle Resource Use

The photovoltaic systems studied in this chapter were assumed to be installed as BIPV windows in a Singapore office building with 90% WWR. The modules' manufacturing phase resource uses were obtained from the ecoinvent (v2.1) database (Jungbluth et al., 2009, Frischknecht et al., 2007) and were modified to represent the actual scenario. Table 6:2 shows additional information required for the life cycle analysis such as country of manufacture, cost and weight of each module. Representative inverters and balance of system components were also selected from the same database. The extracted raw data are shown in Appendix C.

Table 6:2 – Additional information on BIPV modules for LCA

S/N	Module	Country of manufacture	Cost per module (SGD)	Weight (kg)
1	Hanwa Makmax (KN-42)	Japan (Kobe)	754	20
2	Auria Solar (Micromorph – Red)	Taiwan (Kaoshiung)	446	23
3	Auria Solar (Micromorph – Golden)	Taiwan (Kaoshiung)	446	23
4	Auria Solar (Micromorph –Dark Blue)	Taiwan (Kaoshiung)	446	23
5	Schott Solar (Voltarlux ASI-ISO-E1.2)	Germany (Mainz)	1165	40.5
6	Spear Technology Alliance (SSM-50SS0533Air)	Taiwan (Taipei)	1520	49

Conversion rate: US \$1 = SG \$1.3, €1 = SG \$1.7

Singapore's national grid electricity mix which comes from natural gas (75.8%), fuel oil (21.6%), diesel oil (0.3%) and waste incineration (2.3%) (EMA, 2007) was considered for this study. With 2.5% transmission losses, the carbon emissions of Singapore's grid electricity are 601.0 gCO2eq/kWh (Tan et al., 2010). This highlights an added benefit of BIPV systems, which is avoiding transmission losses associated with the national electricity grid due to on-site electricity generation. All unit processes within the system boundary that are likely to make a material contribution (of more than 1%) have been included.

The LCA stages included were the manufacturing of BIPV components from raw materials, their transport from country of origin to the site in Singapore, installation on site, operation and maintenance, and disposal/recycling of waste. Table 6:3 summarises the data sources for each life cycle stage and also indicates the uncertainties in the data used, if any.

Table 6:3 – Summary of data sources for each life cycle stage

Life Cycle Stage	Item	Data Sources	Uncertainty
BIPV manufacturing	a-Si laminate	Jungbluth et al., 2009 (ecoinvent)	Lognormal
	Micromorph module	Bravi et al. 2011	N.A.
	Electricity mix	Jungbluth et al., 2009 (ecoinvent); Tan et al., 2010; Huang and Wu, 2009	Lognormal
	Inverters	Jungbluth et al., 2009 (ecoinvent)	Lognormal
Transport to site	Transoceanic freight	Jungbluth et al., 2009 (ecoinvent); Portworld, 2013	Lognormal
	Courier	Jungbluth et al., 2009 (ecoinvent);	Lognormal
On-site installation	Balance of system (excluding inverter)	Jungbluth et al., 2009 (ecoinvent)	Lognormal
Operation and maintenance	Inverter replacement	Jungbluth et al., 2009 (ecoinvent)	Lognormal
	Maintenance operations	Jungbluth et al., 2009 (ecoinvent)	Lognormal
Decommissioning, disposal and recycling of waste	Municipal solid waste	Tan and Khoo, 2006	N.A.

The following sections discusses the assumptions used for the life cycle inventory.

6.4.1 Manufacturing of BIPV

Manufacturing data were derived from two data sources (Bravi et al., 2011, Jungbluth et al., 2009). The manufacturing processes in *ecoinvent* database did not have primary data on μc-Si module technology. Therefore, for modules 2, 3 and 4 which use μc-Si technology, secondary data were adopted. The manufacturing data thus obtained were modified to reflect the country specific electricity mix used during the manufacturing process based on country of origin for respective modules. Table 6:4 shows the electricity mixes for the various countries. The additional materials required to manufacture modules 5 and 6, which are double-glazed were also included. In addition, two inverters of 2.5 kW each were also included. The total weight of the inverters is 39 kg (18.5 kg each).

Table 6:4 – Electricity mixes of various countries adopted for study

	Unit	**GHG Emissions (kgCO2eq)**	**Cumulative Energy Demand (MJ)**
electricity, medium voltage, at grid, Japan[a]	kWh	0.556	12.1
electricity, medium voltage, at grid, US[a]	kWh	0.770	12.8
electricity, medium voltage, at grid, China[a]	kWh	1.170	11.3
electricity, medium voltage, at grid, Germany[a]	kWh	0.656	11.5
electricity, medium voltage, at grid, UCTE[a]	kWh	0.530	11.4
electricity, Singapore[b]	kWh	0.601	8.28
electricity, Taiwan[c]	kWh	0.826	24.108

[a] extracted from Jungbluth et al. (2009)
[b] extracted from Tan et al. (2010)
[c] extracted from Huang and Wu (2009)

6.4.2 Transport to Site

Since BIPV modules and inverters are assumed to be imported to Singapore, various modes of transport from overseas port to site in Singapore are included. Data were not available to estimate the land transport distance and mode in the country of origin and therefore this has been omitted. Transoceanic freight is assumed to deliver components from overseas port to Singapore’s port, with onward transport to the site by courier. Mass allocation was applied in the calculation of transportation energy to only account for the BIPV system investigated. The distances between are obtained from an online shipping distance calculator (Portworld, 2013) and the courier distance is assumed to be 20km (site assumed to be at the centre of Singapore). The freight distances used for this study are indicated in Table 6:5.

Table 6:5 – Port to port distances adopted for study

Loading Port	Landing Port	Distance (km)
Kobe, Japan	Singapore	4986
Kaoshiung, Taiwan	Singapore	2998
Keelung, Taiwan	Singapore	3337
Mainz, Germany	Singapore	15,972
Shekou, China	Singapore	2634

Source: http://www.portworld.com/map/ (Portworld, 2013)

6.4.3 On-site Installation

Besides the inverter, the remaining balance of system included the façade installation, mounting energy use and electric installation (cabling, trunking, etc.) in Singapore. These data are obtained from *ecoinvent* and modified with Singapore's grid electricity mix.

6.4.4 Operation and Maintenance

The lifetime of the modules are assumed to be 25 years. This is also the warranty provided by the manufacturers and is also in accordance with the IEA (Fthenakis et al., 2011) recommended life expectancy. The inverter life is assumed to be 15 years and therefore, one replacement with an identical inverter during the BIPV system lifetime is included. Other replacement parts are considered as negligible and therefore, disregarded in the calculation.

It is also noted by Jungbluth et al. (2009) that photovoltaic plants do not normally show any emissions to air or water during operation. The emissions due to maintenance operations are already considered in the (*ecoinvent*) inventories of the components. As panels might be washed by the user on an annual basis, it is assumed that the use of 20 litres of water per year per square meter is required. Wastewater will be discharged with the normal rainwater and its treatment is accounted for.

6.4.5 Decommissioning, Disposal and Recycling of Waste

The BIPV modules and components contain glass, aluminium and semiconductor materials that can be successfully recovered and reused, either in new modules or other products. In recent years, there have been suggestions on methods for end-of-life recovery of these materials (Fthenakis, 2000, Larsen, 2009). However, there is still a lack of reliable scientific or empirical data and established recycling strategies (Hammond et al., 2012, Kim et al., 2012, Lu and Yang, 2010, Lim et al., 2008, Pehnt, 2006, Raugei et al., 2007). Hence, the modules are considered to be disposed as municipal solid waste in Singapore (Tan and Khoo, 2006). The aluminium façade mounting are however, assumed to be recycled for future use.

6.5 Life Cycle Environmental Performance

The life cycle embodied energy of the BIPV system is calculated as the sum of the Cumulative Energy Demand (CED). CED represents the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or service. This includes both the direct uses as well as the indirect (grey) consumption of energy due to the use of materials (e.g. plastic or glass for construction), consumables necessary for manufacturing (e.g., solvents, gloves, packaging) and raw materials (Fthenakis et al., 2011). The energy sources in the CED indicator result include fossil, nuclear, biomass, hydro, primary forest, wind and solar.

The life cycle embodied energy and emissions of the individual components of the BIPV system, the six photovoltaic modules and conventional double-glazed windows are presented in

Table 6:6. The results indicate that the environmental burden associated with installing BIPV modules is significantly reduced if we deduct the avoided burden of double-glazed windows, which are currently the de-facto standard for energy efficient tropical buildings. For module 1, the GHG emissions are -951 kgCO_2eq which implies that installing a BIPV façade incorporating module 1 results in even lesser emissions than double-glazed windows. The remaining modules have GHG emissions of between 573–1647 kgCO_2eq. For cumulative energy demand, the six systems require primary energy of 29–106 GJ.

Table 6:6 – Life cycle energy and GHG emissions from BIPV assembly over 25 years

	GHG emissions ($kgCO_2eq$)	**Cumulative Energy Demand (GJ)**
(a) BIPV Module		
Module 1	3231	68.6
Module 2	5779	71.5
Module 3	5139	53.2
Module 4	5411	61.0
Module 5	4744	87.5
Module 6	4897	128.6
(b) Integrated façade construction	3239	51.9
(c) Module installation	2	0.03
(d) Electrical system installation	219	2.9
(e) Inverter (including replacement)	728	13.1
(f) Double-glazed Window	8369	90.6
Net Total [(a)+(b)+(c)+(d)+(e)-(f)]		
Module 1	-951	45.7
Module 2	1647	49.3
Module 3	894	29.5
Module 4	1215	37.9
Module 5	573	64.7
Module 6	755	106.2

*Note: values may not add up due to rounding

Figure 6:1 presents the life cycle energy use at different life stages for the six investigated BIPV façades. Balance of system refers to non-photovoltaic components required for the BIPV system to function and may include framing, mounting, cabling, inverter. It can be seen that the photovoltaic manufacturing process and the balance of systems makes up the largest contribution for all modules. In the case of module five, in addition to the above, transportation energy use is also significant, due to the need for cross-continental shipping as the module is imported from Germany.

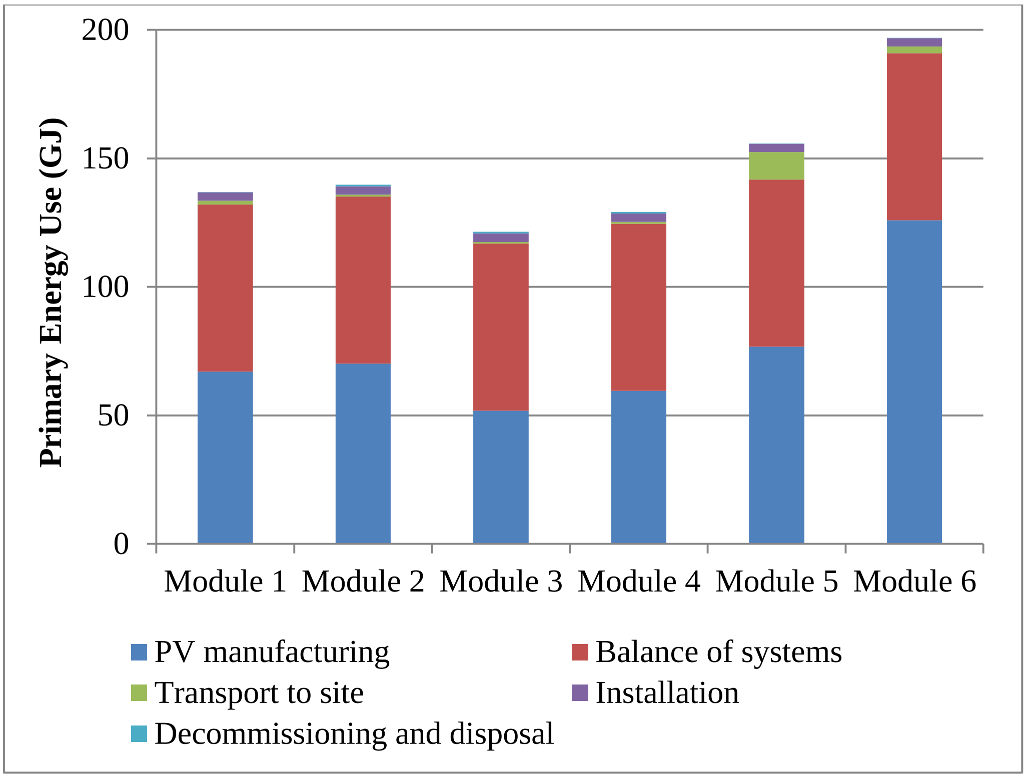


Figure 6:1 – Life cycle energy use at different life stages

6.5.1 *Energy and Emissions Intensity of Photovoltaic Generated Electricity*

The energy and GHG emissions intensities of electricity generated by the facade systems incorporating these modules facing different orientations are illustrated in Figure 6:2. Module 1 performs the best with the lowest energy and emissions intensities, at 240–310 MJ/kWh and -5 gCO2eq/kWh respectively. The double-glazed modules (5 and 6) were the next, in terms of performance, with GHG emissions of 45–62 gCO2eq/kWh and energy intensities of 823–1265 MJ/kWh. The worst-performing modules were the coloured-tinted modules (2, 3 and 4). Their GHG emissions and energy intensities were 98–212 gCO2eq/kWh and 1369–2754 MJ/kWh, respectively.

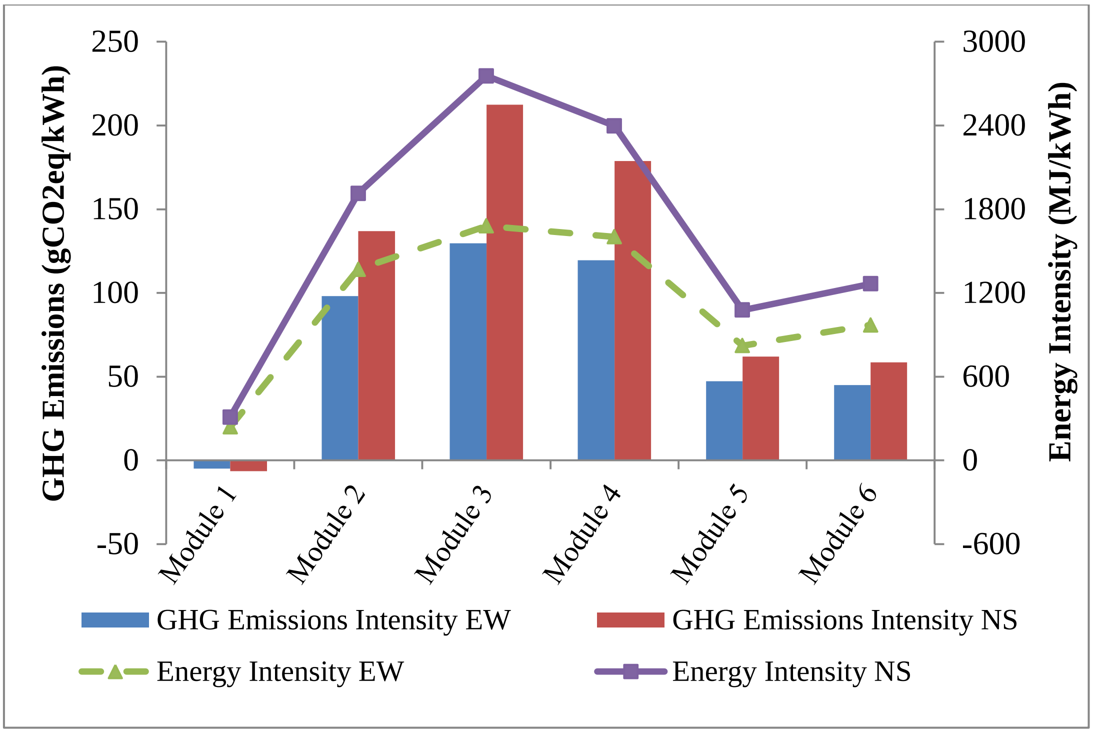


Figure 6:2 – Energy and emissions intensity of PV generated electricity

6.5.2 EPBT and EROEI Investigation

The interpretation of life cycle environmental performance is through the processing of the impact indicator, CED, into EPBT and EROEI. As discussed earlier in section 2.5, EPBT (measured in years) is defined as the period required for the BIPV system to generate the same amount of CED used in producing the system. EROEI is the ratio of the usable energy acquired from the BIPV system over its 25-year lifetime to the CED used to establish the BIPV system.

The six modules have NEB of 42.5–197.9 GWh relative to double-glazed windows and consume 29461–106234 MJ more primary energy over its 25-year lifetime. At the average annual NEB rate of 1888–8229 kWh/year and diminishing electricity efficiency over the years, the EPBT and EROEI of the modules are tabulated and shown in Table 6:7. In terms of EPBT, EW orientations perform better than NS for all modules. The EPBT values range from 0.68–1.52 for EW and 0.87–1.98 for NS orientations, with module 1 the lowest (0.68–0.97) and module 6 the highest (1.52–1.98). For EROEI, the values range from 11.72–34.49. Module 1 has the highest EROEI (26.75–34.39), while module 6 obtained the lowest value (11.72 for NS).

Table 6:7 – EPBT and EROEI for the six BIPV systems

	EPBT (years)		**EROEI**	
	EW	**NS**	**EW**	**NS**
Module 1	0.68	0.87	34.49	26.75
Module 2	1.33	1.83	17.17	12.29
Module 3	1.15	1.85	20.09	12.25
Module 4	1.31	1.91	17.54	11.72
Module 5	0.99	1.29	24.16	18.45
Module 6	1.52	1.98	15.81	12.13

The results obtained generally perform better than previous studies (see section 2.5) which obtained EPBTs of 1.8–3.5 with an average of 2.73 (Peng et al., 2013). This is largely due to the discounting of conventional glass façade's embodied energy from the BIPV systems embodied energy. Although semi-transparent BIPV may perform better than common double-glazing, wider adoption of semi-transparent BIPV will also depend on the economic performance. This is investigated in the next section.

6.6 Life Cycle Economic Performance

The initial cost of semi-transparent BIPV windows includes the costs of module, supply and fixing of aluminium framing, balance of system components and the electrical work. The purchased costs of the modules are shown in Table 6:2 while quotations obtained from local glazing contractors to supply glazing and fixed aluminium framing and to install double- clear-glazed facades are shown in Table 6:8.

A local photovoltaic system integrator estimated the costs of the remaining balance of systems and cost of electrical work (cabling, trunking, inverters, labour, etc.) to be SGD 2/Wp. The individual quotations and the correspondence with the photovoltaic system integrator are attached in Appendix D. The detailed breakdown of costs for the modules and double-glazed windows are shown in Table 6:9.

Table 6:8 – Costs of supply of glazing, aluminium framing and installation of double-glazed windows

	Double-Glazed Window (SGD)		
Company	**Supply of glazing**	**Supply of aluminum framing**	**Installation**
Space Construction PTE LTD	130.00	350.00	120.00
M.S. Kong Contracts PTE LTD	120.00	280.00	100.00
Thiam Building PTE LTD	128.40	128.40	64.20
Average (m^2)	126.13	252.80	94.73
Total (81m^2)	**10216.80**	**20476.80**	**7673.40**

*inclusive of 7% Goods and Service Tax

Table 6:9 – Total costs and breakdown of the six semi-transparent BIPV window systems and double-glazed windows

	PV Module	Glazing contractors' installation	PV System Integrator's electrical and BOS	Total Cost
Module 1	65,600	22,424	7,308	95,332
Module 2	25,263	22,424	9,063	56,749
Module 3	25,263	22,424	5,098	52,784
Module 4	25,263	22,424	6,797	54,484
Module 5	111,901	28,150	7,687	147,738
Module 6	132,245	28,150	8,700	169,095
DGW	-	38,367	-	38,367

*All prices stated are in Singapore Dollars (SGD)
Note: DGW – Double-glazed windows

In a bid to promote environmentally-friendly green building technologies and clean energy adoption, the Singapore government funds up to 30% of the total capital cost of photovoltaic systems (EMA and BCA, 2012). The additional costs of adopting semi-transparent BIPV window systems as compared to a double-glazed façade, with the 30% subsidy deducted, are shown in Table 6:10. The 30% local subsidy plays an important role in lowering the additional costs of adopting BIPV facades instead of the conventional double-glazed windows. The capital costs of modules 3 and 4, are less than that of a double-glazed window façade.

Table 6:10 – Costs of semi-transparent BIPV window systems after government subsidy

	Total Capital Cost	**Actual Cost (after 30% subsidy)**	**Additional cost (after deducting DGW)**
Module 1	95,332	66,732	28,366
Module 2	56,749	46,712	1,358
Module 3	52,784	36,949	-1,418
Module 4	54,484	38,139	-228
Module 5	147,738	103,417	65,050
Module 6	169,095	118,367	80,000

6.6.1 Payback Period of Semi-transparent BIPV Window Systems

According to local contractors, the maintenance of photovoltaic façade is similar to that of a conventional glazing and therefore was not considered. The NEB of adopting the semi-transparent BIPV systems, as opposed to double-glazed windows, were converted to electricity savings, which could be used as on-site generation to offset the operational costs of other building systems. The costs of electricity in Singapore at the beginning of 2013 was 0.281 SGD/kWh (SP-Services, 2013). Only modules 1, 2, 5 and 6 with a higher cost relative to double-glazing were considered. The payback periods, estimated with the 30% government subsidy at constant electricity prices, and constant dollars approach are shown in Table 6:11. When the NEB is included, the initial additional cost of integrating BIPV modules 1 and 2 can be recovered with payback periods of 13.1–17.1 and 1.1–1.5 years respectively. Modules 5 and 6 however, do not payback the additional investment during the 25-year lifetime, irrespective of their superior performance.

Table 6:11 – Economic payback periods of the semi-transparent BIPV window systems

	EW (years)	**NS (years)**
Module 1	13.1	17.1
Module 2	1.1	1.5
Module 5	N/A	N/A
Module 6	N/A	N/A

N/A – Not applicable; BIPV system does not break even

6.7 Sensitivity of Results

From the life cycle performance results, the investigated modules achieve a large variance of results, both environmentally and economically. Hence, to test the sensitivity of the life cycle performance results to the assumptions used, sensitivity analyses are conducted by considering possible variations to the base case scenario.

6.7.1 Environmental Sensitivity Analysis

The different manufacturing locations of the modules result in the embodied energy and GHG emissions to be different. The differences are not only a result of source country electricity mix but also the additional freight transport required, which contributes significantly to the embodied energy in the case of module 5 (approximately 7%). Furthermore, the existence of tall commercial buildings is likely to be common in urban cities where nearby buildings can obstruct the sky view of a façade, and reduce its solar exposure and affect its building energy performance (Ratti et al., 2005).

To account for solar exposure, sky view factor (SVF) is often chosen by architects and urban designers to describe urban geometry and measure urban climate parameters in built-up areas such as daylight availability, solar potential and renewable energy sources (Lin et al., 2010, Svensson, 2004, Ratti et al., 2003, Upmanis, 1999). Existing urban structures or obstacles can affect the visible horizon plus the incoming thermal radiation fluxes and such modifications can be accounted for in the estimation of the SVF (Matzarakis et al., 2007, dos Santos et al., 2003). SVF is a good measure of the openness of the urban texture to the sky and by definition is the ratio of radiation received by a planar surface to the radiation emitted (or received) by the entire hemispheric environment (Ratti et al., 2003, Watson and Johnson, 1987).

It is a dimensionless measure between zero and one, representing a totally obstructed and completely unobstructed (free spaces) view of the sky, respectively (Cheng et al., 2006, Oke, 1988). For an unobstructed vertical façade, the SVF is 0.5 (i.e. the façade is exposed to half of the entire sky) (Compagnon, 2004). Previous research to measure and estimate the SVF values of urban area facades range between 0.2–0.5 (Leung and Steemers, 2008, Montavon et al., 2004, Scartezzini et al., 2002).

Manufacturing location and associated transport impact can play a significant role in determining the environmental performance. The re-location of factories to locations within the same continent may possibly reduce the embodied energy and emissions and improve the environmental performance significantly. China is home to many PV manufacturing plants and photovoltaic manufacturers due to abundance in land and cheap labour. Also, a leading photovoltaic manufacturer, Renewable Energy Corporation (REC), has recently built a photovoltaic manufacturing plant in Singapore, and this eliminates the need for freight transport. With many tall buildings located in high density urban areas, shading by adjacent buildings will impact the environmental performance of semi-transparent BIPV facades.

In order to test the sensitivity of life cycle environmental performance results to the assumptions used and consider other possible scenarios, a sensitivity analysis is conducted with variations to the base case scenario which considered the impact of manufacturing locations and likelihood if shading during realistic applications, six variations are considered. They are:

- Scenario 1: Module 5 is manufactured in Asia, instead of Europe. It is assumed to be manufactured in southern China, in the city of Shekou. Chinese energy mix is used for manufacture with respective transport requirements.
- Scenario 2: Module 1–6 are manufactured in Singapore. Hence, cross-continental freight transport is eliminated and Singapore's electricity mix is used.
- Scenario 3a: Shading due to nearby buildings in the urban context that lower solar incident on façade windows are considered. The SVF is reduced by 1/3 to obtain 0.333.

- Scenario 3b: Similar to 3a, but SVF is reduced by 2/3 to 0.167. The higher reduction of 0.167 SVF is to examine extreme cases and also the potential of integrating semi-transparent BIPV at lower levels of tall high-rise buildings.
- Scenario 4a: Modules manufactured in Singapore are used in buildings with SVF of 0.333.
- Scenario 4b: Similar to 4a, but SVF is reduced by 2/3 to 0.167.

The modelling of the various SVFs in *EnergyPlus* was performed by placing objects at various heights around the building perimeter to act as obstructions. As illustrated in Figure 6:3, an obstruction object covering one-third (equivalent to 30°) of the exterior view was erected to achieve a SVF of 0.333. For SVF of 0.167, a higher obstruction object was placed to cover two-thirds (equivalent to 60°) of the exterior view.

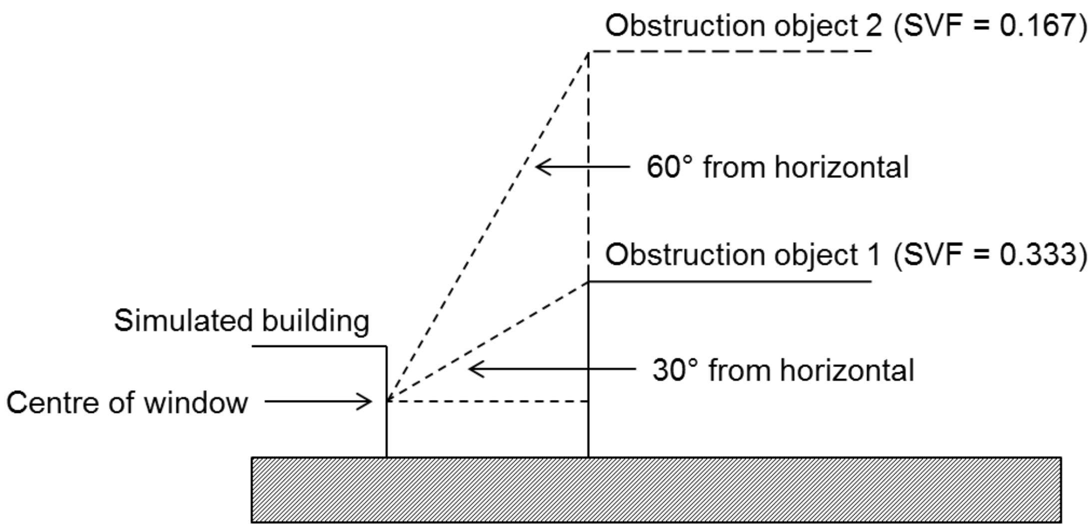


Figure 6:3 – Illustration of obstruction objects to achieve reduced SVF

The environmental performance results in terms of GHG emissions and CED of the sensitivity analysis are shown in Table 6:12 and Table 6:13. The embodied energy for scenarios 3 and 4 are equal to that of base case and scenario 2, respectively and hence are not shown. Life cycle energy use for scenario 1 indicates a 15% decrease, when cross-continental freight is changed to shipping within the continent and China's national electricity mix is used instead of Japan's. For scenario 2, with all modules made in Singapore (eliminating freight and adopting Singapore's electricity mix), the life cycle energy decreases significantly for all modules, ranging from 19–55% of the base case. However, module 1's life cycle GHG emissions under scenario 1 are 253% higher than the base case scenario. For scenario 2, all modules indicate a reduction of 25–231% except for module 1, which has an increase of 9%. The consistent decrease in life cycle energy compared to the mixed results for the GHG emissions show that while reducing the transport by manufacturing in a closer country has a major impact on reducing CED, it might increase the GHG emissions due to the electricity mix used in the country of manufacture. In the sensitivity analysis considered here, the increase in GHG emissions is due to Singapore's and China's electricity mix having a GHG emissions rate of 0.601 kwhCO_2eq/kWh (compared to Japan's rate of 0.556 kwhCO_2eq/kWh) and 1.170 kwhCO_2eq/kWh (compared to Germany's rate of 0.656 kwhCO_2eq/kWh) respectively.

Table 6:12 – Comparison of the six semi-transparent BIPV modules' life cycle CED under different scenarios

Cumulative Energy Demand (GJ)						
	Module 1	**Module 2**	**Module 3**	**Module 4**	**Module 5**	**Module 6**
Base case	45.7	49.3	29.5	37.9	64.7	106.2
Scenario 1	-	-	-	-	55.1	-
Scenario 2	29.3	22.1	13.9	17.4	36.5	86.2

Table 6:13 – Comparison of the six semi-transparent BIPV modules' life cycle GHG emissions under different scenarios

GHG emissions ($kgCO_2eq$)						
	Module 1	**Module 2**	**Module 3**	**Module 4**	**Module 5**	**Module 6**
Base case	-951	1,647	894	1215	573	755
Scenario 1	-	-	-	-	2,025	-
Scenario 2	-869	1228	640	890	-753	-58

The EPBT and EROEI for the different scenarios derived based on their respective life cycle energy use are shown in Table 6:14. For scenario 1, where module 5 is manufactured in Asia, the EPBT improved to 0.84 and 1.1 years, along with moderately higher EROEI of 28.37 and 21.67 for east/west and north/south orientations, respectively. This translates to a 15% decrease in EPBT and 17% increase in EROEI as compared to the base case. For scenario 2, EPBT for various modules and orientations decreases while the EROEI increases as expected from the lower CEDs. The EPBT ranges from 0.43–1.6 years while the EROEI ranges from 14.96–53.81.

Table 6:14 – EPBT and EROEI of the six semi-transparent BIPV modules under different scenarios

		Base Case		Scenario 1		Scenario 2		Scenario 3				Scenario 4			
								33.3% SVF		16.7% SVF		33.3% SVF		16.7% SVF	
		EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI	EPBT	EROEI
Module 1	E/W	0.68	34.49	-	-	0.43	53.81	1.40	16.24	4.74	4.59	0.90	25.33	3.00	7.17
	N/S	0.87	26.75	-	-	0.56	41.73	1.94	11.50	3.82	5.76	1.24	17.95	2.43	8.98
Module 2	E/W	1.33	17.17	-	-	0.60	38.23	3.53	6.09	N/A	0.24	1.56	13.56	N/A	0.53
	N/S	1.83	12.29	-	-	0.82	27.36	6.31	3.20	21.35	1.08	2.74	7.13	7.36	2.40
Module 3	E/W	1.15	20.09	-	-	0.54	42.56	3.32	6.58	N/A	-1.73	1.55	13.94	N/A	-3.65
	N/S	1.85	12.25	-	-	0.87	25.96	12.39	1.54	N/A	-0.64	5.14	3.26	N/A	-1.36
Module 4	E/W	1.31	17.54	-	-	0.60	38.24	4.12	5.12	N/A	-1.14	1.86	11.17	N/A	-2.49
	N/S	1.91	11.72	-	-	0.87	25.56	11.79	1.60	N/A	-0.21	4.78	3.48	N/A	-0.45
Module 5	E/W	0.99	24.16	0.84	28.37	0.56	42.82	1.99	11.85	6.93	3.34	1.12	21.01	3.86	5.92
	N/S	1.29	18.45	1.10	21.67	0.73	32.71	2.77	8.43	5.55	4.19	1.56	14.95	3.10	7.42
Module 6	E/W	1.52	15.81	-	-	1.23	19.49	3.03	7.88	10.41	2.28	2.45	9.72	8.38	2.81
	N/S	1.98	12.13	-	-	1.60	14.96	4.18	5.67	8.46	2.80	3.38	6.99	6.82	3.45

N/A – BIPV system does not break even

For scenario 3, where the windows SVF are reduced by 1/3 (SVF of 0.333), the EPBTs are 1.4–12.39 years (increase of 105–526%) and the EROEIs are 1.54–16.24 (decrease of 53–87%). When the SVF is further decreased in order to obstruct 2/3 of a window (SVF of 0.167), both modules 3 and 4 do not pay back within its lifetime for all orientations. Module 2 achieves pay back when facing north/south orientations but not east/west orientations. The EPBTs obtained are 3.82–21.35 years (an increase of 462–978%). The EROEI for those that can pay back ranged from 1.08–5.76, signalling a decrease of 83–91%.

For scenario 4, where locally manufactured modules are investigated with 1/3 reduction in SVF, all modules still achieve energy breakeven during the lifetime. The EPBTs are between 0.9–5.14 years (an increase of 32–160%) and EROEI of 3.26–25.33 which equates to a reduction of between 27–72%. When the obstruction is increased to 2/3 of window area (SVF of 0.167), performance similar to the higher reduction in scenario 3 was observed. The modules that can breakeven obtained EPBT of 2.43–8.38 years and the increase as compared to base case was 223–257%. As for their EROEI, they ranged from 2.4–8.98, signifying a decrease of between 74 to 80%.

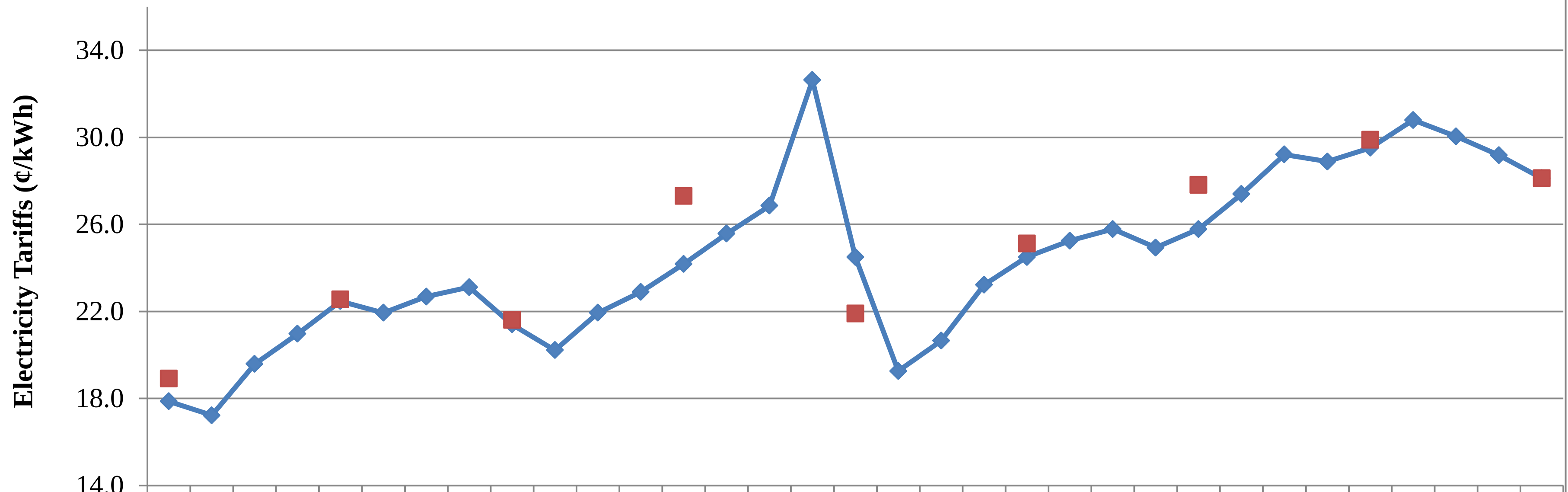
The results suggest that manufacturing the modules in a nearby country can greatly decrease the life cycle energy use by reducing the transport required. However, it is also important to note the electricity mix of the country, as some countries generate more GHG emissions per kWh of electricity which can result in displacement rather than an overall reduction in life cycle GHG emissions. In addition, the shadowing effects of surrounding buildings in an urban context, as reflected by the two levels of reduced SVF, can decrease the overall effectiveness of semi-transparent BIPV. All the modules and orientations investigated are able to achieve payback within its lifetime with 1/3 shaded windows, but only half of them are able to do so when shading is increased to 2/3.

6.7.2 Economic Sensitivity Analysis

For life cycle cost analysis, the cost of electricity is an important factor in determining the BIPV system economic viability. Future increase in electricity tariffs might result in the more expensive modules being viable and conversely, any reduction in electricity tariffs might deem the BIPV systems to be uneconomical. The quarterly fluctuations of Singapore's electricity prices over the past eight years obtained from the sole provider of electricity (SP-Services, 2013), is shown in Figure 6:4. These are used to formulate three scenarios for the sensitivity analysis of economic performance over the 25-year lifetime as follows:

- Scenario 1: Electricity prices to increase based on the average increase rate on a year-on-year basis.
- Scenario 2: Electricity prices to increase based on the minimum increase on a year-on-year basis.
- Scenario 3: Electricity prices to increase based on the maximum increase on a year-on-year basis.

Figure 6:4 – Singapore electricity tariffs (2005–2013)



	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
	2005				2006				2007				2008				2009				2010				2011				2012				2013
Quarterly Tariffs	17.9	17.2	19.6	21.0	22.5	21.9	22.7	23.1	21.4	20.2	21.9	22.9	24.2	25.6	26.9	32.6	24.5	19.3	20.7	23.2	24.5	25.3	25.8	24.9	25.8	27.4	29.2	28.9	29.5	30.8	30	29.2	28.1
Annual Average	18.9				22.6				21.6				27.3				21.9				25.1				27.8				29.9				28.1

Based on: Singapore Power (SP-Services, 2013)

The analysis is limited to modules 1, 2, 5 and 6 only, as modules 3 and 4 are cheaper to install than double-glazed windows after the 30% government subsidy. The results of this economic analysis are shown in Table 6:15.

Table 6:15 – Payback periods of the semi-transparent BIPV systems' life cycle cost for different scenarios

	Base case (constant rate for 25 years)		Scenario 1 (year-on-year average increase of 1.15 SG cents)		Scenario 2 (year-on-year min. increase of 2.1 SG cents)		Scenario 3 (year-on-year max. increase of 5.7 SG cents)	
	E/W	N/S	E/W	N/S	E/W	N/S	E/W	N/S
Module 1	13.1	17.1	10.9	13.5	9.8	12.0	7.7	9.2
Module 2	1.1	1.5	1.1	1.5	1.1	1.5	1.1	1.4
Module 5	N/A	N/A	21.9	N/A	18.8	22.9	13.6	16.1
Module 6	N/A	N/A	24.4	N/A	20.8	N/A	14.8	17.4

For module 1, the payback period decreases gradually from scenario 1 to 3 compared with the base case, while module 2 remained the same for all 3 scenarios, with the N/S orientation decreasing from 1.5 to 1.4 for scenario 3. This is due to the very low additional cost of installing it as a semi-transparent BIPV window façade. If module 5 is considered, with scenario 1, the cost of the module, can be recovered in 21.9 years with E/W orientation but not with the N/S orientation. For scenario 2 and 3, both orientations achieved payback with the period required progressively decreased from scenario 2 to 3. Module 6 has the worst performance in terms of payback period for all scenarios. For the E/W orientation, it achieves payback periods of 14.8–24.4 for all the variations. For N/S orientation, it can only payback for scenario 3, with a period of 17.4 years. The results indicate that the potential future increase in electricity prices can further improve the economic feasibility of semi-transparent BIPV windows.

6.8 Summary

This chapter considered the life cycle performance of the investigated semi-transparent BIPV windows. The analysis considered the relative environmental and economic performance of semi-transparent BIPV windows compared with conventional clear double-glazed windows.

The results indicate the major life cycle stages that require significant primary energy use are the manufacturing of photovoltaic modules and balance of systems. Cross-continental freight can be a major contributor to the total primary energy of a photovoltaic module. The EPBT is less than two years while EROEI can be as high as 35 times. Although purchasing photovoltaic components from a nearby country can greatly reduce the transport energy demand, it can also lead to increased GHG emissions, depending on the electricity mix of the country. Hence, purchasing choices should encompass a holistic view. The shadows created by nearby buildings can decrease the overall efficiency of semi-transparent BIPV which should be considered during design stage.

The government subsidy means that, certain photovoltaic modules are cheaper to install than conventional double-glazed windows, while the cost of the worst-performing module can also be recovered in 13 years. Any increase in the electricity prices improves the viability of semi-transparent photovoltaic systems. By indicating the life cycle performance in both environmental and economic terms, this chapter has provided essential information on balancing environmental benefits with cost-related aspects so as to achieve the best outcome to implement the use of semi-transparent BIPV windows.

Nonetheless, there are still practical difficulties faced by architects in integrating BIPV in their building design. As discussed in section 2.7, integration of BIPV systems should be addressed in the early stages of building design and this can only be possible if architects and developers possess appropriate information to assist them. However, such information does not exist as most current PV tools are simulation tools aimed to use for system sizing and electricity generation prediction which cater more towards engineers. Hence, a graphical representation of their long term performance can aid selection and application of BIPV systems. They should not only include performance of BIPV but also the long-term economic and environmental impacts. Hence, the next chapter discusses the development of a BIPV graphical representation to illustrate the long term performance and is aimed at promoting the ease of BIPV adoption in early stages of building design.

CHAPTER 7 GRAPHICAL REPRESENTATION OF SEMI-TRANSPARENT BIPV LONG TERM PERFORMANCE

This chapter documents the development of a graphical representation that can support architects' or building designers' key decisions in the implementation of semi-transparent BIPV modules as window facades. First, the performance categories are chosen before the individual criteria are being discussed. Next, the long term performance of the six BIPV modules are presented in a graph. Lastly, an example of how the informative graph may be used is demonstrated.

7.1 Categories and Criteria for Graphical Matrix

As discussed previously in section 2.5, a main reason why solar energy systems are not commonly used in buildings today is due to the lack of technical knowledge among architects. A major problem that architects face during the building design stage that integrates photovoltaic systems is the complexity. One way to overcome this problem is to present the long term performances' information in an easily comprehendible form to guide architects in the selection of photovoltaic materials.

To simplify the decision-making process as much as possible, the information should be introduced in a graphical form to assist them on the key performance aspects of semi-transparent BIPV window façade. Exact numbers and quantities derived from measurements or even simulations should be "hidden" from the tool user and only a simple matrix system for comparing key criteria should be adopted. Considering the performance of BIPV systems are long term in nature, their life cycle environmental and economic performance should be the basis of the decision tool.

Life cycle environmental performance serves as a long term indicator by ensuring that materials or systems used in any application reduces its burden to the environment by assessing its GHG emissions and cumulative energy demand required for its manufacturing and usage. The primary idea of adopting clean or renewable energy systems is to reduce emissions and mitigate possible climate change by ensuring materials and systems are used in the most energy efficient manner. The specific criteria for environmental performance adopted to be included in the graphical representation are: (1) GHG emissions, (2) energy payback time (EPBT) and (3) energy return on energy investment (EROEI). GHG emissions total the total amount of CO_2eq that contributes to the 100-year global warming. Its inclusion into the selection matrix allows the consideration of implications of climate change. EPBT and EROEI should also be essential elements within the environmental performance category as they assess if the adoption of the specific renewable material or system is justifiable in terms of energy used versus energy generated.

For building owners to adopt a certain technology or system, one of the key considerations is the cost. Hence, architects should also take cost into considerations when adopting BIPV facades. While capital cost is important, the payback period (if possible) is also essential to determine if it is worth investing in applying photovoltaic technologies. As such, both capital costs and payback time are included in the selection matrix.

This study has primarily adopted an objective and quantitative approach to assess semi-transparent BIPV window applications in terms of energy and cost efficiency. However, throughout the course of research, it was also evident that the investigated semi-transparent BIPV modules have very low visible light transmittance (VLT). This could pose as a limitation as visible connectivity to the exterior environment and daylighting are main reasons why windows are preferred by occupants. To consider this as a possible issue in the decision-making process, the VLT is also incorporated, as to allow users to make informed decisions on both performance and suitability for intended use.

7.2 Development of Selection Matrix

The performance results for the indicators selected as discussed above based on the previous chapters are shown in Table 7:1. Only the E/W orientation is included here, as this section serves as a guide to the development of the selection matrix. All six investigated modules' data are included to allow comparisons of the relative performance when making the decision to adopt semi-transparent BIPV modules.

To plot the data on the selection matrix which is in the form of a radar chart, the values were first normalised. In order to do so, the worst and best values of a given performance indicators are first identified to form a range before placing the remaining ones as percentage values. For the VLT, the values are placed on a logarithmic scale (base 10) prior to obtaining the relative percentages. An example of normalization using GHG emissions, are shown in the below-mentioned steps:

Step 1: Worst value of category = 10016 (0^{th} percentile)

Step 2: Best value of category = 7418 (100^{th} percentile)

Step 3: Range obtained = 10016 – 7418 = 2598

Step 4: Position remaining modules within range and determine percentile. Module 3's percentile = 100% - [(9264 – 7418) / 2598 * 100%] = 28.96%

The normalised relative percentages for all six modules and double glazing are shown in Table 7:2. The next step is to transfer the relative percentage values into the radar chart as shown in Figure 7:1. The intended use for comparative purposes is to have all modules aiming for higher values (green portion) which will indicate a better performance for the specific indicator.

Table 7:1 – Consolidated data on performance indicators selected for the matrix (only E/W)

			East/West Orientation					
Category	**Performance Indicator**	**Double-Glazing**	**Module 1**	**Module 2**	**Module 3**	**Module 4**	**Module 5**	**Module 6**
Life cycle Environmental Performance	GHG Emissions ($kgCO_2eq$)	8370	7418	10016	9264	9585	8942	9125
	EPBT (years)	N/A	0.68	1.33	1.15	1.31	0.99	1.52
	EROEI	N/A	34.49	17.17	20.09	17.54	24.16	15.81
Life cycle Economic Performance	Capital Cost	38,367	66,733	39,725	36,949	38,139	103,417	118,367
	Payback Period (years)	N/A	13.13	1.10	N/A	N/A	N/A	N/A
Occupant Preference	VLT (%)	74.6	9.17	5.19	1.84	4.17	6.91	7.34

Table 7:2 – Modified data (only E/W) on relative performance

			East/West Orientation					
Category	**Performance Indicator**	**Double-Glazing**	**Module 1**	**Module 2**	**Module 3**	**Module 4**	**Module 5**	**Module 6**
Environmental Performance	GHG Emissions	63.38	100.00	0.00	28.96	16.63	41.34	34.33
	EPBT	N/A	100.00	22.94	43.53	25.62	62.91	0.00
	EROEI	N/A	100.00	7.30	22.94	9.24	44.69	0.00
Economic Performance	Capital Cost	98.26	63.42	96.59	100.00	98.54	18.36	0.00
	Payback Period	N/A	49.68	100.00	0.00	0.00	0.00	0.00
Occupant Preference	VLT	100.00	43.38	28.01	0.00	22.10	35.74	37.37

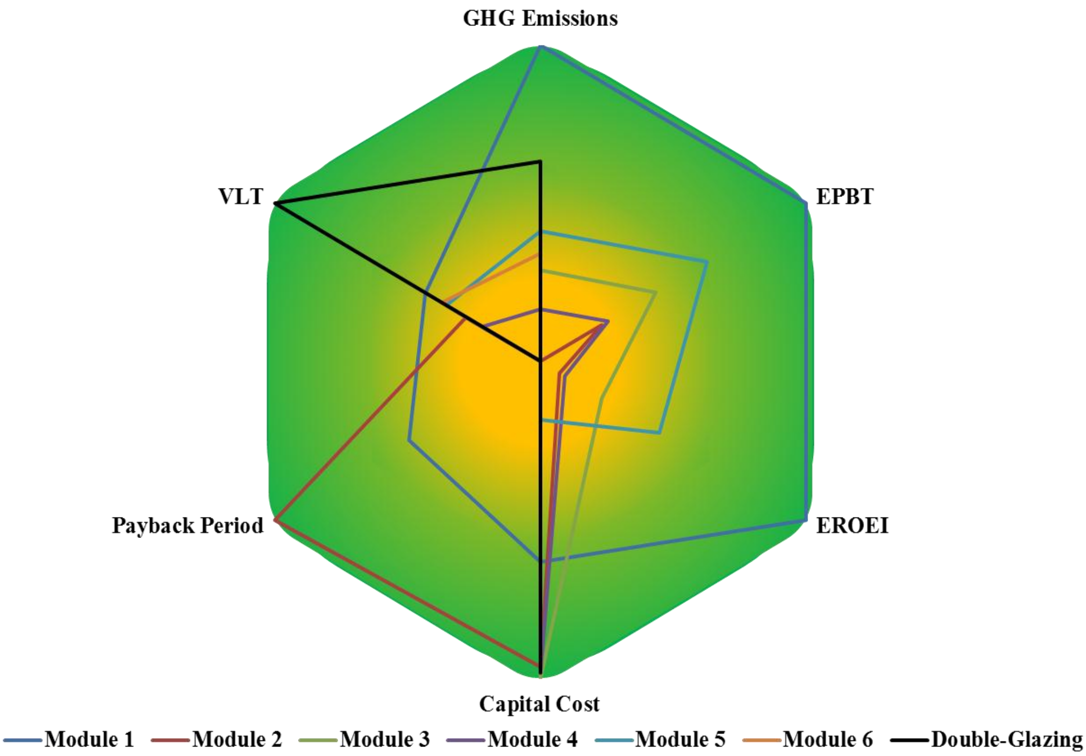


Figure 7:1 – Selection matrix representing six semi-transparent BIPV modules and double glazing

7.3 Example of selection process

In this section, an example of how the above graphical representation may be used in the selection is discussed. To simplify the discussion, only two modules are included in the selection matrix, along with double glazing which can be used for base comparison. Figure 7:2 illustrates the results with double glazing and the two semi-transparent BIPV modules (modules 1 and 2) as options for considerations.

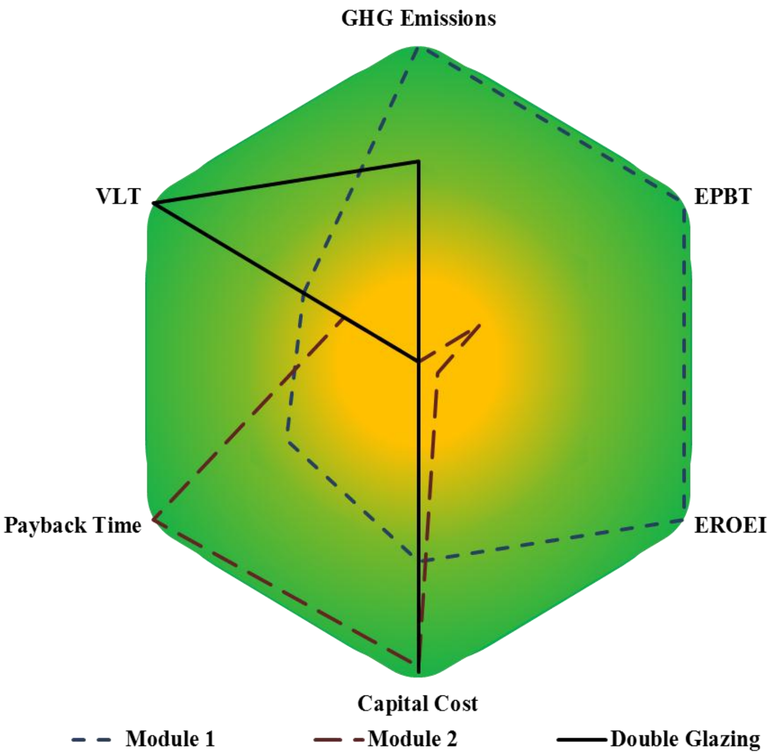


Figure 7:2 – Selection matrix representing two semi-transparent BIPV modules and double glazing

As seen, the two modules portray very different performance with respect to the decision categories. Module 1 has much better environmental performance, which is observed from the higher scores for GHG emissions, EPBT and EROEI. However, module 2's economic performance is significantly better with higher values for both payback time and capital cost. This information allows architects or building designers to decide on the criteria that they consider as more important. If there are regulations or company's environmental policies governing the material usage, module 1 is likely to be chosen. In the case where the building owner has cost limitations and a short term view on the building development project, he might choose module 2 instead. In addition, with the VLT information included, the architect can also make an informed decision on the effect of the chosen module on the view. If both environmental and economic performances are not able to provide for a clear "winner", the VLT can assist in making the decision depending on occupants' preference.

7.4 Summary

This chapter documents the development of a graphical representation to illustrate the long term performance of semi-transparent BIPV for building use. The previous chapter findings are represented in an illustration aimed at providing architects or building designers with easy-to-use information on integrating semi-transparent BIPV modules as windows facades. The process of representing the information in a chart form is discussed and an example for selecting alternative glazing choices is provided.

CHAPTER 8 CONCLUSIONS

This research study investigated semi-transparent BIPV applications in the tropics in four major steps: (1) measuring of critical parameters relating to tropical performance, (2) predicting of overall energy benefits through building simulations, (3) determining the life cycle performance and (4) developing a graphical representation for building use. This chapter concludes the thesis. Here, the key findings are summarised and the limitations are discussed. Also, the significance and major contributions to architecture are presented. Last, the areas that can be used for future research are highlighted.

8.1 Summary of Key Findings

The results of this study revealed the following key findings:

1. The electrical measurements conducted were aimed at determining the performance of BIPV modules under different shading types (parallel or cross) and irradiance (direct or diffuse). The modules selected covered a range of photovoltaic technologies (a-Si, CIGS, organic plastic and multi-Si) and construction assemblies (single glass laminate, cylindrical glass tube, double-glazed unit, flexible laminate and glass tedlar). The results indicated that shading orientation with respect to cell strings has contrasting impacts on the power production for all modules. While a certain fraction of the power is still generated for parallel shading, cross shading produces little or almost no power. As for the irradiance measurements results, it showed that the photovoltaic modules tested generally prefer diffuse to direct irradiance which was indicated by the higher power generated for all tested modules.

2. Thermal measurements conducted using SERIS's calorimetric hot box system measured the U-value and SHGC of six semi-transparent BIPV modules. The U-value results are generally lower as compared to traditional single glaze window types but are close to those recorded in previous studies on single-glazed semi-transparent BIPV modules. The values achieved for the double-glazed modules are generally in line with conventional double-glazing units.
3. The SHGC values obtained for the single-glazed modules have a range from 0.289–0.413 while the double-glazed modules' range is 0.123–0.154.The measured SHGC values for the modules are lower than coloured single glazing and close to that of double low-e glazing. As for the double-glazed modules, their SHGCs are similar to triple-glazed low-e windows.
4. Optical measurements were conducted using SERIS's large diameter integrating sphere to obtain the VLT of the six semi-transparent modules. The results showed that the standard-coloured modules generally have a higher range (6.91–9.17%), notwithstanding the difference in construction while the coloured modules exhibit the lowest VLTs (1.84–5.19%).
5. Singapore's solar radiation profile was also analysed to understand the local prevalent climatic conditions. It was observed that the monthly solar radiation in Singapore is similar throughout the year and the diffuse component accounts for more than 60% of the global horizontal solar radiation. Such high diffuse solar radiation component might allow vertical facades on various orientations to receive sufficient sunlight for BIPV applications. A subsequent analysis on the solar radiation received by the various orientations showed that the East and West facades receive the highest solar radiation (approximately 670 kWh/m^2/yr) while the North and South facades receive

relatively lesser solar radiation of roughly 530 kWh/m^2/yr. The diffuse component, which forms the majority of the vertical façade's solar radiation, is generally consistent on all orientations. This highlights the potential of implementing BIPV on all facades and not limited to only those that face the direct sun path.

6. An index was also formulated to assess the overall energy benefits of semi-transparent BIPV modules by considering the savings in artificial lighting, change in electricity consumption for space conditioning and the photovoltaic electricity generation. A building model was simulated to integrate the six semi-transparent BIPV modules based on the properties measured previously, with a parametric analysis on both the WRR and façade orientations. The results indicate that the NEBs of BIPV can be very different and depend on the WWR adopted, when compared to an opaque wall. The double-glazed modules show good performance due to their better thermal performance, even though they have slightly lower photovoltaic efficiencies. Only one out of the four single-glazed modules achieved similar good performances which were largely due to its higher photovoltaic efficiency. The results also suggested that it is possible to integrate semi-transparent BIPV modules on facades that do not face the sun path in Singapore. A subsequent analysis to compare performance of the six modules against conventional double-glazed windows indicated that the semi-transparent BIPV modules are capable of increasing a building's energy efficiency and is a much better alternative for double-glazed window when choosing window façade materials.
7. The life cycle analysis was performed for the six semi-transparent modules to be integrated as BIPV systems over a life time of 25-years. The results indicated that the environmental burden associated with installing BIPV systems is significantly

reduced if we deduct the avoided burden of double-glazed windows, which is currently the de-facto standard for energy efficient tropical buildings. The life cycle energy use at different life stages also showed that the photovoltaic manufacturing process and balance of systems makes up the largest contributions for all BIPV systems. The need for cross-continental shipping can also result in transportation energy use to be significant.

8. The life cycle environmental performance results indicated EPBT of less than two years and EROEI of up to 35 for different modules and orientations. As for their economic performance, the modules achieved varying results. Modules 3 and 4 are already cheaper than double-glazed facades, after considering 30% subsidy that is handed out by the Singapore government. For the remaining, only modules 1 and 2 achieved payback of between 1.1–17.1 years. The two remaining modules (5 and 6) do not break even.
9. Sensitivity analyses were also conducted to test the validity of environmental and economic performance results. The environmental performance sensitivity analysis considered varying the manufacturing locations and the effects of reduced solar exposure when facades are obstructed by nearby buildings. The results suggest that manufacturing the modules in a nearby country can greatly decrease its life cycle energy use. It is also important to note the electricity mix of the country, as some countries may generate more GHG emissions. In addition, the shadowing effects of surrounding buildings can decrease the overall effectiveness of BIPV systems. The economic sensitivity analysis considered possible future increases in electricity tariffs based on past trends. The results indicated that any increase in electricity prices improves the economic viability of semi-transparent BIPV systems. It can greatly

reduce the payback periods and even some BIPV systems which did not achieve payback previously were able to do so with increased electricity prices.

10. A graphical representation on semi-transparent BIPV's long term performance to support decision-making during early building design stage aimed at architects or building designers is developed. Details technicalities and quantities are streamed away from the tool and presented in the form of a radar chart with six performance indicators included. They are GHG emissions, EPBT, EROEI, capital cost, payback time and VLT. It can be used to compare different performance aspects of BIPV modules and the inclusion of double glazing allows comparisons to be made as well.

8.2 Limitations of Study

This research study has several limitations which should be noted:

1. Shading devices such as external overhangs, fins and interior blinds which can be incorporated into buildings are not considered. However, this can affect building performances which might also possibly alter the BIPV systems' energy benefits and life cycle performance.
2. The weather data used by *EnergyPlus* include solar radiation pattern, outdoor temperatures and outdoor illuminance which are generated and obtained as a typical meteorological year data file. Hence, there could be some discrepancies in simulating the building energy use and BIPV performance as opposed to real-life performance data.
3. The photovoltaic efficiencies adopted for the simulation study are constant values although they were already adjusted for Singapore's diffuse skylight and higher

temperatures. It is to be noted that these conversion efficiencies are subject to vary in real life applications varying temperatures and also actual skylight conditions.

4. The BIPV simulations performed to assess the contribution to building energy are mainly based on commercial office buildings, but the application of BIPV systems can also be extended to other building types such as residential, industrial or even hotels.

8.3 Significance and Major Contribution to Architecture

This study makes the following significant contributions to architecture:

1. The study can be considered as complementary to solar and energy efficient building studies that focus on implementing renewable technologies to increase energy efficiency levels in buildings. On a larger and macro perspective, it also helps in reducing the carbon footprint of built environments and assist in global efforts in mitigating climate change.
2. It contributes to the knowledge in solar buildings in the tropics that focus on alternative energy sources and optimise the application of semi-transparent BIPV windows. By proposing the implementation on vertical facades, tall buildings within city landscape can also have the possibility of adopting BIPV systems as they are likely to have limited roof space.
3. The technical specifications of semi-transparent BIPV modules and their implications on building energy use are studied which serves as critical information for promotion of solar technologies to the built environment. As architects are seldom concerned with technical details of materials, a method is provided to holistically represent the

overall energy benefits of semi-transparent BIPV which also accounts for its life cycle performance. This enhances the building designer's abilities in producing more energy efficient design and also to encourage building owners to adopt solar as a renewable and clean source of energy.

8.4 Recommendations for Future Research

The following summarises a few areas of future research that could possibly be beneficial towards the implementation of BIPV:

1. This research is performed from a building designer or architect's point of view where commercially-available modules are already in the market and decisions are required to be made in order to optimise the energy use. This can be further improved where the desired properties are provided to photovoltaic engineers and the modules can then be manufactured to achieve the best outcome for building integration.
2. More studies can be conducted to investigate the impact of low visible light transmission of photovoltaic modules on the well-being of occupants and also their behaviour and sentiments towards adopting renewable energy while making some sacrifices on preference. Such studies can also include occupants' comfort such as thermal comfort and glare for a more holistic review for BIPV application.
3. This research has assumed that only semi-transparent photovoltaic modules are adopted to replace traditional window glazing. Further research can consider opaque modules as well as semi-transparent modules (of various transmittances) or even current window glazing types to obtain the best energy outcome and occupants' satisfaction.

4. A further development of the current work could include shading systems (vertical and horizontal) that are commonly adopted in tropics to reduce solar heat gain. Because of the reduced solar energy reaching the photovoltaic modules, the power generation, solar heat and indoor daylight level will all be affected by the shading systems. It could also consider the application of photovoltaic modules being integrated unto the shading systems directly.
5. A software program with an easy-to-use computer interface can be developed to provide potential users with quick first-hand information on the energy-related benefits, long-term environmental as well as economic performance.
6. An investigation of other possible barriers within design and implementation of BIPV modules can also be conducted. These barriers can affect the selection outcome and final costs of BIPV systems and this can guide the future direction of BIPV's architectural design.
7. Currently, the local green building design code classifies BIPV's contributions solely through its photovoltaic generation. As this study notes, this is only a fraction of the overall energy performance of BIPV. The information provided here, can be used as a reference to further improve the policies pertaining to photovoltaic adoption in buildings.

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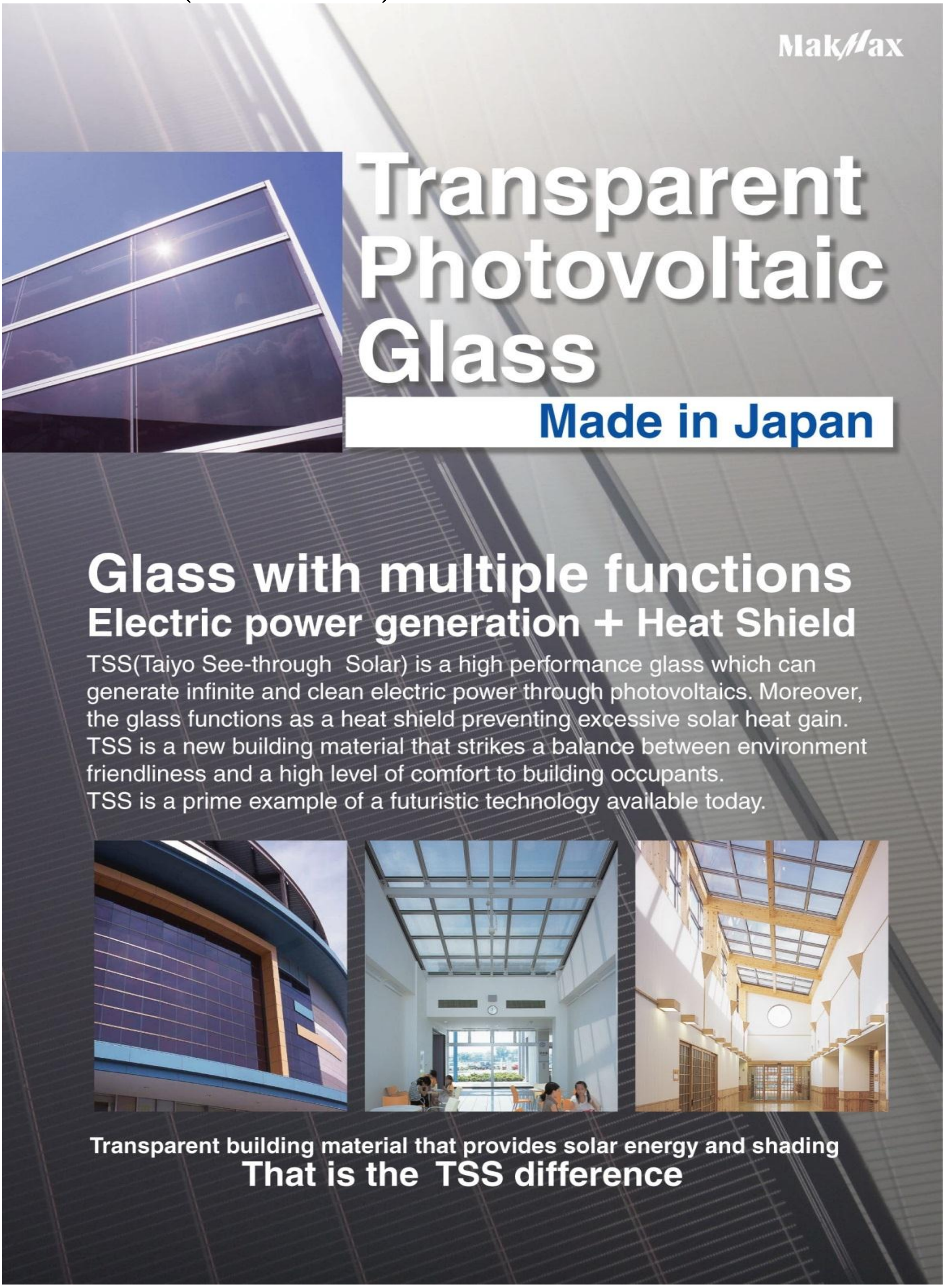
APPENDICES

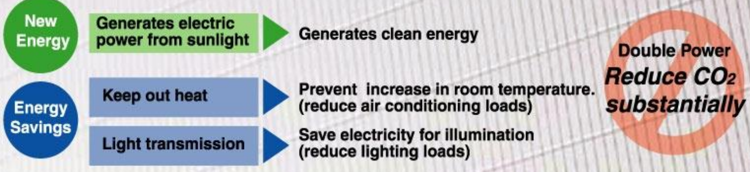
APPENDIX A – BIPV Manufacturer's Data Sheets
Hanwa Makmax (KN-50 and KN-42)



Features of products

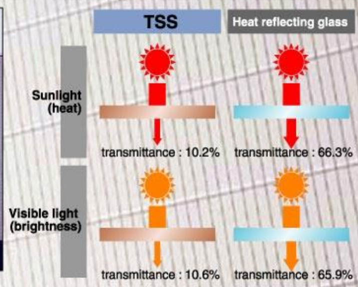
1. True Environmental Responsiveness "New Energy + Energy Savings"

Dual functions of New Energy (Electric power generation) and Energy Savings (reduction of Air Conditioning/ Lighting loads) greatly reduce overall energy costs.
TSS is effective in curbing the generation of CO2, and enhances the value of your building as an environmentally friendly facility.



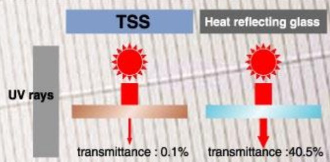
2. Futuristic Comfort "See-Through"

TSS provides a space that distributes daylight comfortably.
It changes the sun fs rays into delicately diffused light by transmitting light moderately, and reduces intrusion of heat from the sun- all this while maintaining exterior views.
Multifunctional, effective, comfortable see-through glass.



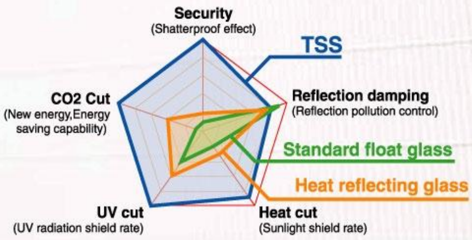
3. Assured safety "UV Cut + Shatterproof"

UV rays, which are hazardous to the human body as well as interior furnishings, will be cut almost completely.
Moreover, TSS boasts shatterproof performance against incoming objects and high penetrability resistance from all types of impact.



4.Comparison of glass products

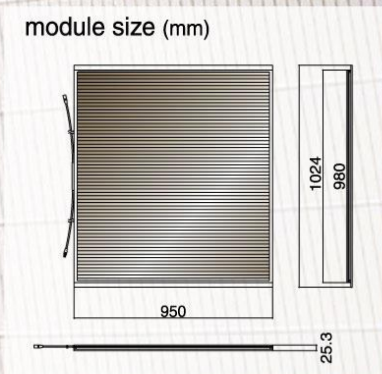
TSS has superior functional advantages over other glass products.
It is a multifunctional glass which has both energy generation and energy saving functions.



TSS Spec

UV cut	99.9%
Heat cut	89.8%
Light transmission	10.6%
Power generation	42w/m²

module size (mm)



5.Variations and output

type	size(mm)	transparency(%)	Pmax(W)	Vpm(V)	Ipm(A)	Voc(V)	Isc(A)
KN-42	980×950	10	42.0	59.6	0.705	91.8	0.972
KN-50	980×950	5	50.0	66.0	0.758	91.8	1.090

MakMax
TAIYOKOGYO CORPORATION
4-8-4 Kigawa-higashi, Yodogawa, Osaka,
532-0012, Japan
Phone: +81-6-6306-3078

http://www.taiyokogyo.com

Auria Solar (Micromorph)

Photovoltaic Modules

Low Voltage Modules

Auria Micromorph BIPV Specification

Electrical Characteristics(STC:1000W/m²; 25°C; AM1.5)

Color	Purple	Dark Blue	Light Blue	Golden	Silver	Orange	Red-wind	Coffee
Transmittance (400~800nm) *	11.6%	10.9%	9.5%	6.3%	9.5%	19.9	16.2%	5.9%
Rated Power (Wp±3%) *	70-80W	70-80W	55-65W	40~50W	40-50W	75-85W	85~95W	100~115W
Max. Power Voltage Vmpp (V)	85~87	84~86	89~91	91~92	89~91	96~98	85~95	99~101.38
Max. Power Current Impp (A)	0.84~0.94	0.84~0.93	0.63~0.70	0.48~0.54	0.49~0.54	0.79~0.88	0.90~1.00	0.99~1.11
Open Circuit Voltage Voc (V)	115~117	114~115	116~117	116~117	117~118	126~127	124~125	128~130
Short Circuit Current Isc(A)	1.01~1.06	0.99~1.04	0.74~0.78	0.57~0.60	0.60~0.62	0.92~0.96	1.04~1.09	1.21~1.305

* can be customized upon request

Mechanical Characteristics

Standard Size (W×L)	1,100mm×1,300mm
Thickness	Front: 3.2mm low iron glass PVB: 0.76mm Back: 3.2mm tempered glass
Weight	23kg
Maximum size	2,200mm×2,600mm
Junction Box	Yukita pen type
Connectors	MC3 compatible

Electrical Data

Maximum System Voltage (V)	1000(600UL＊＊)
Bypass Diodes	Optional
Reverse Current Loading (A)	3

＊＊Reqired to maintain UL compliance

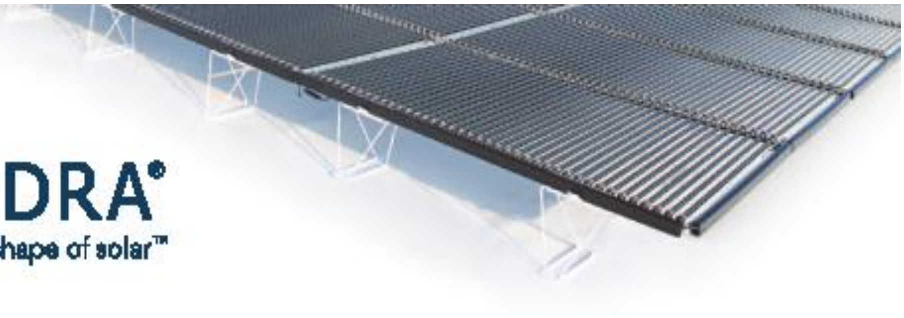
Limited Warranty

Material and Workmanship Warranty	5 Years
90% of the minimal rated Power Output	10 Years
80% of the minimal rated Power Output	25 Years

Temperature Coefficients

Nominal Operation Cell Temperature(NOCT)	45%
Temperature Coefficient of Pmpp (%/K)	-0.25
Temperature Coefficient of Voc (%/K)	-0.30
Temperature Coefficient of Isc (%/K)	+0.07

Solyndra (SL-001-150)

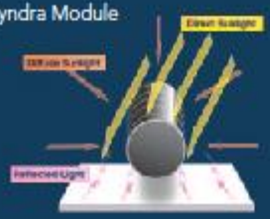


SOLYNDRA®

The new shape of solar™

Solar photovoltaic systems comprised of panels and mounting hardware for low slope, commercial rooftops.

Proprietary cylindrical modules optimize the collection of sunlight and enable Solyndra panels to achieve the highest rooftop coverage without the need for costly mounting hardware or rooftop penetrations. By significantly reducing installation costs and increasing the electricity generated per rooftop, Solyndra delivers electricity at low cost per kilowatt hour.



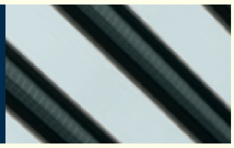
Maximize roof coverage with no need for tilting and spacing.
Greater coverage means more solar electricity per rooftop per year

Fast, simple, and economical installation

Lightweight and self-ballasting
No penetrations or attachments required

Product Specifications

100 SERIES



Electrical Data

Measured at Standard Test Conditions (STC) irradiance of 1000 W/m², air mass 1.5, and cell temperature 25° C

Model Number		SL-001-150	SL-001-157	SL-001-165	SL-001-173	SL-001-182	SL-001-191	SL-001-200 Release Date TBD
Power Rating (P_{mp})	Wp	150 Wp	157 Wp	165 Wp	173 Wp	182 Wp	191 Wp	200 Wp
Power Tolerance (%)	%/Wp	+4, -5	+/-4	+/-4	+/-4	+/-4	+/-4	+/-4
V_{mp} (Voltage at Maximum Power)	Volts	65.7 V	67.5 V	69.6 V	71.7 V	73.9 V	76.1 V	78.3 V
I_{mp} (Current at Maximum Power)	Amps	2.28 A	2.33 A	2.37 A	2.41 A	2.46 A	2.51 A	2.55 A
V_{oc} (Open Circuit Voltage)	Volts	91.4 V	92.5 V	93.9 V	95.2 V	96.7 V	98.2 V	99.7 V
I_{sc} (Short Ciruit Current)	Amps	2.72 A	2.73 A	2.74 A	2.75 A	2.76 A	2.77 A	2.78 A
Temp. Coefficient of V_{oc}	%/°C	-.29						
Temp. Coefficient of I_{sc}	%/°C	-.02						
Temp. Coefficient of Power	%/°C	-.38						

System Information*

Cell type	Cylindrical CIGS
Maximum System Voltage	Universal design: 1000V (IEC) & 600V (UL) systems
Dimensions	Panel: 1.82 m x 1.08 m x 0.05 m Height: 0.3 m to top of panel on mounts
Mounts	Non-penetrating, powder-coated Aluminum
Connectors	4 Tyco Solarlok; 0.20 m cable
Series Fuse Rating	23 Amps
Roof Load	16 kg/m² (3.3 lb/ft²) panel and mounts
Panel Weight	31 kg (68 lb) without mounts
Snow Load Maximum	2,400 Pa (50.1 lb/ft²)
Hailstone Impact	25 mm, 7.53 g at 23 m/s per IEC 61646
Wind Performance	208 km/h (130 mph) maximum Self-ballasting with no attachments
Operating and Storage Temp	-40°C to +85°C
Normal Operating Cell Temperature (NOCT)	41.7°C at 800 W/m², Temp = 20°C, Wind = 1m/s
Certifications/Listings	UL1703, IEC 61646, CEC listing IEC 61730, CE Mark, Fire Class C Application Class A per IEC 61730-2
Warranty	25 year limited power warranty 5 year limited product warranty

Solyndra's panels come with all of the mounts, grounding connectors, lateral clips, and fasteners required to build a standard array.

Solyndra, Inc.
47700 Kato Road
Fremont, CA
www.solyndra.com

SOLYNDRA®
The new shape of solar™

*Product Specifications are only valid when using the product in accordance with Solyndra's design and installation guidelines using Solyndra supplied mounts and interconnecting hardware. Product Specifications are subject to change without notice.

Revision: 7 / Released: 08/04/10

Schott Solar (Vlotarlux ASI-ISO-E1.2)

ASI®-Glass

Modular Sizes

ASI THRU®

ASI OPAK®

- Solar electricity
- Light management
- Comfort
- Effective shading
- Glare protection
- Thermal management
- Innovative architecture
- Cost savings by combining and integrating several functions

The frameless glass laminates and double glazing elements are designed to be compatible with most conventional clamping systems for facades and skylights.

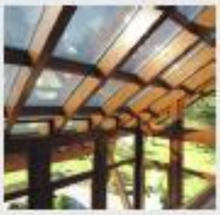
ASI® Glass elements are designed on the basis of silicium thin-film technology as ASI® tandem cells on glass substrate. ASI® Glass elements demonstrably produce maximum energy yields.
Whether a façade or a roof, today's building envelope has to fulfil multiple purposes. Alongside its conventional roles of providing privacy and protection from rain and noise, additional factors are becoming increasingly important, such as thermal insulation and shading. All of these tasks have to be performed by the shell of a building. Today, building integrated photovoltaic systems are able to provide all of these functions **plus** solar electricity.

ASI OPAK® White

ASI OPAK® Elegance^Line

SCHOTT solar

Applications with double glazing



ASI THRU®

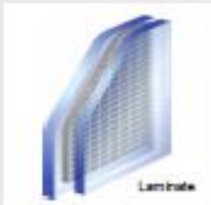
Double glazing up to 2,4m^2
for façade and over head glazing
applications.

Applications with glass laminates

Semitransparent glazing

ASI THRU®

Laminated glass up to 2,4m^2
for façade and over head glazing
applications.



Façade applications

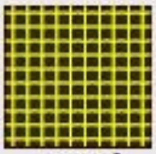
ASI OPAK®

Laminated glass up to 2,4m^2
for façade and roof applications

Available design variations:

ASI OPAK®

ASI OPAK® White

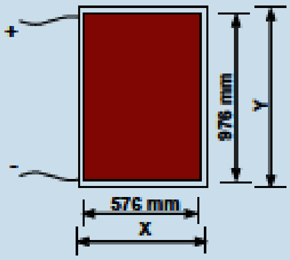


ASI OPAK® Creative Line

ASI OPAK® Elegance Line

ASI®-Glass

Laminate	1027mm x 627 mm
Double Glazing	1018mm x 624 mm



Type:	ASIOPAK-1-L	ASITHRU-1-L	ASITHRU-1-IO (Double Glazing)

Mechanical Construction:

Front Glass	6mm HSG	6mm HSG	6mm HSG
Interlayer	1.1mm PVB	1.1mm PVB	1.1mm PVB
ASI-Glass® (1x)	ASI OPAK®	ASI THRU®	ASI THRU®
Interlayer	1.1mm PVB	1.1mm PVB	/
Spacer	/	/	16 mm
Back Glass	6mm HSG	6mm HSG	8mm LSG
Cable Outlet	rear side	rear side	lateral
Cable Type / Diameter (+ and -)	Double isolated, black / 2.5mm²		
Outer Diameter / Cable Length	5.2mm / 1m		
Connector (Male / Female)	Multi-Contact PV-KBT3 / PV-KST3		

Dimension, Weight*:

Dimension (X / Y)	1027mm x 627 mm		1018mm x 624 mm
Total Glass Thickness	17mm	17mm	34mm
Total Weight	27kg	27kg	29kg

Physical Data***:

Heat Transmittance U_g-Value (DIN EN 673)	~5 W/m²K	~5 W/m²K	1.2 W/m²K
(American)	~0.88 Btu/hr ft²F	~0.88 Btu/hr ft²F	0.21 Btu/hr ft²F
Solar Heat Gain Coefficient (SHGC)	23 %	27%	10%
Light Transmission	1%	10%	10%

Electrical Data:

Initial Nominal Power P_{mpp}	35 Wp	31 Wp	31 Wp
Nominal Power P_{mpp} **	29 Wp	25 Wp	25 Wp
Current at Nominal Power I_{mpp} **	0.43 A	0.37 A	0.37 A
Short Circuit Current I_{sc} **	0.55 A	0.49 A	0.49 A
Voltage at Nominal Power U_{mpp} **	68 V	68V	68V
Open Circuit Voltage U_{oc} **	93 V	93 V	93 V
Maximum System Voltage	600 V	600 V	600 V

SCHOTT solar

Notes on given technical data

* The tolerances of the outer glass dimensions are ±3mm.

** These data represent stabilised electrical module performance at standard test conditions (STC -1000W/m²; AM 1.5; 25°C cell temperature). The nominal power may be initially approx. 18% higher than the quoted stabilised power data. This power bonus has to be considered when designing the system. All given electrical data are subject to a production tolerance of ± 10%.

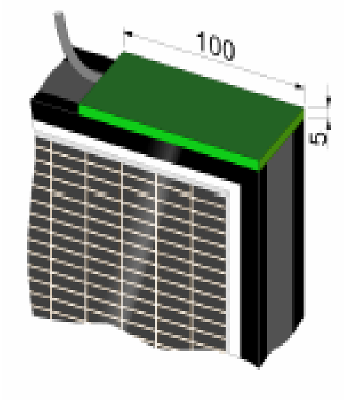
*** The given SHGC- and U-values are approximate data.

Cell temperature coefficients

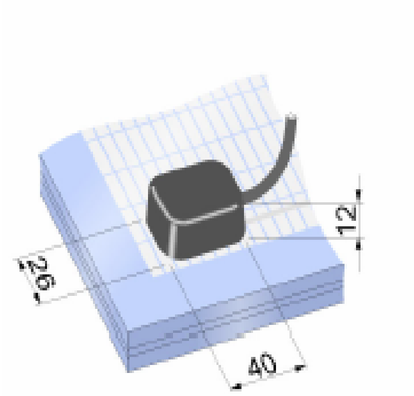
Referred to nominal power	$T_k (P_n)$	- 0.2 % / K
Referred to open circuit voltage	$T_k (U_{oc})$	- 0.31 % / K
Referred to short-circuit current	$T_k (I_{sc})$	+ 0.08% / K

Cable outlet

The type of cable outlet has to be considered when designing the mechanical support structure of the photovoltaic installation



Double glazing unit



Laminate

Electrical system design

When designing a system fuses for each string (serial interconnection of single PV-elements) are recommended The maximum fuse rating for string fuses is two times the short-circuit current (2 x I_{sc}). Never exceed the given maximum system voltage. Under normal conditions, a photovoltaic module may experience conditions that produce more current and/or voltage than reported at Standard Test Conditions.

For installations in the USA:
Accordingly, the values of I_{sc} V_{oc} marked on UL listed modules should be multiplied by a factor of 1.25 when determining component voltage ratings, conductor capacities, fuse sizes and size of controls connected to the module output. Refer to section 690-8 of the National Electric Code for an additional multiplying factor of 1.25, which may be applicable.

Abbreviations and product nomenclature

Nomenclature: **ASITHRU - 3 - L**

Technology — Number of sub modules — Version:

- L = Laminate
- I = (Insulating) Double Glazing
- IO = (Insulation) Double Glazing with safety glass, also suitable for overhead glazing

Appearance

Thin-film silicon modules may exhibit slight variations in colour, both across any given module and from module to module. These non-uniformities are caused by optical interference effects within the semiconductor layers, and are thus inherent to the manufacturing process. Most importantly, however, the perceived colour differences have no influence whatsoever on the electrical performance of the modules and their service life, and, therefore, present no reason for rejection.

Quality of glass and lamination

Glass:

- HSG: Heat Strengthened Glass (semi toughened glass) according to DIN EN 1863-1
- LSG: Laminated Safety Glass (float glass / PVB foil /float glass) according to DIN EN 12543-1

Lamination foil:
For all given laminates and double glazing elements only PVB (Polyvinylbutyral) interlayer will be used with the following mechanical parameters:

- Tensile Strength > 20 N/mm²
- Breaking Elongation > 250 %

The glass edges are not polished. Due to the production process, isolated and sporadic small bubbles in the Laminate in the rim area and main areas of the glass panes may appear and are not considered to be defects.

The choice of glass thickness and quality, such as float glass heat strengthened glass or fully hardened glass is not in the responsibility of SCHOTT Solar. All glazing has to be built according to relevant building codes, national standards and best practice for glazed structures. The actual specifications for glass configuration has to be determined by the architect or buyer based upon local building codes. On request the inner glass can be offered as safety glass laminate with heat strengthened glass.

Qualification

All modules are qualified according UL 1703 as recognized component, see file E226443

The modules are built according to safety class II (see given maximum system voltage)

Specifications subject to change without notice.

IECQ Approval of Manufacturer

MANAGEMENT SYSTEM
Certified by DQS according to
DIN EN ISO 9001 Reg.-Nr. 2184
DIN EN ISO 14001 Reg.-Nr. 2184

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SCHOTT solar

Konarka (KT-800)

20 Series

Konarka Power Plastic® 20 Series

Product Specifications

Konarka Power Plastic 20 Series panels are ideal for charging batteries for portable electronic devices. Connect in series for increased voltage, and remote power applications.

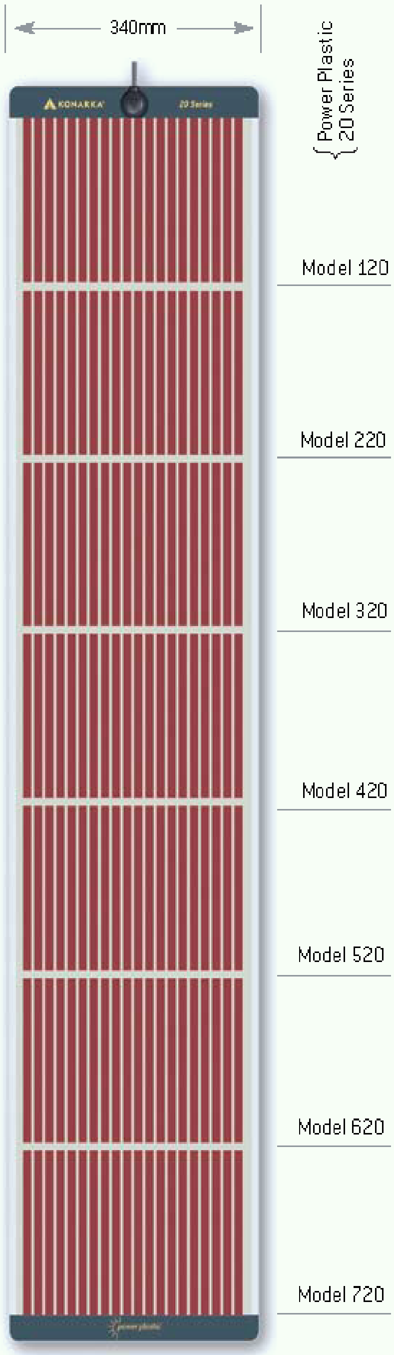
Material Characteristics

Power Plastic is a lightweight, thin-film photovoltaic material that is much more versatile in application than traditional solar panels. Konarka's unique technology is based on patented photo-reactive materials made from conductive polymers and organic nano-engineered materials. These materials can be printed or coated onto flexible plastic using an inexpensive, energy-efficient manufacturing process.

Power Plastic reacts with both indoor and outdoor light, greatly expanding its potential applications. By integrating Power Plastic into everyday products, devices can produce their own low-cost source of renewable energy.

Construction Characteristics

- **Material thickness:** 0.5mm+/-0.05mm
- **Operating temperature range:** -20°C to 65°C (-4°F to 149°F)
- **Weatherproof materials**
- **By-pass/blocking diode optional**
- **User friendly design:** Easily integrated
- **Laminate encapsulation:** High light transmissive polymer
- **Power terminals:** *Option 1*: Solderable leads *Option 2*: Konarka junction box with universal connection
- **Available with corner grommets**



Scalable Energy Independence

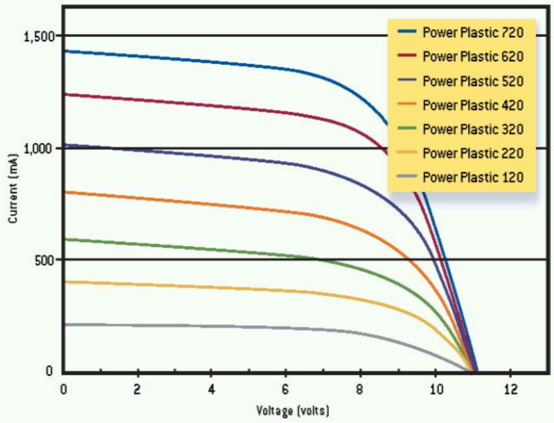
The Power Plastic 20 Series is available in 7 standard sizes, and can be built to any length for custom applications.

20 Series

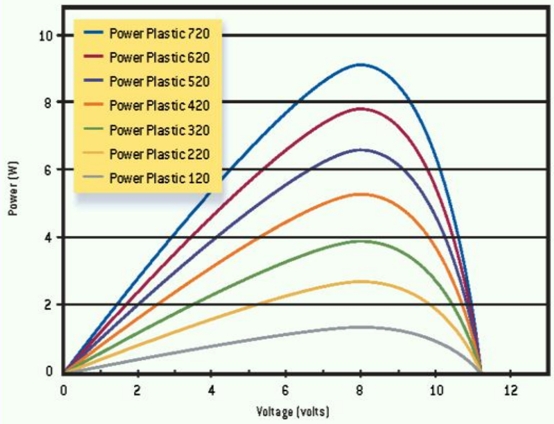
Konarka Power Plastic® 20 Series

KONARKA®

Power Plastic 20 Series: IV Curves



Power Plastic 20 Series: Power Curves



Outdoor Performance

Electrical Data		Units	1 Sun			1/2 Sun		
All 20 Series	Vmpp	V	7.9			7.6		
	Voc	V	11.3			10.9		
	Impp / Isc	mA	Impp	Isc	Watts	Impp	Isc	Watts
	Power Plastic 120		164	202	1.3	82	101	0.6
	Power Plastic 220		329	404	2.6	164	202	1.3
	Power Plastic 320		493	605	3.9	246	303	1.9
	Power Plastic 420		657	807	5.2	329	404	2.5
	Power Plastic 520		821	1009	6.5	411	505	3.1
	Power Plastic 620		986	1211	7.8	493	605	3.8
	Power Plastic 720		1150	1413	9.1	575	706	4.4

Panel Dimensions

	length (mm)	width (mm)
Power Plastic 120	273	340
Power Plastic 220	487	340
Power Plastic 320	700	340
Power Plastic 420	913	340
Power Plastic 520	1127	340
Power Plastic 620	1340	340
Power Plastic 720	1553	340

Temperature Range

Operating Temperature	-20°C to 65°C (-4°F to 149°F)
Storage Temperature	-40°C to 75°C (-40°F to 167°F)

Temperature Coefficients

Pmax	+0.05% / °C (based on air temperature)
Vmpp	-0.27% / °C (based on air temperature)
Voc	-0.21% / °C (based on air temperature)

Konarka Power Plastic
takes light in and delivers power out. When integrated into products, this direct current (DC) electrical energy can be used immediately or stored for later use.

Headquarters: Lowell, MA, USA
Manufacturing: New Bedford, MA, USA
R&D Facilities: Lowell, MA, USA; Linz, Austria; Nurnberg, Germany

Learn more at www.konarka.com
or call +1-978-569-1400

rev 10.1

Spear Technology Alliance (SSM-42S0533Air)

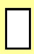
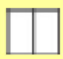
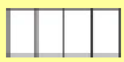
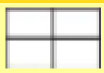
ISOLAR® GLAS

GLASWERKE ARNOLD

Voltarlux®-ASI-T-ISO-E

Type of solar cells	Amorphous silicon thin-film ASI® tandem cell, uniform dark brown glass pane (ASI®OPAK made by SCHOTT Solar), neutral colour.
Electrical connections	Solar cable - length 100 cm per pole, conductor cross-section 2.5 mm² - and MC® plug connector.
Laminate technology	All glass listed in this data sheet is laminated exclusively with polyvinyl butyral (PVB) and has the following mechanical properties: - Ultimate tensile strength > 20 N/mm² - Elongation at break > 250 %
Cell temperature coefficient	based on nominal power T_K (P_n) -0,2 %/K based on open-circuit voltage T_K (U_{oc}) -0,31 %/K based on short circuit current T_K (I_{sc}) +0,08 %/K
Depth of frame **Cable outlet**	On the cable outlet side 15 mm margin (conforms to ISO), otherwise according to guidelines for glazing. Covering or shading of the active module surface by the frame etc.is to be avoided. Connector blocks raised 5 mm from glass (on the face) as stipulated by ISO.
All electrical data represents stabilized performance under standard test conditions (STC - 1000W/m², spectrum AM 1.5, 25 °C cell temperature;). All figures are subject to production tolerance of ± 10%. The initial nominal power may be approx. 18% higher than the quoted nominal power. This added output is worth considering when installing a system. The dark brown side of the module is the outer side and should face the sun.	
Module operating temperatures **Maximum system voltage**	-40 .....+85 °C 600 V
Qualification	All modules are qualified as "recognised components" under the UL 1703 standard. All PV equipment meets the German safety standard "Schutzklasse II".

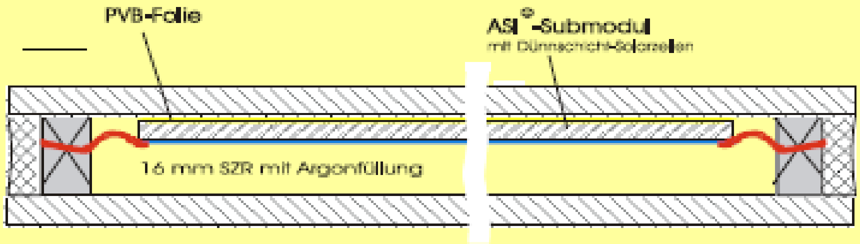
The packages listed below are standard types. Different dimensions, glass assemblies, and electrical connections are available. Maximum dimensions: 2450 mm x 1150 mm, and 2400 mm x 1230 mm.

G-ratio: approx. 23 % Ug: 1,1 W/m²K			Electrical Data						
Assembly	**Layout and Thickness**	**Dimension and Weight**	Max. Initial Nominal Power P_{max}	Open Circuit Voltage Uoc	Voltage at Nominal Power Umpp	Short Circuit Current Isc	Current at Nominal Power Impp	Nominal Power Pmpp	Sketch
ISO 1	TVG6WG/PV3 SZR 16 Float 6 N 41 32 mm	1018 mm 624 mm ca. 25 kg	29 W 31 W	49 V 93 V	36 V 68 V	0,90 A 0,49 A	0,67 A 0,37 A	24 W 25 W	
ISO 2	TVG6WG/PV3 SZR 16 Float 6 N 41 32 mm	1201 mm 1018 mm ca. 47 kg	61 W 59 W	93 V 98 V	68 V 72 V	0,98 A 0,90 A	0,74 A 0,67 A	50 W 48 W	
ISO 2x	TVG6WG/PV3 SZR 16 Float 6 N 41	2001 mm 618 mm ca. 48 kg	59 W	49 V	36 V	1,80 A	1,33 A	48 W	
ISO 3	TVG6WG/PV3 SZR 16 Float 6 N 41 32 mm	1777 mm 1018 mm ca. 70 kg	92 W	93 V	68 V	1,48 A	1,11 A	75 W	
ISO 4	TVG6WG/PV3 SZR 16 Float 6 N 41	2358 mm 1027 mm ca. 92 kg	122 W	93 V	68 V	1,97 A	1,48 A	100 W	
ISO 4x	TVG6WG/PV3 SZR 16 Float 6 N 41 32 mm	2001 mm 1198 mm ca. 92 kg	117 W	98 V	72 V	1,80 A	1,33 A	96 W	

Voltarlux-ASI-T-ISO-E-Englisch_rev4.doc   Erstelldatum: 20.07.2006

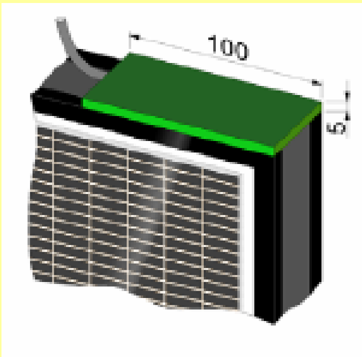
Voltarlux®-ASI-T-ISO-E

Sectional view:



If required, glass margins > 3 mm can be fitted. The inner glass is available in standard glass an in laminated safety glass.

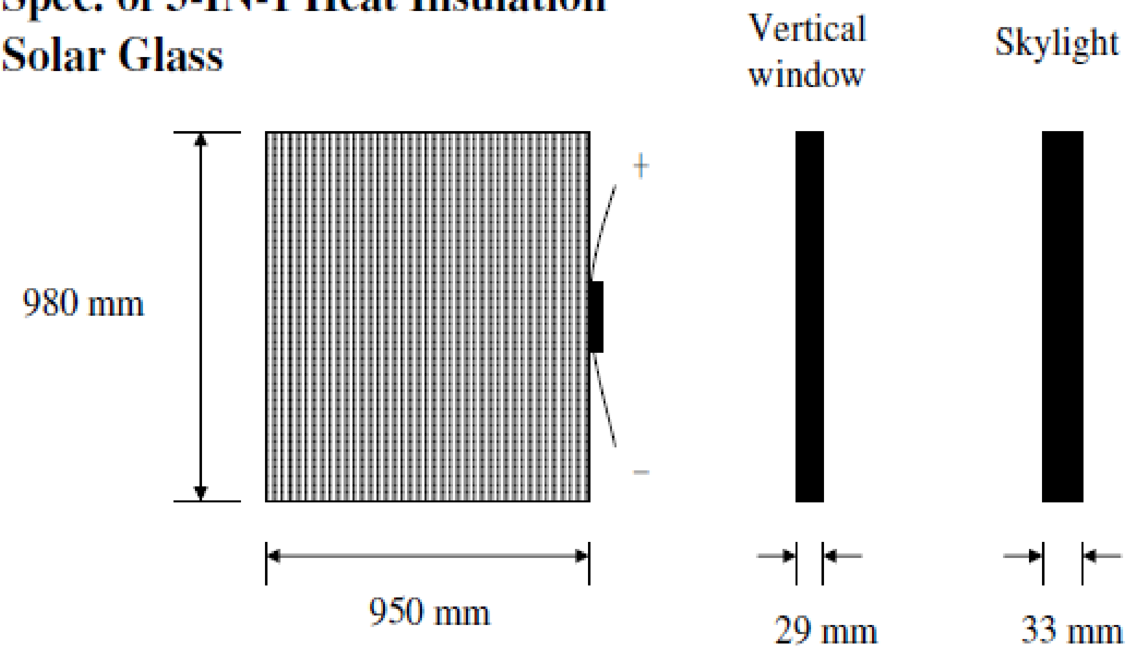
Connector blocks:



Measurements in mm

Glaswerke Arnold GmbH & Co. KG
Department SolAr
Neuseser Straße 1
D-91732 Merkendorf
Tel.: +49 (0) 9826 656 0
Fax: +49 (0) 9826 656 400
Email: solar@glaswerke-arnold.de
www.voltarlux.de

Spec. of 3-IN-1 Heat Insulation Solar Glass



ELECTRICAL DATA

Transmittance	10%	5%	1%
Output power	44 W	50 W	55 W
Max. power voltage	59.6 V	64.4 V	68.0 V
Max. power current	0.74 A	0.78 A	0.81 A
Open circuit voltage	91.8 V	91.8 V	91.8 V
Short circuit current	0.97 A	1.09 A	1.14 A

HEAT INSULATION DATA

SC (Shading Coefficient)	0.144
U ($W/m^2 K$)	1.65
RHG (W/m^2)	104
Heat transmittance (%)	2.6
Air condition saving (%)	50
K value (W/m K)	0.032

OPTICAL DATA

Visible light	Transmitted	7.34 %
	Reflected	7.9 %
Total solar energy	Transmitted	2.8 %
	Reflected	18 %
	absorbed	79.35 %
IR	rejected	100 %
UV	rejected	100 %

MECHANICAL DATA

Length (mm)		980
Width (mm)		950
Thickness (mm)	Vertical window	29
	Skylight	33
Wind resistance (kg/cm^2)		580
Weight (Kg)	Vertical window	37
	Skylight	46

APPENDIX B – *EnergyPlus* Input File of Building Model

```
!-Generator IDFEditor 1.41
!-Option SortedOrder

!-NOTE: All comments with '!-' are ignored by the IDFEditor and are generated automatically.
!-      Use '!' comments if they need to be retained when using the IDFEditor.


!-   ===========  ALL OBJECTS IN CLASS: VERSION ===========

Version,
    7.0;                     !- Version Identifier


!-   ===========  ALL OBJECTS IN CLASS: SIMULATIONCONTROL ===========

SimulationControl,
    No,                      !- Do Zone Sizing Calculation
    No,                      !- Do System Sizing Calculation
    No,                      !- Do Plant Sizing Calculation
    No,                      !- Run Simulation for Sizing Periods
    Yes;                     !- Run Simulation for Weather File Run Periods


!-   ===========  ALL OBJECTS IN CLASS: BUILDING ===========

Building,
    30x30,                   !- Name
    0.0,                     !- North Axis {deg}
    City,                    !- Terrain
    0.04,                    !- Loads Convergence Tolerance Value
    0.4,                     !- Temperature Convergence Tolerance Value {deltaC}
    FullInteriorAndExterior, !- Solar Distribution
    25,                      !- Maximum Number of Warmup Days
    6;                       !- Minimum Number of Warmup Days


!-   ===========  ALL OBJECTS IN CLASS: TIMESTEP ===========

Timestep,
    6;                       !- Number of Timesteps per Hour


!-   ===========  ALL OBJECTS IN CLASS: SITE:LOCATION ===========

Site:Location,
    Singapore,               !- Name
    1.37,                    !- Latitude {deg}
    103.98,                  !- Longitude {deg}
    8.0,                     !- Time Zone {hr}
    16;                      !- Elevation {m}


!-   ===========  ALL OBJECTS IN CLASS: RUNPERIOD ===========

RunPeriod,
    RunPeriod,               !- Name
    1,                       !- Begin Month
    1,                       !- Begin Day of Month
    12,                      !- End Month
    31,                      !- End Day of Month
    UseWeatherFile,          !- Day of Week for Start Day
    Yes,                     !- Use Weather File Holidays and Special Days
    Yes,                     !- Use Weather File Daylight Saving Period
    No,                      !- Apply Weekend Holiday Rule
    Yes,                     !- Use Weather File Rain Indicators
    Yes,                     !- Use Weather File Snow Indicators
    3;                       !- Number of Times Runperiod to be Repeated
```

```
!-   ===========  ALL OBJECTS IN CLASS: SCHEDULETYPELIMITS ===========

ScheduleTypeLimits,
    Any Number;              !- Name

ScheduleTypeLimits,
    Fraction,                !- Name
    0.0,                     !- Lower Limit Value
    1.0,                     !- Upper Limit Value
    CONTINUOUS;              !- Numeric Type

ScheduleTypeLimits,
    Temperature,             !- Name
    -60,                     !- Lower Limit Value
    200,                     !- Upper Limit Value
    CONTINUOUS;              !- Numeric Type

ScheduleTypeLimits,
    On/Off,                  !- Name
    0,                       !- Lower Limit Value
    1,                       !- Upper Limit Value
    DISCRETE;                !- Numeric Type

ScheduleTypeLimits,
    Control Type,            !- Name
    0,                       !- Lower Limit Value
    4,                       !- Upper Limit Value
    DISCRETE;                !- Numeric Type

ScheduleTypeLimits,
    Humidity,                !- Name
    10,                      !- Lower Limit Value
    90,                      !- Upper Limit Value
    CONTINUOUS;              !- Numeric Type

ScheduleTypeLimits,
    Number;                  !- Name

!
! ------------------------------------------------------------
! New objects created from ExpandObjects
! ------------------------------------------------------------
!
ScheduleTypeLimits,
    HVACTemplate Any Number; !- Name


!-   ===========  ALL OBJECTS IN CLASS: SCHEDULE:COMPACT ===========

Schedule:Compact,
    Office Lights Schedule,  !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 05:00,            !- Field 3
    0.05,                    !- Field 4
    Until: 07:00,            !- Field 5
    0.1,                     !- Field 6
    Until: 08:00,            !- Field 7
    0.3,                     !- Field 8
    Until: 17:00,            !- Field 9
    0.9,                     !- Field 10
    Until: 18:00,            !- Field 11
    0.5,                     !- Field 12
    Until: 20:00,            !- Field 13
    0.3,                     !- Field 14
    Until: 22:00,            !- Field 15
    0.2,                     !- Field 16
    Until: 23:00,            !- Field 17
```

```
    0.1,                     !- Field 18
    Until: 24:00,            !- Field 19
    0.05,                    !- Field 20
    For: SummerDesignDay,    !- Field 21
    Until: 24:00,            !- Field 22
    1.0,                     !- Field 23
    For: Saturday,           !- Field 24
    Until: 06:00,            !- Field 25
    0.05,                    !- Field 26
    Until: 08:00,            !- Field 27
    0.1,                     !- Field 28
    Until: 12:00,            !- Field 29
    0.3,                     !- Field 30
    Until: 17:00,            !- Field 31
    0.15,                    !- Field 32
    Until: 24:00,            !- Field 33
    0.05,                    !- Field 34
    For: WinterDesignDay,    !- Field 35
    Until: 24:00,            !- Field 36
    0.0,                     !- Field 37
    For: Sunday Holidays AllOtherDays, !- Field 38
    Until: 24:00,            !- Field 39
    0.05;                    !- Field 40

Schedule:Compact,
    Office Equipment Schedule,  !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 08:00,            !- Field 3
    0.40,                    !- Field 4
    Until: 12:00,            !- Field 5
    0.90,                    !- Field 6
    Until: 13:00,            !- Field 7
    0.80,                    !- Field 8
    Until: 17:00,            !- Field 9
    0.90,                    !- Field 10
    Until: 18:00,            !- Field 11
    0.50,                    !- Field 12
    Until: 24:00,            !- Field 13
    0.40,                    !- Field 14
    For: SummerDesignDay,    !- Field 15
    Until: 24:00,            !- Field 16
    1.0,                     !- Field 17
    For: Saturday,           !- Field 18
    Until: 06:00,            !- Field 19
    0.30,                    !- Field 20
    Until: 08:00,            !- Field 21
    0.4,                     !- Field 22
    Until: 12:00,            !- Field 23
    0.5,                     !- Field 24
    Until: 17:00,            !- Field 25
    0.35,                    !- Field 26
    Until: 24:00,            !- Field 27
    0.30,                    !- Field 28
    For: WinterDesignDay,    !- Field 29
    Until: 24:00,            !- Field 30
    0.0,                     !- Field 31
    For: Sunday Holidays AllOtherDays, !- Field 32
    Until: 24:00,            !- Field 33
    0.30;                    !- Field 34

Schedule:Compact,
    Office Occupancy Schedule,  !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 06:00,            !- Field 3
    0.0,                     !- Field 4
    Until: 07:00,            !- Field 5
    0.1,                     !- Field 6
```

```
    Until: 08:00,            !- Field 7
    0.2,                     !- Field 8
    Until: 12:00,            !- Field 9
    0.95,                    !- Field 10
    Until: 13:00,            !- Field 11
    0.5,                     !- Field 12
    Until: 17:00,            !- Field 13
    0.95,                    !- Field 14
    Until: 18:00,            !- Field 15
    0.3,                     !- Field 16
    Until: 20:00,            !- Field 17
    0.1,                     !- Field 18
    Until: 24:00,            !- Field 19
    0.05,                    !- Field 20
    For: SummerDesignDay,    !- Field 21
    Until: 06:00,            !- Field 22
    0.0,                     !- Field 23
    Until: 22:00,            !- Field 24
    1.0,                     !- Field 25
    Until: 24:00,            !- Field 26
    0.05,                    !- Field 27
    For: Saturday,           !- Field 28
    Until: 06:00,            !- Field 29
    0.0,                     !- Field 30
    Until: 08:00,            !- Field 31
    0.1,                     !- Field 32
    Until: 12:00,            !- Field 33
    0.3,                     !- Field 34
    Until: 17:00,            !- Field 35
    0.1,                     !- Field 36
    Until: 19:00,            !- Field 37
    0.0,                     !- Field 38
    Until: 24:00,            !- Field 39
    0.0,                     !- Field 40
    For: WinterDesignDay,    !- Field 41
    Until: 24:00,            !- Field 42
    0.0,                     !- Field 43
    For: Sunday Holidays AllOtherDays,  !- Field 44
    Until: 06:00,            !- Field 45
    0.0,                     !- Field 46
    Until: 18:00,            !- Field 47
    0.0,                     !- Field 48
    Until: 24:00,            !- Field 49
    0.0;                     !- Field 50

  Schedule:Compact,
    Infiltration Schedule,   !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays SummerDesignDay,  !- Field 2
    Until: 06:00,            !- Field 3
    1.0,                     !- Field 4
    Until: 22:00,            !- Field 5
    1,                       !- Field 6
    Until: 24:00,            !- Field 7
    1.0,                     !- Field 8
    For: Saturday WinterDesignDay,  !- Field 9
    Until: 06:00,            !- Field 10
    1.0,                     !- Field 11
    Until: 18:00,            !- Field 12
    1,                       !- Field 13
    Until: 24:00,            !- Field 14
    1.0,                     !- Field 15
    For: Sunday Holidays AllOtherDays,  !- Field 16
    Until: 24:00,            !- Field 17
    1.0;                     !- Field 18

  Schedule:Compact,
    Infiltration Half On Schedule,  !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
```

```
    For: Weekdays SummerDesignDay,  !- Field 2
    Until: 06:00,           !- Field 3
    1.0,                    !- Field 4
    Until: 22:00,           !- Field 5
    0.5,                    !- Field 6
    Until: 24:00,           !- Field 7
    1.0,                    !- Field 8
    For: Saturday WinterDesignDay,  !- Field 9
    Until: 06:00,           !- Field 10
    1.0,                    !- Field 11
    Until: 18:00,           !- Field 12
    0.5,                    !- Field 13
    Until: 24:00,           !- Field 14
    1.0,                    !- Field 15
    For: Sunday Holidays AllOtherDays,  !- Field 16
    Until: 24:00,           !- Field 17
    1.0;                    !- Field 18

Schedule:Compact,
    Infiltration Quarter On Schedule,  !- Name
    Fraction,               !- Schedule Type Limits Name
    Through: 12/31,         !- Field 1
    For: Weekdays SummerDesignDay,  !- Field 2
    Until: 06:00,           !- Field 3
    1.0,                    !- Field 4
    Until: 22:00,           !- Field 5
    0.25,                   !- Field 6
    Until: 24:00,           !- Field 7
    1.0,                    !- Field 8
    For: Saturday WinterDesignDay,  !- Field 9
    Until: 06:00,           !- Field 10
    1.0,                    !- Field 11
    Until: 18:00,           !- Field 12
    0.25,                   !- Field 13
    Until: 24:00,           !- Field 14
    1.0,                    !- Field 15
    For: Sunday Holidays AllOtherDays,  !- Field 16
    Until: 24:00,           !- Field 17
    1.0;                    !- Field 18

Schedule:Compact,
    Hours of Operation Schedule,  !- Name
    On/Off,                 !- Schedule Type Limits Name
    Through: 12/31,         !- Field 1
    For: Weekdays SummerDesignDay,  !- Field 2
    Until: 09:00,           !- Field 3
    0.0,                    !- Field 4
    Until: 18:00,           !- Field 5
    1.0,                    !- Field 6
    Until: 24:00,           !- Field 7
    0.0,                    !- Field 8
    For: Saturday WinterDesignDay,  !- Field 9
    Until: 06:00,           !- Field 10
    0.0,                    !- Field 11
    Until: 18:00,           !- Field 12
    0,                      !- Field 13
    Until: 24:00,           !- Field 14
    0.0,                    !- Field 15
    For: Sunday Holidays AllOtherDays,  !- Field 16
    Until: 24:00,           !- Field 17
    0.0;                    !- Field 18

Schedule:Compact,
    Always On,              !- Name
    Fraction,               !- Schedule Type Limits Name
    Through: 12/31,         !- Field 1
    For: AllDays,           !- Field 2
    Until: 24:00,           !- Field 3
    1.0;                    !- Field 4

Schedule:Compact,
```

```
    Always Off,              !- Name
    Fraction,                !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    0.0;                     !- Field 4

Schedule:Compact,
    Heating Setpoint Schedule,  !- Name
    Temperature,             !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays,           !- Field 2
    Until: 05:00,            !- Field 3
    15.6,                    !- Field 4
    Until: 19:00,            !- Field 5
    21.0,                    !- Field 6
    Until: 24:00,            !- Field 7
    15.6,                    !- Field 8
    For SummerDesignDay,     !- Field 9
    Until: 24:00,            !- Field 10
    15.6,                    !- Field 11
    For: Saturday,           !- Field 12
    Until: 06:00,            !- Field 13
    15.6,                    !- Field 14
    Until: 17:00,            !- Field 15
    21.0,                    !- Field 16
    Until: 24:00,            !- Field 17
    15.6,                    !- Field 18
    For: WinterDesignDay,    !- Field 19
    Until: 24:00,            !- Field 20
    21.0,                    !- Field 21
    For: Sunday Holidays AllOtherDays,  !- Field 22
    Until: 24:00,            !- Field 23
    15.6;                    !- Field 24

Schedule:Compact,
    Cooling Setpoint Schedule,  !- Name
    Temperature,             !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: Weekdays SummerDesignDay,  !- Field 2
    Until: 06:00,            !- Field 3
    30.0,                    !- Field 4
    Until: 22:00,            !- Field 5
    24.0,                    !- Field 6
    Until: 24:00,            !- Field 7
    30.0,                    !- Field 8
    For: Saturday,           !- Field 9
    Until: 06:00,            !- Field 10
    30.0,                    !- Field 11
    Until: 18:00,            !- Field 12
    24.0,                    !- Field 13
    Until: 24:00,            !- Field 14
    30.0,                    !- Field 15
    For WinterDesignDay,     !- Field 16
    Until: 24:00,            !- Field 17
    30.0,                    !- Field 18
    For: Sunday Holidays AllOtherDays,  !- Field 19
    Until: 24:00,            !- Field 20
    30.0;                    !- Field 21

Schedule:Compact,
    Office Activity Schedule,!- Name
    Any Number,              !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    120.;                    !- Field 4

Schedule:Compact,
    Office Work Eff. Schedule,  !- Name
    Fraction,                !- Schedule Type Limits Name
```

```
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    0.0;                     !- Field 4

Schedule:Compact,
    Office Clothing Schedule,!- Name
    Any Number,              !- Schedule Type Limits Name
    Through: 04/30,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    1.0,                     !- Field 4
    Through: 09/30,          !- Field 5
    For: AllDays,            !- Field 6
    Until: 24:00,            !- Field 7
    0.5,                     !- Field 8
    Through: 12/31,          !- Field 9
    For: AllDays,            !- Field 10
    Until: 24:00,            !- Field 11
    1.0;                     !- Field 12

Schedule:Compact,
    HVACTemplate-Always 1,   !- Name
    HVACTemplate Any Number, !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    1;                       !- Field 4

Schedule:Compact,
    HVACTemplate-Always 4,   !- Name
    HVACTemplate Any Number, !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    4;                       !- Field 4

Schedule:Compact,
    HVACTemplate-Always 20,  !- Name
    HVACTemplate Any Number, !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    20;                      !- Field 4

Schedule:Compact,
    HVACTemplate-Always 22,  !- Name
    HVACTemplate Any Number, !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    22;                      !- Field 4

Schedule:Compact,
    HVACTemplate-Always 2,   !- Name
    HVACTemplate Any Number, !- Schedule Type Limits Name
    Through: 12/31,          !- Field 1
    For: AllDays,            !- Field 2
    Until: 24:00,            !- Field 3
    2;                       !- Field 4


!-   ===========  ALL OBJECTS IN CLASS: MATERIAL ===========

Material,
    F08 Metal surface,       !- Name
    Smooth,                  !- Roughness
    0.0008,                  !- Thickness {m}
    45.28,                   !- Conductivity {W/m-K}
    7824,                    !- Density {kg/m3}
    500;                     !- Specific Heat {J/kg-K}
```

```
Material,
    I01 25mm insulation board,  !- Name
    MediumRough,             !- Roughness
    0.0254,                  !- Thickness {m}
    0.03,                    !- Conductivity {W/m-K}
    43,                      !- Density {kg/m3}
    1210;                    !- Specific Heat {J/kg-K}

Material,
    I02 50mm insulation board,  !- Name
    MediumRough,             !- Roughness
    0.0508,                  !- Thickness {m}
    0.03,                    !- Conductivity {W/m-K}
    43,                      !- Density {kg/m3}
    1210;                    !- Specific Heat {J/kg-K}

Material,
    G01a 19mm gypsum board,  !- Name
    MediumSmooth,            !- Roughness
    0.019,                   !- Thickness {m}
    0.16,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    1090;                    !- Specific Heat {J/kg-K}

Material,
    M11 100mm lightweight concrete,  !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    0.53,                    !- Conductivity {W/m-K}
    1280,                    !- Density {kg/m3}
    840;                     !- Specific Heat {J/kg-K}

Material,
    F16 Acoustic tile,       !- Name
    MediumSmooth,            !- Roughness
    0.0191,                  !- Thickness {m}
    0.06,                    !- Conductivity {W/m-K}
    368,                     !- Density {kg/m3}
    590;                     !- Specific Heat {J/kg-K}

Material,
    M01 100mm brick,         !- Name
    MediumRough,             !- Roughness
    0.1016,                  !- Thickness {m}
    0.89,                    !- Conductivity {W/m-K}
    1920,                    !- Density {kg/m3}
    790;                     !- Specific Heat {J/kg-K}

Material,
    M15 200mm heavyweight concrete,  !- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    1.95,                    !- Conductivity {W/m-K}
    2240,                    !- Density {kg/m3}
    900;                     !- Specific Heat {J/kg-K}

Material,
    M05 200mm concrete block,!- Name
    MediumRough,             !- Roughness
    0.2032,                  !- Thickness {m}
    1.11,                    !- Conductivity {W/m-K}
    800,                     !- Density {kg/m3}
    920;                     !- Specific Heat {J/kg-K}

Material,
    G05 25mm wood,           !- Name
    MediumSmooth,            !- Roughness
    0.0254,                  !- Thickness {m}
    0.15,                    !- Conductivity {W/m-K}
    608,                     !- Density {kg/m3}
```

```
    1630;                    !- Specific Heat {J/kg-K}


!-   ===========  ALL OBJECTS IN CLASS: MATERIAL:AIRGAP ===========

Material:AirGap,
    F04 Wall air space resistance,  !- Name
    0.15;                    !- Thermal Resistance {m2-K/W}

Material:AirGap,
    F05 Ceiling air space resistance,  !- Name
    0.18;                    !- Thermal Resistance {m2-K/W}


!-   ===========  ALL OBJECTS IN CLASS: WINDOWMATERIAL:SIMPLEGLAZINGSYSTEM ===========

WindowMaterial:SimpleGlazingSystem,
    Hanwa Makmax KN-42,      !- Name
    5.076,                   !- U-Factor {W/m2-K}
    0.289,                   !- Solar Heat Gain Coefficient
    0.09165;                 !- Visible Transmittance

WindowMaterial:SimpleGlazingSystem,
    Auria Micromorph (Red),  !- Name
    4.795,                   !- U-Factor {W/m2-K}
    0.413,                   !- Solar Heat Gain Coefficient
    0.162;                   !- Visible Transmittance

WindowMaterial:SimpleGlazingSystem,
    Auria Micromorph (Golden),  !- Name
    5.08,                    !- U-Factor {W/m2-K}
    0.298,                   !- Solar Heat Gain Coefficient
    0.063;                   !- Visible Transmittance

WindowMaterial:SimpleGlazingSystem,
    Auria Micromorph (DarkBlue),  !- Name
    5.096,                   !- U-Factor {W/m2-K}
    0.387,                   !- Solar Heat Gain Coefficient
    0.109;                   !- Visible Transmittance


!-   ===========  ALL OBJECTS IN CLASS: WINDOWMATERIAL:GLAZING ===========

WindowMaterial:Glazing,
    Clear 3mm,               !- Name
    SpectralAverage,         !- Optical Data Type
    ,                        !- Window Glass Spectral Data Set Name
    0.003,                   !- Thickness {m}
    0.837,                   !- Solar Transmittance at Normal Incidence
    0.075,                   !- Front Side Solar Reflectance at Normal Incidence
    0.075,                   !- Back Side Solar Reflectance at Normal Incidence
    0.898,                   !- Visible Transmittance at Normal Incidence
    0.081,                   !- Front Side Visible Reflectance at Normal Incidence
    0.081,                   !- Back Side Visible Reflectance at Normal Incidence
    0,                       !- Infrared Transmittance at Normal Incidence
    0.84,                    !- Front Side Infrared Hemispherical Emissivity
    0.84,                    !- Back Side Infrared Hemispherical Emissivity
    0.9;                     !- Conductivity {W/m-K}


!-   ===========  ALL OBJECTS IN CLASS: WINDOWMATERIAL:GAS ===========

WindowMaterial:Gas,
    Air 13mm,                !- Name
    Air,                     !- Gas Type
    0.0127;                  !- Thickness {m}


!-   ===========  ALL OBJECTS IN CLASS: CONSTRUCTION ===========

Construction,
```

```
    Exterior Floor,          !- Name
    I02 50mm insulation board,  !- Outside Layer
    M15 200mm heavyweight concrete;  !- Layer 2

Construction,
    Interior Floor,          !- Name
    F16 Acoustic tile,       !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    M11 100mm lightweight concrete;  !- Layer 3

Construction,
    Exterior Wall,           !- Name
    M15 200mm heavyweight concrete,  !- Outside Layer
    I02 50mm insulation board,  !- Layer 2
    F04 Wall air space resistance,  !- Layer 3
    G01a 19mm gypsum board;  !- Layer 4

Construction,
    Interior Wall,           !- Name
    G01a 19mm gypsum board,  !- Outside Layer
    F04 Wall air space resistance,  !- Layer 2
    G01a 19mm gypsum board;  !- Layer 3

Construction,
    Exterior Roof,           !- Name
    M11 100mm lightweight concrete,  !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    F16 Acoustic tile;       !- Layer 3

Construction,
    Interior Ceiling,        !- Name
    M11 100mm lightweight concrete,  !- Outside Layer
    F05 Ceiling air space resistance,  !- Layer 2
    F16 Acoustic tile;       !- Layer 3

Construction,
    Exterior Window,         !- Name
    Hanwa Makmax KN-42;      !- Outside Layer

Construction,
    Interior Window,         !- Name
    Clear 3mm;               !- Outside Layer

Construction,
    Exterior Door,           !- Name
    F08 Metal surface,       !- Outside Layer
    I01 25mm insulation board;  !- Layer 2

Construction,
    Interior Door,           !- Name
    G05 25mm wood;           !- Outside Layer


!-   ===========  ALL OBJECTS IN CLASS: GLOBALGEOMETRYRULES ===========

GlobalGeometryRules,
    UpperLeftCorner,         !- Starting Vertex Position
    Counterclockwise,        !- Vertex Entry Direction
    Relative,                !- Coordinate System
    World;                   !- Daylighting Reference Point Coordinate System


!-   ===========  ALL OBJECTS IN CLASS: ZONE ===========

Zone,
    South Zone,              !- Name
    0.0,                     !- Direction of Relative North {deg}
    0.0,                     !- X Origin {m}
    0.0,                     !- Y Origin {m}
    0.0,                     !- Z Origin {m}
    ,                        !- Type
```

```
    1;                       !- Multiplier

Zone,
    West Zone,               !- Name
    0.0,                     !- Direction of Relative North {deg}
    0.0,                     !- X Origin {m}
    10.0,                    !- Y Origin {m}
    0.0,                     !- Z Origin {m}
    ,                        !- Type
    1;                       !- Multiplier

Zone,
    East Zone,               !- Name
    0.0,                     !- Direction of Relative North {deg}
    30.0,                    !- X Origin {m}
    10.0,                    !- Y Origin {m}
    0.0,                     !- Z Origin {m}
    ,                        !- Type
    1;                       !- Multiplier

Zone,
    Core Zone,               !- Name
    0.0,                     !- Direction of Relative North {deg}
    16.003408,               !- X Origin {m}
    15.984079,               !- Y Origin {m}
    0.0,                     !- Z Origin {m}
    ,                        !- Type
    1;                       !- Multiplier

Zone,
    North Zone,              !- Name
    0.0,                     !- Direction of Relative North {deg}
    10.0,                    !- X Origin {m}
    30.0,                    !- Y Origin {m}
    0.0,                     !- Z Origin {m}
    ,                        !- Type
    1;                       !- Multiplier


!-   ===========  ALL OBJECTS IN CLASS: BUILDINGSURFACE:DETAILED ===========

BuildingSurface:Detailed,
    14F0A8,                  !- Name
    Floor,                   !- Surface Type
    Exterior Floor,          !- Construction Name
    South Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    20.000000000000,         !- Vertex 1 X-coordinate {m}
    10.000000000000,         !- Vertex 1 Y-coordinate {m}
    0.000000000000,          !- Vertex 1 Z-coordinate {m}
    30.000000000000,         !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    10.000000000000,         !- Vertex 4 X-coordinate {m}
    10.000000000000,         !- Vertex 4 Y-coordinate {m}
    0.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    EC6389,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    South Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
```

```
    ,                    !- Outside Boundary Condition Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    ,                    !- View Factor to Ground
    4,                   !- Number of Vertices
    30.000000000000,     !- Vertex 1 X-coordinate {m}
    0.000000000000,      !- Vertex 1 Y-coordinate {m}
    3.000000000000,      !- Vertex 1 Z-coordinate {m}
    30.000000000000,     !- Vertex 2 X-coordinate {m}
    0.000000000000,      !- Vertex 2 Y-coordinate {m}
    0.000000000000,      !- Vertex 2 Z-coordinate {m}
    20.000000000000,     !- Vertex 3 X-coordinate {m}
    10.000000000000,     !- Vertex 3 Y-coordinate {m}
    0.000000000000,      !- Vertex 3 Z-coordinate {m}
    20.000000000000,     !- Vertex 4 X-coordinate {m}
    10.000000000000,     !- Vertex 4 Y-coordinate {m}
    3.000000000000;      !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    71DD34,              !- Name
    Wall,                !- Surface Type
    Exterior Wall,       !- Construction Name
    South Zone,          !- Zone Name
    Adiabatic,           !- Outside Boundary Condition
    ,                    !- Outside Boundary Condition Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    ,                    !- View Factor to Ground
    4,                   !- Number of Vertices
    20.000000000000,     !- Vertex 1 X-coordinate {m}
    10.000000000000,     !- Vertex 1 Y-coordinate {m}
    3.000000000000,      !- Vertex 1 Z-coordinate {m}
    20.000000000000,     !- Vertex 2 X-coordinate {m}
    10.000000000000,     !- Vertex 2 Y-coordinate {m}
    0.000000000000,      !- Vertex 2 Z-coordinate {m}
    10.000000000000,     !- Vertex 3 X-coordinate {m}
    10.000000000000,     !- Vertex 3 Y-coordinate {m}
    0.000000000000,      !- Vertex 3 Z-coordinate {m}
    10.000000000000,     !- Vertex 4 X-coordinate {m}
    10.000000000000,     !- Vertex 4 Y-coordinate {m}
    3.000000000000;      !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    E81186,              !- Name
    Roof,                !- Surface Type
    Exterior Roof,       !- Construction Name
    South Zone,          !- Zone Name
    Adiabatic,           !- Outside Boundary Condition
    ,                    !- Outside Boundary Condition Object
    NoSun,               !- Sun Exposure
    NoWind,              !- Wind Exposure
    ,                    !- View Factor to Ground
    4,                   !- Number of Vertices
    0.000000000000,      !- Vertex 1 X-coordinate {m}
    0.000000000000,      !- Vertex 1 Y-coordinate {m}
    3.000000000000,      !- Vertex 1 Z-coordinate {m}
    30.000000000000,     !- Vertex 2 X-coordinate {m}
    0.000000000000,      !- Vertex 2 Y-coordinate {m}
    3.000000000000,      !- Vertex 2 Z-coordinate {m}
    20.000000000000,     !- Vertex 3 X-coordinate {m}
    10.000000000000,     !- Vertex 3 Y-coordinate {m}
    3.000000000000,      !- Vertex 3 Z-coordinate {m}
    10.000000000000,     !- Vertex 4 X-coordinate {m}
    10.000000000000,     !- Vertex 4 Y-coordinate {m}
    3.000000000000;      !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    62203C,              !- Name
    Wall,                !- Surface Type
    Exterior Wall,       !- Construction Name
    South Zone,          !- Zone Name
```

```
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    10.000000000000,         !- Vertex 1 X-coordinate {m}
    10.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    10.000000000000,         !- Vertex 2 X-coordinate {m}
    10.000000000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    South Wall,              !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    South Zone,              !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    30.000000000000,         !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    30.000000000000,         !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    FFE892,                  !- Name
    Floor,                   !- Surface Type
    Exterior Floor,          !- Construction Name
    West Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    10.000000000000,         !- Vertex 1 X-coordinate {m}
    10.000000000000,         !- Vertex 1 Y-coordinate {m}
    0.000000000000,          !- Vertex 1 Z-coordinate {m}
    10.000000000000,         !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    20.000000000000,         !- Vertex 4 Y-coordinate {m}
    0.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    DA9951,                  !- Name
    Roof,                    !- Surface Type
    Exterior Roof,           !- Construction Name
```

```
    West Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    20.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    3.000000000000,          !- Vertex 2 Z-coordinate {m}
    10.000000000000,         !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    3.000000000000,          !- Vertex 3 Z-coordinate {m}
    10.000000000000,         !- Vertex 4 X-coordinate {m}
    10.000000000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    West Wall,               !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    West Zone,               !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    20.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    20.000000000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    668E3E,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    West Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    10.000000000000,         !- Vertex 1 X-coordinate {m}
    10.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    10.000000000000,         !- Vertex 2 X-coordinate {m}
    10.000000000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    20.000000000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    20.000000000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    762918,                  !- Name
    Wall,                    !- Surface Type
```

```
    Exterior Wall,           !- Construction Name
    West Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    10.000000000000,         !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    10.000000000000,         !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    10.000000000000,         !- Vertex 3 X-coordinate {m}
    10.000000000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    10.000000000000,         !- Vertex 4 X-coordinate {m}
    10.000000000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    7151B6,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    West Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    10.000000000000,         !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    10.000000000000,         !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    CEA751,                  !- Name
    Floor,                   !- Surface Type
    Exterior Floor,          !- Construction Name
    East Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    20.000000000000,         !- Vertex 1 Y-coordinate {m}
    0.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -10.000000000000,        !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -10.000000000000,        !- Vertex 4 X-coordinate {m}
    10.000000000000,         !- Vertex 4 Y-coordinate {m}
    0.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    DBDADA,                  !- Name
```

```
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    East Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    20.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    20.000000000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -10.000000000000,        !- Vertex 3 X-coordinate {m}
    10.000000000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -10.000000000000,        !- Vertex 4 X-coordinate {m}
    10.000000000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    48142A,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    East Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -10.000000000000,        !- Vertex 1 X-coordinate {m}
    10.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -10.000000000000,        !- Vertex 2 X-coordinate {m}
    10.000000000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -10.000000000000,        !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -10.000000000000,        !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    8B65C5,                  !- Name
    Roof,                    !- Surface Type
    Exterior Roof,           !- Construction Name
    East Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -10.000000000000,        !- Vertex 1 X-coordinate {m}
    10.000000000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -10.000000000000,        !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    3.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    3.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    20.000000000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
```

```
    F508AE,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    East Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -10.000000000000,        !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -10.000000000000,        !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    East Wall,               !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    East Zone,               !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    20.000000000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    20.000000000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    DCDB4E,                  !- Name
    Floor,                   !- Surface Type
    Exterior Floor,          !- Construction Name
    Core Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    3.996592000000,          !- Vertex 1 X-coordinate {m}
    4.015921000000,          !- Vertex 1 Y-coordinate {m}
    0.000000000000,          !- Vertex 1 Z-coordinate {m}
    3.996592000000,          !- Vertex 2 X-coordinate {m}
    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -6.003408000000,         !- Vertex 3 X-coordinate {m}
    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -6.003408000000,         !- Vertex 4 X-coordinate {m}
    4.015921000000,          !- Vertex 4 Y-coordinate {m}
    0.000000000000;          !- Vertex 4 Z-coordinate {m}
```

```
BuildingSurface:Detailed,
    FF003C,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    Core Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -6.003408000000,         !- Vertex 1 X-coordinate {m}
    -5.984079000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -6.003408000000,         !- Vertex 2 X-coordinate {m}
    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    3.996592000000,          !- Vertex 3 X-coordinate {m}
    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    3.996592000000,          !- Vertex 4 X-coordinate {m}
    -5.984079000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    EA7F7B,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    Core Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    3.996592000000,          !- Vertex 1 X-coordinate {m}
    -5.984079000000,         !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    3.996592000000,          !- Vertex 2 X-coordinate {m}
    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    3.996592000000,          !- Vertex 3 X-coordinate {m}
    4.015921000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    3.996592000000,          !- Vertex 4 X-coordinate {m}
    4.015921000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    98104C,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    Core Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -6.003408000000,         !- Vertex 1 X-coordinate {m}
    4.015921000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -6.003408000000,         !- Vertex 2 X-coordinate {m}
    4.015921000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -6.003408000000,         !- Vertex 3 X-coordinate {m}
    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -6.003408000000,         !- Vertex 4 X-coordinate {m}
    -5.984079000000,         !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}
```

```
BuildingSurface:Detailed,
    Core Roof,               !- Name
    Roof,                    !- Surface Type
    Exterior Roof,           !- Construction Name
    Core Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    0.0,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    -6.003408000000,         !- Vertex 1 X-coordinate {m}
    4.015921000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -6.003408000000,         !- Vertex 2 X-coordinate {m}
    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
    3.000000000000,          !- Vertex 2 Z-coordinate {m}
    3.996592000000,          !- Vertex 3 X-coordinate {m}
    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
    3.000000000000,          !- Vertex 3 Z-coordinate {m}
    3.996592000000,          !- Vertex 4 X-coordinate {m}
    4.015921000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    7BBFE0,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    Core Zone,               !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    3.996592000000,          !- Vertex 1 X-coordinate {m}
    4.015921000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    3.996592000000,          !- Vertex 2 X-coordinate {m}
    4.015921000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -6.003408000000,         !- Vertex 3 X-coordinate {m}
    4.015921000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -6.003408000000,         !- Vertex 4 X-coordinate {m}
    4.015921000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    795B5E,                  !- Name
    Floor,                   !- Surface Type
    Exterior Floor,          !- Construction Name
    North Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    20.000000000000,         !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    0.000000000000,          !- Vertex 1 Z-coordinate {m}
    10.000000000000,         !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -10.000000000000,        !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
```

```
    0.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    North Wall,              !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    North Zone,              !- Zone Name
    Outdoors,                !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    SunExposed,              !- Sun Exposure
    WindExposed,             !- Wind Exposure
    0.0,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    20.000000000000,         !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    20.000000000000,         !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    -10.000000000000,        !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    -10.000000000000,        !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    996064,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    North Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -10.000000000000,        !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    -10.000000000000,        !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    403F94,                  !- Name
    Roof,                    !- Surface Type
    Exterior Roof,           !- Construction Name
    North Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    -10.000000000000,        !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    3.000000000000,          !- Vertex 2 Z-coordinate {m}
    10.000000000000,         !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    3.000000000000,          !- Vertex 3 Z-coordinate {m}
    20.000000000000,         !- Vertex 4 X-coordinate {m}
```

```
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    31AE50,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    North Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    ,                        !- View Factor to Ground
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    10.000000000000,         !- Vertex 3 X-coordinate {m}
    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    10.000000000000,         !- Vertex 4 X-coordinate {m}
    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}

BuildingSurface:Detailed,
    123456,                  !- Name
    Wall,                    !- Surface Type
    Exterior Wall,           !- Construction Name
    North Zone,              !- Zone Name
    Adiabatic,               !- Outside Boundary Condition
    ,                        !- Outside Boundary Condition Object
    NoSun,                   !- Sun Exposure
    NoWind,                  !- Wind Exposure
    0.0,                     !- View Factor to Ground
    4,                       !- Number of Vertices
    10.000000000000,         !- Vertex 1 X-coordinate {m}
    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
    3.000000000000,          !- Vertex 1 Z-coordinate {m}
    10.000000000000,         !- Vertex 2 X-coordinate {m}
    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
    0.000000000000,          !- Vertex 2 Z-coordinate {m}
    20.000000000000,         !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.000000000000,          !- Vertex 3 Z-coordinate {m}
    20.000000000000,         !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    3.000000000000;          !- Vertex 4 Z-coordinate {m}


!-   ===========  ALL OBJECTS IN CLASS: FENESTRATIONSURFACE:DETAILED ===========

FenestrationSurface:Detailed,
    South Window,            !- Name
    Window,                  !- Surface Type
    Exterior Window,         !- Construction Name
    South Wall,              !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    ,                        !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    ,                        !- Multiplier
    4,                       !- Number of Vertices
    4.393500000000,          !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    2.560500000000,          !- Vertex 1 Z-coordinate {m}
    4.393500000000,          !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.439500000000,          !- Vertex 2 Z-coordinate {m}
```

```
    25.606500000000,         !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.439500000000,          !- Vertex 3 Z-coordinate {m}
    25.606500000000,         !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    2.560500000000;          !- Vertex 4 Z-coordinate {m}

FenestrationSurface:Detailed,
    West Window,             !- Name
    Window,                  !- Surface Type
    Exterior Window,         !- Construction Name
    West Wall,               !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    ,                        !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    ,                        !- Multiplier
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    15.606500000000,         !- Vertex 1 Y-coordinate {m}
    2.560500000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    15.606500000000,         !- Vertex 2 Y-coordinate {m}
    0.439500000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    -5.606500000000,         !- Vertex 3 Y-coordinate {m}
    0.439500000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    -5.606500000000,         !- Vertex 4 Y-coordinate {m}
    2.560500000000;          !- Vertex 4 Z-coordinate {m}

FenestrationSurface:Detailed,
    North Window,            !- Name
    Window,                  !- Surface Type
    Exterior Window,         !- Construction Name
    North Wall,              !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    ,                        !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    ,                        !- Multiplier
    4,                       !- Number of Vertices
    15.606500000000,         !- Vertex 1 X-coordinate {m}
    0.000000000000,          !- Vertex 1 Y-coordinate {m}
    2.560500000000,          !- Vertex 1 Z-coordinate {m}
    15.606500000000,         !- Vertex 2 X-coordinate {m}
    0.000000000000,          !- Vertex 2 Y-coordinate {m}
    0.439500000000,          !- Vertex 2 Z-coordinate {m}
    -5.606500000000,         !- Vertex 3 X-coordinate {m}
    0.000000000000,          !- Vertex 3 Y-coordinate {m}
    0.439500000000,          !- Vertex 3 Z-coordinate {m}
    -5.606500000000,         !- Vertex 4 X-coordinate {m}
    0.000000000000,          !- Vertex 4 Y-coordinate {m}
    2.560500000000;          !- Vertex 4 Z-coordinate {m}

FenestrationSurface:Detailed,
    East Window,             !- Name
    Window,                  !- Surface Type
    Exterior Window,         !- Construction Name
    East Wall,               !- Building Surface Name
    ,                        !- Outside Boundary Condition Object
    ,                        !- View Factor to Ground
    ,                        !- Shading Control Name
    ,                        !- Frame and Divider Name
    ,                        !- Multiplier
    4,                       !- Number of Vertices
    0.000000000000,          !- Vertex 1 X-coordinate {m}
    -5.606500000000,         !- Vertex 1 Y-coordinate {m}
    2.560500000000,          !- Vertex 1 Z-coordinate {m}
    0.000000000000,          !- Vertex 2 X-coordinate {m}
    -5.606500000000,         !- Vertex 2 Y-coordinate {m}
```

```
    0.439500000000,          !- Vertex 2 Z-coordinate {m}
    0.000000000000,          !- Vertex 3 X-coordinate {m}
    15.606500000000,         !- Vertex 3 Y-coordinate {m}
    0.439500000000,          !- Vertex 3 Z-coordinate {m}
    0.000000000000,          !- Vertex 4 X-coordinate {m}
    15.606500000000,         !- Vertex 4 Y-coordinate {m}
    2.560500000000;          !- Vertex 4 Z-coordinate {m}


!-   ===========  ALL OBJECTS IN CLASS: PEOPLE ===========

People,
    South Occupancy,         !- Name
    South Zone,              !- Zone or ZoneList Name
    Office Occupancy Schedule,  !- Number of People Schedule Name
    People/Area,             !- Number of People Calculation Method
    ,                        !- Number of People
    0.2,                     !- People per Zone Floor Area {person/m2}
    ,                        !- Zone Floor Area per Person {m2/person}
    0.6,                     !- Fraction Radiant
    autocalculate,           !- Sensible Heat Fraction
    Office Activity Schedule,!- Activity Level Schedule Name
    3.82E-08,                !- Carbon Dioxide Generation Rate {m3/s-W}
    No,                      !- Enable ASHRAE 55 Comfort Warnings
    ZoneAveraged;            !- Mean Radiant Temperature Calculation Type

People,
    West Occupancy,          !- Name
    West Zone,               !- Zone or ZoneList Name
    Office Occupancy Schedule,  !- Number of People Schedule Name
    People/Area,             !- Number of People Calculation Method
    ,                        !- Number of People
    0.2,                     !- People per Zone Floor Area {person/m2}
    ,                        !- Zone Floor Area per Person {m2/person}
    0.6,                     !- Fraction Radiant
    autocalculate,           !- Sensible Heat Fraction
    Office Activity Schedule,!- Activity Level Schedule Name
    3.82E-08,                !- Carbon Dioxide Generation Rate {m3/s-W}
    No,                      !- Enable ASHRAE 55 Comfort Warnings
    ZoneAveraged;            !- Mean Radiant Temperature Calculation Type

People,
    East Occupancy,          !- Name
    East Zone,               !- Zone or ZoneList Name
    Office Occupancy Schedule,  !- Number of People Schedule Name
    People/Area,             !- Number of People Calculation Method
    ,                        !- Number of People
    0.2,                     !- People per Zone Floor Area {person/m2}
    ,                        !- Zone Floor Area per Person {m2/person}
    0.6,                     !- Fraction Radiant
    autocalculate,           !- Sensible Heat Fraction
    Office Activity Schedule,!- Activity Level Schedule Name
    3.82E-08,                !- Carbon Dioxide Generation Rate {m3/s-W}
    No,                      !- Enable ASHRAE 55 Comfort Warnings
    ZoneAveraged;            !- Mean Radiant Temperature Calculation Type

People,
    North Occupancy,         !- Name
    North Zone,              !- Zone or ZoneList Name
    Office Occupancy Schedule,  !- Number of People Schedule Name
    People/Area,             !- Number of People Calculation Method
    ,                        !- Number of People
    0.2,                     !- People per Zone Floor Area {person/m2}
    ,                        !- Zone Floor Area per Person {m2/person}
    0.6,                     !- Fraction Radiant
    autocalculate,           !- Sensible Heat Fraction
    Office Activity Schedule,!- Activity Level Schedule Name
    3.82E-08,                !- Carbon Dioxide Generation Rate {m3/s-W}
    No,                      !- Enable ASHRAE 55 Comfort Warnings
    ZoneAveraged;            !- Mean Radiant Temperature Calculation Type
```

```
!-   ===========  ALL OBJECTS IN CLASS: LIGHTS ===========

Lights,
    South Lights,            !- Name
    South Zone,              !- Zone or ZoneList Name
    Office Lights Schedule,  !- Schedule Name
    Watts/Area,              !- Design Level Calculation Method
    ,                        !- Lighting Level {W}
    10,                      !- Watts per Zone Floor Area {W/m2}
    ,                        !- Watts per Person {W/person}
    0,                       !- Return Air Fraction
    0.37,                    !- Fraction Radiant
    0.18,                    !- Fraction Visible
    1,                       !- Fraction Replaceable
    General,                 !- End-Use Subcategory
    No;                      !- Return Air Fraction Calculated from Plenum Temperature

Lights,
    West Lights,             !- Name
    West Zone,               !- Zone or ZoneList Name
    Office Lights Schedule,  !- Schedule Name
    Watts/Area,              !- Design Level Calculation Method
    ,                        !- Lighting Level {W}
    10,                      !- Watts per Zone Floor Area {W/m2}
    ,                        !- Watts per Person {W/person}
    0,                       !- Return Air Fraction
    0.37,                    !- Fraction Radiant
    0.18,                    !- Fraction Visible
    1,                       !- Fraction Replaceable
    General,                 !- End-Use Subcategory
    No;                      !- Return Air Fraction Calculated from Plenum Temperature

Lights,
    East Lights,             !- Name
    East Zone,               !- Zone or ZoneList Name
    Office Lights Schedule,  !- Schedule Name
    Watts/Area,              !- Design Level Calculation Method
    ,                        !- Lighting Level {W}
    10,                      !- Watts per Zone Floor Area {W/m2}
    ,                        !- Watts per Person {W/person}
    0,                       !- Return Air Fraction
    0.37,                    !- Fraction Radiant
    0.18,                    !- Fraction Visible
    1,                       !- Fraction Replaceable
    General,                 !- End-Use Subcategory
    No;                      !- Return Air Fraction Calculated from Plenum Temperature

Lights,
    North Lights,            !- Name
    North Zone,              !- Zone or ZoneList Name
    Office Lights Schedule,  !- Schedule Name
    Watts/Area,              !- Design Level Calculation Method
    ,                        !- Lighting Level {W}
    10,                      !- Watts per Zone Floor Area {W/m2}
    ,                        !- Watts per Person {W/person}
    0,                       !- Return Air Fraction
    0.37,                    !- Fraction Radiant
    0.18,                    !- Fraction Visible
    1,                       !- Fraction Replaceable
    General,                 !- End-Use Subcategory
    No;                      !- Return Air Fraction Calculated from Plenum Temperature


!-   ===========  ALL OBJECTS IN CLASS: ELECTRICEQUIPMENT ===========

ElectricEquipment,
    South Electric,          !- Name
    South Zone,              !- Zone or ZoneList Name
    Office Equipment Schedule,  !- Schedule Name
    Watts/Area,              !- Design Level Calculation Method
```

```
    ,                   !- Design Level {W}
    8,                  !- Watts per Zone Floor Area {W/m2}
    ,                   !- Watts per Person {W/person}
    ,                   !- Fraction Latent
    ,                   !- Fraction Radiant
    ,                   !- Fraction Lost
    General;            !- End-Use Subcategory

ElectricEquipment,
    West Electric,      !- Name
    West Zone,          !- Zone or ZoneList Name
    Office Equipment Schedule,  !- Schedule Name
    Watts/Area,         !- Design Level Calculation Method
    ,                   !- Design Level {W}
    8,                  !- Watts per Zone Floor Area {W/m2}
    ,                   !- Watts per Person {W/person}
    ,                   !- Fraction Latent
    ,                   !- Fraction Radiant
    ,                   !- Fraction Lost
    General;            !- End-Use Subcategory

ElectricEquipment,
    East Electric,      !- Name
    East Zone,          !- Zone or ZoneList Name
    Office Equipment Schedule,  !- Schedule Name
    Watts/Area,         !- Design Level Calculation Method
    ,                   !- Design Level {W}
    8,                  !- Watts per Zone Floor Area {W/m2}
    ,                   !- Watts per Person {W/person}
    ,                   !- Fraction Latent
    ,                   !- Fraction Radiant
    ,                   !- Fraction Lost
    General;            !- End-Use Subcategory

ElectricEquipment,
    North Electric,     !- Name
    North Zone,         !- Zone or ZoneList Name
    Office Equipment Schedule,  !- Schedule Name
    Watts/Area,         !- Design Level Calculation Method
    ,                   !- Design Level {W}
    8,                  !- Watts per Zone Floor Area {W/m2}
    ,                   !- Watts per Person {W/person}
    ,                   !- Fraction Latent
    ,                   !- Fraction Radiant
    ,                   !- Fraction Lost
    General;            !- End-Use Subcategory


!-   ===========  ALL OBJECTS IN CLASS: DAYLIGHTING:CONTROLS ===========

Daylighting:Controls,
    South Zone,         !- Zone Name
    2,                  !- Total Daylighting Reference Points
    10,                 !- X-Coordinate of First Reference Point {m}
    5.000000,           !- Y-Coordinate of First Reference Point {m}
    0.800000,           !- Z-Coordinate of First Reference Point {m}
    20,                 !- X-Coordinate of Second Reference Point {m}
    5,                  !- Y-Coordinate of Second Reference Point {m}
    0.8,                !- Z-Coordinate of Second Reference Point {m}
    0.5,                !- Fraction of Zone Controlled by First Reference Point
    0.5,                !- Fraction of Zone Controlled by Second Reference Point
    500,                !- Illuminance Setpoint at First Reference Point {lux}
    500,                !- Illuminance Setpoint at Second Reference Point {lux}
    1,                  !- Lighting Control Type
    180,                !- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis {deg}
    22,                 !- Maximum Allowable Discomfort Glare Index
    0.3,                !- Minimum Input Power Fraction for Continuous Dimming Control
    0.2,                !- Minimum Light Output Fraction for Continuous Dimming Control
    1,                  !- Number of Stepped Control Steps
    1;                  !- Probability Lighting will be Reset When Needed in Manual Stepped Control
```

```
Daylighting:Controls,
    West Zone,               !- Zone Name
    2,                       !- Total Daylighting Reference Points
    5.000000,                !- X-Coordinate of First Reference Point {m}
    10,                      !- Y-Coordinate of First Reference Point {m}
    0.800000,                !- Z-Coordinate of First Reference Point {m}
    5,                       !- X-Coordinate of Second Reference Point {m}
    20,                      !- Y-Coordinate of Second Reference Point {m}
    0.8,                     !- Z-Coordinate of Second Reference Point {m}
    0.5,                     !- Fraction of Zone Controlled by First Reference Point
    0.5,                     !- Fraction of Zone Controlled by Second Reference Point
    500,                     !- Illuminance Setpoint at First Reference Point {lux}
    500,                     !- Illuminance Setpoint at Second Reference Point {lux}
    1,                       !- Lighting Control Type
    270,                     !- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis {deg}
    22,                      !- Maximum Allowable Discomfort Glare Index
    0.3,                     !- Minimum Input Power Fraction for Continuous Dimming Control
    0.2,                     !- Minimum Light Output Fraction for Continuous Dimming Control
    1,                       !- Number of Stepped Control Steps
    1;                       !- Probability Lighting will be Reset When Needed in Manual Stepped Control

Daylighting:Controls,
    East Zone,               !- Zone Name
    2,                       !- Total Daylighting Reference Points
    25.000000,               !- X-Coordinate of First Reference Point {m}
    10,                      !- Y-Coordinate of First Reference Point {m}
    0.800000,                !- Z-Coordinate of First Reference Point {m}
    25,                      !- X-Coordinate of Second Reference Point {m}
    20,                      !- Y-Coordinate of Second Reference Point {m}
    0.8,                     !- Z-Coordinate of Second Reference Point {m}
    0.5,                     !- Fraction of Zone Controlled by First Reference Point
    0.5,                     !- Fraction of Zone Controlled by Second Reference Point
    500,                     !- Illuminance Setpoint at First Reference Point {lux}
    500,                     !- Illuminance Setpoint at Second Reference Point {lux}
    1,                       !- Lighting Control Type
    90,                      !- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis {deg}
    22,                      !- Maximum Allowable Discomfort Glare Index
    0.3,                     !- Minimum Input Power Fraction for Continuous Dimming Control
    0.2,                     !- Minimum Light Output Fraction for Continuous Dimming Control
    1,                       !- Number of Stepped Control Steps
    1;                       !- Probability Lighting will be Reset When Needed in Manual Stepped Control

Daylighting:Controls,
    North Zone,              !- Zone Name
    2,                       !- Total Daylighting Reference Points
    10,                      !- X-Coordinate of First Reference Point {m}
    25.000000,               !- Y-Coordinate of First Reference Point {m}
    0.800000,                !- Z-Coordinate of First Reference Point {m}
    20,                      !- X-Coordinate of Second Reference Point {m}
    25,                      !- Y-Coordinate of Second Reference Point {m}
    0.8,                     !- Z-Coordinate of Second Reference Point {m}
    0.5,                     !- Fraction of Zone Controlled by First Reference Point
    0.5,                     !- Fraction of Zone Controlled by Second Reference Point
    500,                     !- Illuminance Setpoint at First Reference Point {lux}
    500,                     !- Illuminance Setpoint at Second Reference Point {lux}
    1,                       !- Lighting Control Type
    0,                       !- Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis {deg}
    22,                      !- Maximum Allowable Discomfort Glare Index
    0.3,                     !- Minimum Input Power Fraction for Continuous Dimming Control
    0.2,                     !- Minimum Light Output Fraction for Continuous Dimming Control
    1,                       !- Number of Stepped Control Steps
    1;                       !- Probability Lighting will be Reset When Needed in Manual Stepped Control


!-   ===========  ALL OBJECTS IN CLASS: ZONEINFILTRATION:DESIGNFLOWRATE ===========

ZoneInfiltration:DesignFlowRate,
    South Infiltration,      !- Name
    South Zone,              !- Zone or ZoneList Name
    Infiltration Schedule,   !- Schedule Name
    AirChanges/Hour,         !- Design Flow Rate Calculation Method
```

```
    ,                    !- Design Flow Rate {m3/s}
    ,                    !- Flow per Zone Floor Area {m3/s-m2}
    ,                    !- Flow per Exterior Surface Area {m3/s-m2}
    0.1,                 !- Air Changes per Hour
    1,                   !- Constant Term Coefficient
    ,                    !- Temperature Term Coefficient
    ,                    !- Velocity Term Coefficient
    ;                    !- Velocity Squared Term Coefficient

ZoneInfiltration:DesignFlowRate,
    West Infiltration,       !- Name
    West Zone,               !- Zone or ZoneList Name
    Infiltration Schedule,   !- Schedule Name
    AirChanges/Hour,         !- Design Flow Rate Calculation Method
    ,                    !- Design Flow Rate {m3/s}
    ,                    !- Flow per Zone Floor Area {m3/s-m2}
    ,                    !- Flow per Exterior Surface Area {m3/s-m2}
    0.1,                 !- Air Changes per Hour
    1,                   !- Constant Term Coefficient
    ,                    !- Temperature Term Coefficient
    ,                    !- Velocity Term Coefficient
    ;                    !- Velocity Squared Term Coefficient

ZoneInfiltration:DesignFlowRate,
    East Infiltration,       !- Name
    East Zone,               !- Zone or ZoneList Name
    Infiltration Schedule,   !- Schedule Name
    AirChanges/Hour,         !- Design Flow Rate Calculation Method
    ,                    !- Design Flow Rate {m3/s}
    ,                    !- Flow per Zone Floor Area {m3/s-m2}
    ,                    !- Flow per Exterior Surface Area {m3/s-m2}
    0.1,                 !- Air Changes per Hour
    1,                   !- Constant Term Coefficient
    ,                    !- Temperature Term Coefficient
    ,                    !- Velocity Term Coefficient
    ;                    !- Velocity Squared Term Coefficient

ZoneInfiltration:DesignFlowRate,
    North Infiltration,      !- Name
    North Zone,              !- Zone or ZoneList Name
    Infiltration Schedule,   !- Schedule Name
    AirChanges/Hour,         !- Design Flow Rate Calculation Method
    ,                    !- Design Flow Rate {m3/s}
    ,                    !- Flow per Zone Floor Area {m3/s-m2}
    ,                    !- Flow per Exterior Surface Area {m3/s-m2}
    0.1,                 !- Air Changes per Hour
    1,                   !- Constant Term Coefficient
    ,                    !- Temperature Term Coefficient
    ,                    !- Velocity Term Coefficient
    ;                    !- Velocity Squared Term Coefficient


!-   ===========  ALL OBJECTS IN CLASS: ZONEVENTILATION:DESIGNFLOWRATE ===========

ZoneVentilation:DesignFlowRate,
    South Ventilation,       !- Name
    South Zone,              !- Zone or ZoneList Name
    Hours of Operation Schedule,  !- Schedule Name
    Flow/Area,               !- Design Flow Rate Calculation Method
    ,                    !- Design Flow Rate {m3/s}
    0.0008,              !- Flow Rate per Zone Floor Area {m3/s-m2}
    ,                    !- Flow Rate per Person {m3/s-person}
    ,                    !- Air Changes per Hour
    Natural,             !- Ventilation Type
    ,                    !- Fan Pressure Rise {Pa}
    1,                   !- Fan Total Efficiency
    1,                   !- Constant Term Coefficient
    ,                    !- Temperature Term Coefficient
    ,                    !- Velocity Term Coefficient
    ,                    !- Velocity Squared Term Coefficient
    -100,                !- Minimum Indoor Temperature {C}
```

```
    ,                        !- Minimum Indoor Temperature Schedule Name
    100,                     !- Maximum Indoor Temperature {C}
    ,                        !- Maximum Indoor Temperature Schedule Name
    -100,                    !- Delta Temperature {deltaC}
    ,                        !- Delta Temperature Schedule Name
    -100,                    !- Minimum Outdoor Temperature {C}
    ,                        !- Minimum Outdoor Temperature Schedule Name
    100,                     !- Maximum Outdoor Temperature {C}
    ,                        !- Maximum Outdoor Temperature Schedule Name
    40;                      !- Maximum Wind Speed {m/s}

ZoneVentilation:DesignFlowRate,
    West Ventilation,        !- Name
    West Zone,               !- Zone or ZoneList Name
    Hours of Operation Schedule,  !- Schedule Name
    Flow/Area,               !- Design Flow Rate Calculation Method
    ,                        !- Design Flow Rate {m3/s}
    0.0008,                  !- Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Flow Rate per Person {m3/s-person}
    ,                        !- Air Changes per Hour
    Natural,                 !- Ventilation Type
    ,                        !- Fan Pressure Rise {Pa}
    1,                       !- Fan Total Efficiency
    1,                       !- Constant Term Coefficient
    ,                        !- Temperature Term Coefficient
    ,                        !- Velocity Term Coefficient
    ,                        !- Velocity Squared Term Coefficient
    -100,                    !- Minimum Indoor Temperature {C}
    ,                        !- Minimum Indoor Temperature Schedule Name
    100,                     !- Maximum Indoor Temperature {C}
    ,                        !- Maximum Indoor Temperature Schedule Name
    -100,                    !- Delta Temperature {deltaC}
    ,                        !- Delta Temperature Schedule Name
    -100,                    !- Minimum Outdoor Temperature {C}
    ,                        !- Minimum Outdoor Temperature Schedule Name
    100,                     !- Maximum Outdoor Temperature {C}
    ,                        !- Maximum Outdoor Temperature Schedule Name
    40;                      !- Maximum Wind Speed {m/s}

ZoneVentilation:DesignFlowRate,
    East Ventilation,        !- Name
    East Zone,               !- Zone or ZoneList Name
    Hours of Operation Schedule,  !- Schedule Name
    Flow/Area,               !- Design Flow Rate Calculation Method
    ,                        !- Design Flow Rate {m3/s}
    0.0008,                  !- Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Flow Rate per Person {m3/s-person}
    ,                        !- Air Changes per Hour
    Natural,                 !- Ventilation Type
    ,                        !- Fan Pressure Rise {Pa}
    1,                       !- Fan Total Efficiency
    1,                       !- Constant Term Coefficient
    ,                        !- Temperature Term Coefficient
    ,                        !- Velocity Term Coefficient
    ,                        !- Velocity Squared Term Coefficient
    -100,                    !- Minimum Indoor Temperature {C}
    ,                        !- Minimum Indoor Temperature Schedule Name
    100,                     !- Maximum Indoor Temperature {C}
    ,                        !- Maximum Indoor Temperature Schedule Name
    -100,                    !- Delta Temperature {deltaC}
    ,                        !- Delta Temperature Schedule Name
    -100,                    !- Minimum Outdoor Temperature {C}
    ,                        !- Minimum Outdoor Temperature Schedule Name
    100,                     !- Maximum Outdoor Temperature {C}
    ,                        !- Maximum Outdoor Temperature Schedule Name
    40;                      !- Maximum Wind Speed {m/s}

ZoneVentilation:DesignFlowRate,
    North Ventilation,       !- Name
    North Zone,              !- Zone or ZoneList Name
    Hours of Operation Schedule,  !- Schedule Name
```

```
    Flow/Area,               !- Design Flow Rate Calculation Method
    ,                        !- Design Flow Rate {m3/s}
    0.0008,                  !- Flow Rate per Zone Floor Area {m3/s-m2}
    ,                        !- Flow Rate per Person {m3/s-person}
    ,                        !- Air Changes per Hour
    Natural,                 !- Ventilation Type
    ,                        !- Fan Pressure Rise {Pa}
    1,                       !- Fan Total Efficiency
    1,                       !- Constant Term Coefficient
    ,                        !- Temperature Term Coefficient
    ,                        !- Velocity Term Coefficient
    ,                        !- Velocity Squared Term Coefficient
    -100,                    !- Minimum Indoor Temperature {C}
    ,                        !- Minimum Indoor Temperature Schedule Name
    100,                     !- Maximum Indoor Temperature {C}
    ,                        !- Maximum Indoor Temperature Schedule Name
    -100,                    !- Delta Temperature {deltaC}
    ,                        !- Delta Temperature Schedule Name
    -100,                    !- Minimum Outdoor Temperature {C}
    ,                        !- Minimum Outdoor Temperature Schedule Name
    100,                     !- Maximum Outdoor Temperature {C}
    ,                        !- Maximum Outdoor Temperature Schedule Name
    40;                      !- Maximum Wind Speed {m/s}


!-   ===========  ALL OBJECTS IN CLASS: ZONECONTROL:THERMOSTAT ===========

ZoneControl:Thermostat,
    South Zone Thermostat,   !- Name
    South Zone,              !- Zone or ZoneList Name
    HVACTemplate-Always 2,   !- Control Type Schedule Name
    ThermostatSetpoint:SingleCooling,  !- Control 1 Object Type
    Constant Setpoint Thermostat Single Cooling;  !- Control 1 Name

ZoneControl:Thermostat,
    West Zone Thermostat,    !- Name
    West Zone,               !- Zone or ZoneList Name
    HVACTemplate-Always 2,   !- Control Type Schedule Name
    ThermostatSetpoint:SingleCooling,  !- Control 1 Object Type
    Constant Setpoint Thermostat Single Cooling;  !- Control 1 Name

ZoneControl:Thermostat,
    East Zone Thermostat,    !- Name
    East Zone,               !- Zone or ZoneList Name
    HVACTemplate-Always 2,   !- Control Type Schedule Name
    ThermostatSetpoint:SingleCooling,  !- Control 1 Object Type
    Constant Setpoint Thermostat Single Cooling;  !- Control 1 Name

ZoneControl:Thermostat,
    North Zone Thermostat,   !- Name
    North Zone,              !- Zone or ZoneList Name
    HVACTemplate-Always 2,   !- Control Type Schedule Name
    ThermostatSetpoint:SingleCooling,  !- Control 1 Object Type
    Constant Setpoint Thermostat Single Cooling;  !- Control 1 Name


!-   ===========  ALL OBJECTS IN CLASS: THERMOSTATSETPOINT:SINGLECOOLING ===========

ThermostatSetpoint:SingleCooling,
    Constant Setpoint Thermostat Single Cooling,  !- Name
    HVACTemplate-Always 22;  !- Setpoint Temperature Schedule Name


!-   ===========  ALL OBJECTS IN CLASS: ZONEHVAC:IDEALLOADSAIRSYSTEM ===========

ZoneHVAC:IdealLoadsAirSystem,
    South ZoneZoneHVAC:IdealLoadsAirSystem,  !- Name
    Hours of Operation Schedule,  !- Availability Schedule Name
    South Zone Supply Inlet, !- Zone Supply Air Node Name
    ,                        !- Zone Exhaust Air Node Name
    50,                      !- Maximum Heating Supply Air Temperature {C}
```

```
    13,                      !- Minimum Cooling Supply Air Temperature {C}
    0.008,                   !- Maximum Heating Supply Air Humidity Ratio {kg-H2O/kg-air}
    0.009,                   !- Minimum Cooling Supply Air Humidity Ratio {kg-H2O/kg-air}
    NoLimit,                 !- Heating Limit
    ,                        !- Maximum Heating Air Flow Rate {m3/s}
    ,                        !- Maximum Sensible Heating Capacity {W}
    NoLimit,                 !- Cooling Limit
    ,                        !- Maximum Cooling Air Flow Rate {m3/s}
    ,                        !- Maximum Total Cooling Capacity {W}
    ,                        !- Heating Availability Schedule Name
    ,                        !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                     !- Cooling Sensible Heat Ratio {dimensionless}
    ConstantSupplyHumidityRatio,  !- Humidification Control Type
    ,                        !- Design Specification Outdoor Air Object Name
    ,                        !- Outdoor Air Inlet Node Name
    None,                    !- Demand Controlled Ventilation Type
    NoEconomizer,            !- Outdoor Air Economizer Type
    None,                    !- Heat Recovery Type
    0.7,                     !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                    !- Latent Heat Recovery Effectiveness {dimensionless}

  ZoneHVAC:IdealLoadsAirSystem,
    West ZoneZoneHVAC:IdealLoadsAirSystem,  !- Name
    Hours of Operation Schedule,  !- Availability Schedule Name
    West Zone Supply Inlet,  !- Zone Supply Air Node Name
    ,                        !- Zone Exhaust Air Node Name
    50,                      !- Maximum Heating Supply Air Temperature {C}
    13,                      !- Minimum Cooling Supply Air Temperature {C}
    0.008,                   !- Maximum Heating Supply Air Humidity Ratio {kg-H2O/kg-air}
    0.009,                   !- Minimum Cooling Supply Air Humidity Ratio {kg-H2O/kg-air}
    NoLimit,                 !- Heating Limit
    ,                        !- Maximum Heating Air Flow Rate {m3/s}
    ,                        !- Maximum Sensible Heating Capacity {W}
    NoLimit,                 !- Cooling Limit
    ,                        !- Maximum Cooling Air Flow Rate {m3/s}
    ,                        !- Maximum Total Cooling Capacity {W}
    ,                        !- Heating Availability Schedule Name
    ,                        !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                     !- Cooling Sensible Heat Ratio {dimensionless}
    ConstantSupplyHumidityRatio,  !- Humidification Control Type
    ,                        !- Design Specification Outdoor Air Object Name
    ,                        !- Outdoor Air Inlet Node Name
    None,                    !- Demand Controlled Ventilation Type
    NoEconomizer,            !- Outdoor Air Economizer Type
    None,                    !- Heat Recovery Type
    0.7,                     !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                    !- Latent Heat Recovery Effectiveness {dimensionless}

  ZoneHVAC:IdealLoadsAirSystem,
    East ZoneZoneHVAC:IdealLoadsAirSystem,  !- Name
    Hours of Operation Schedule,  !- Availability Schedule Name
    East Zone Supply Inlet,  !- Zone Supply Air Node Name
    ,                        !- Zone Exhaust Air Node Name
    50,                      !- Maximum Heating Supply Air Temperature {C}
    13,                      !- Minimum Cooling Supply Air Temperature {C}
    0.008,                   !- Maximum Heating Supply Air Humidity Ratio {kg-H2O/kg-air}
    0.009,                   !- Minimum Cooling Supply Air Humidity Ratio {kg-H2O/kg-air}
    NoLimit,                 !- Heating Limit
    ,                        !- Maximum Heating Air Flow Rate {m3/s}
    ,                        !- Maximum Sensible Heating Capacity {W}
    NoLimit,                 !- Cooling Limit
    ,                        !- Maximum Cooling Air Flow Rate {m3/s}
    ,                        !- Maximum Total Cooling Capacity {W}
    ,                        !- Heating Availability Schedule Name
    ,                        !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                     !- Cooling Sensible Heat Ratio {dimensionless}
    ConstantSupplyHumidityRatio,  !- Humidification Control Type
    ,                        !- Design Specification Outdoor Air Object Name
```

```
    ,                       !- Outdoor Air Inlet Node Name
    None,                   !- Demand Controlled Ventilation Type
    NoEconomizer,           !- Outdoor Air Economizer Type
    None,                   !- Heat Recovery Type
    0.7,                    !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                   !- Latent Heat Recovery Effectiveness {dimensionless}

  ZoneHVAC:IdealLoadsAirSystem,
    North ZoneZoneHVAC:IdealLoadsAirSystem,  !- Name
    Hours of Operation Schedule,  !- Availability Schedule Name
    North Zone Supply Inlet, !- Zone Supply Air Node Name
    ,                       !- Zone Exhaust Air Node Name
    50,                     !- Maximum Heating Supply Air Temperature {C}
    13,                     !- Minimum Cooling Supply Air Temperature {C}
    0.008,                  !- Maximum Heating Supply Air Humidity Ratio {kg-H2O/kg-air}
    0.009,                  !- Minimum Cooling Supply Air Humidity Ratio {kg-H2O/kg-air}
    NoLimit,                !- Heating Limit
    ,                       !- Maximum Heating Air Flow Rate {m3/s}
    ,                       !- Maximum Sensible Heating Capacity {W}
    NoLimit,                !- Cooling Limit
    ,                       !- Maximum Cooling Air Flow Rate {m3/s}
    ,                       !- Maximum Total Cooling Capacity {W}
    ,                       !- Heating Availability Schedule Name
    ,                       !- Cooling Availability Schedule Name
    ConstantSensibleHeatRatio,  !- Dehumidification Control Type
    0.7,                    !- Cooling Sensible Heat Ratio {dimensionless}
    ConstantSupplyHumidityRatio,  !- Humidification Control Type
    ,                       !- Design Specification Outdoor Air Object Name
    ,                       !- Outdoor Air Inlet Node Name
    None,                   !- Demand Controlled Ventilation Type
    NoEconomizer,           !- Outdoor Air Economizer Type
    None,                   !- Heat Recovery Type
    0.7,                    !- Sensible Heat Recovery Effectiveness {dimensionless}
    0.65;                   !- Latent Heat Recovery Effectiveness {dimensionless}


!-   ===========  ALL OBJECTS IN CLASS: ZONEHVAC:EQUIPMENTLIST ===========

  ZoneHVAC:EquipmentList,
    South Zone Equipment,    !- Name
    ZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Object Type
    South ZoneZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Name
    1,                      !- Zone Equipment 1 Cooling Sequence
    1;                      !- Zone Equipment 1 Heating or No-Load Sequence

  ZoneHVAC:EquipmentList,
    West Zone Equipment,     !- Name
    ZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Object Type
    West ZoneZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Name
    1,                      !- Zone Equipment 1 Cooling Sequence
    1;                      !- Zone Equipment 1 Heating or No-Load Sequence

  ZoneHVAC:EquipmentList,
    East Zone Equipment,     !- Name
    ZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Object Type
    East ZoneZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Name
    1,                      !- Zone Equipment 1 Cooling Sequence
    1;                      !- Zone Equipment 1 Heating or No-Load Sequence

  ZoneHVAC:EquipmentList,
    North Zone Equipment,    !- Name
    ZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Object Type
    North ZoneZoneHVAC:IdealLoadsAirSystem,  !- Zone Equipment 1 Name
    1,                      !- Zone Equipment 1 Cooling Sequence
    1;                      !- Zone Equipment 1 Heating or No-Load Sequence


!-   ===========  ALL OBJECTS IN CLASS: ZONEHVAC:EQUIPMENTCONNECTIONS ===========

  ZoneHVAC:EquipmentConnections,
    South Zone,             !- Zone Name
```

```
    South Zone Equipment,    !- Zone Conditioning Equipment List Name
    South Zone Supply Inlet, !- Zone Air Inlet Node or NodeList Name
    ,                        !- Zone Air Exhaust Node or NodeList Name
    South Zone Zone Air Node,!- Zone Air Node Name
    South Zone Return Outlet;!- Zone Return Air Node Name

ZoneHVAC:EquipmentConnections,
    West Zone,               !- Zone Name
    West Zone Equipment,     !- Zone Conditioning Equipment List Name
    West Zone Supply Inlet,  !- Zone Air Inlet Node or NodeList Name
    ,                        !- Zone Air Exhaust Node or NodeList Name
    West Zone Zone Air Node, !- Zone Air Node Name
    West Zone Return Outlet; !- Zone Return Air Node Name

ZoneHVAC:EquipmentConnections,
    East Zone,               !- Zone Name
    East Zone Equipment,     !- Zone Conditioning Equipment List Name
    East Zone Supply Inlet,  !- Zone Air Inlet Node or NodeList Name
    ,                        !- Zone Air Exhaust Node or NodeList Name
    East Zone Zone Air Node, !- Zone Air Node Name
    East Zone Return Outlet; !- Zone Return Air Node Name

ZoneHVAC:EquipmentConnections,
    North Zone,              !- Zone Name
    North Zone Equipment,    !- Zone Conditioning Equipment List Name
    North Zone Supply Inlet, !- Zone Air Inlet Node or NodeList Name
    ,                        !- Zone Air Exhaust Node or NodeList Name
    North Zone Zone Air Node,!- Zone Air Node Name
    North Zone Return Outlet;!- Zone Return Air Node Name


!-   ===========  ALL OBJECTS IN CLASS: GENERATOR:PHOTOVOLTAIC ===========

Generator:Photovoltaic,
    South Photovoltaic Generator ,  !- Name
    South Window,            !- Surface Name
    PhotovoltaicPerformance:Simple,  !- Photovoltaic Performance Object Type
    Simple PV - Hanwa,       !- Module Performance Name
    IntegratedSurfaceOutsideFace,  !- Heat Transfer Integration Mode
    1,                       !- Number of Modules in Parallel {dimensionless}
    1;                       !- Number of Modules in Series {dimensionless}

Generator:Photovoltaic,
    West Photovoltaic Generator,  !- Name
    West Window,             !- Surface Name
    PhotovoltaicPerformance:Simple,  !- Photovoltaic Performance Object Type
    Simple PV - Hanwa,       !- Module Performance Name
    IntegratedSurfaceOutsideFace,  !- Heat Transfer Integration Mode
    1,                       !- Number of Modules in Parallel {dimensionless}
    1;                       !- Number of Modules in Series {dimensionless}

Generator:Photovoltaic,
    North Photovoltaic Generator,  !- Name
    North Window,            !- Surface Name
    PhotovoltaicPerformance:Simple,  !- Photovoltaic Performance Object Type
    Simple PV - Hanwa,       !- Module Performance Name
    IntegratedSurfaceOutsideFace,  !- Heat Transfer Integration Mode
    1,                       !- Number of Modules in Parallel {dimensionless}
    1;                       !- Number of Modules in Series {dimensionless}

Generator:Photovoltaic,
    East Photovoltaic Generator,  !- Name
    East Window,             !- Surface Name
    PhotovoltaicPerformance:Simple,  !- Photovoltaic Performance Object Type
    Simple PV - Hanwa,       !- Module Performance Name
    IntegratedSurfaceOutsideFace,  !- Heat Transfer Integration Mode
    1,                       !- Number of Modules in Parallel {dimensionless}
    1;                       !- Number of Modules in Series {dimensionless}


!-   ==========  ALL OBJECTS IN CLASS: PHOTOVOLTAICPERFORMANCE:SIMPLE ==========
```

```
PhotovoltaicPerformance:Simple,
    Simple PV - Hanwa,       !- Name
    1,                       !- Fraction of Surface Area with Active Solar Cells {dimensionless}
    Fixed,                   !- Conversion Efficiency Input Mode
    0.0802;                  !- Value for Cell Efficiency if Fixed

PhotovoltaicPerformance:Simple,
    Simple PV - Auria Micromorph,  !- Name
    1,                       !- Fraction of Surface Area with Active Solar Cells {dimensionless}
    Fixed;                   !- Conversion Efficiency Input Mode


!-   ===========  ALL OBJECTS IN CLASS: ELECTRICLOADCENTER:GENERATORS ===========

ElectricLoadCenter:Generators,
    PV List,                 !- Name
    South Photovoltaic Generator ,  !- Generator 1 Name
    Generator:Photovoltaic,  !- Generator 1 Object Type
    20000,                   !- Generator 1 Rated Electric Power Output {W}
    Always On,               !- Generator 1 Availability Schedule Name
    ,                        !- Generator 1 Rated Thermal to Electrical Power Ratio
    West Photovoltaic Generator,  !- Generator 2 Name
    Generator:Photovoltaic,  !- Generator 2 Object Type
    20000,                   !- Generator 2 Rated Electric Power Output {W}
    Always On,               !- Generator 2 Availability Schedule Name
    ,                        !- Generator 2 Rated Thermal to Electrical Power Ratio
    North Photovoltaic Generator,  !- Generator 3 Name
    Generator:Photovoltaic,  !- Generator 3 Object Type
    20000,                   !- Generator 3 Rated Electric Power Output {W}
    Always On,               !- Generator 3 Availability Schedule Name
    ,                        !- Generator 3 Rated Thermal to Electrical Power Ratio
    East Photovoltaic Generator,  !- Generator 4 Name
    Generator:Photovoltaic,  !- Generator 4 Object Type
    20000,                   !- Generator 4 Rated Electric Power Output {W}
    Always On;               !- Generator 4 Availability Schedule Name


!-   ===========  ALL OBJECTS IN CLASS: ELECTRICLOADCENTER:INVERTER:SIMPLE ===========

ElectricLoadCenter:Inverter:Simple,
    Simple Ideal Inverter,   !- Name
    Always On,               !- Availability Schedule Name
    ,                        !- Zone Name
    0,                       !- Radiative Fraction
    0.85;                    !- Inverter Efficiency


!-   ===========  ALL OBJECTS IN CLASS: ELECTRICLOADCENTER:DISTRIBUTION ===========

ElectricLoadCenter:Distribution,
    Simple Electric Load,    !- Name
    PV List,                 !- Generator List Name
    Baseload,                !- Generator Operation Scheme Type
    0,                       !- Demand Limit Scheme Purchased Electric Demand Limit {W}
    ,                        !- Track Schedule Name Scheme Schedule Name
    ,                        !- Track Meter Scheme Meter Name
    DirectCurrentWithInverter,  !- Electrical Buss Type
    Simple Ideal Inverter;   !- Inverter Object Name


!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:VARIABLEDICTIONARY ===========

!
!
!
! BuildingSurface:Detailed,
!     14F0A8,                  !- Name
!     Floor,                   !- Surface Type
!     Exterior Floor,          !- Construction Name
!     South Zone,              !- Zone Name
```

```
!    Adiabatic,              !- Outside Boundary Condition
!    ,                       !- Outside Boundary Condition Object
!    NoSun,                  !- Sun Exposure
!    NoWind,                 !- Wind Exposure
!    ,                       !- View Factor to Ground
!    4,                      !- Number of Vertices
!    20.000000000000,        !- Vertex 1 X-coordinate {m}
!    10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    0.000000000000,         !- Vertex 1 Z-coordinate {m}
!    30.000000000000,        !- Vertex 2 X-coordinate {m}
!    0.000000000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,         !- Vertex 2 Z-coordinate {m}
!    0.000000000000,         !- Vertex 3 X-coordinate {m}
!    0.000000000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,         !- Vertex 3 Z-coordinate {m}
!    10.000000000000,        !- Vertex 4 X-coordinate {m}
!    10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    0.000000000000;         !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    EC6389,                 !- Name
!    Wall,                   !- Surface Type
!    Exterior Wall,          !- Construction Name
!    South Zone,             !- Zone Name
!    Adiabatic,              !- Outside Boundary Condition
!    ,                       !- Outside Boundary Condition Object
!    SunExposed,             !- Sun Exposure
!    WindExposed,            !- Wind Exposure
!    ,                       !- View Factor to Ground
!    4,                      !- Number of Vertices
!    30.000000000000,        !- Vertex 1 X-coordinate {m}
!    0.000000000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,         !- Vertex 1 Z-coordinate {m}
!    30.000000000000,        !- Vertex 2 X-coordinate {m}
!    0.000000000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,         !- Vertex 2 Z-coordinate {m}
!    20.000000000000,        !- Vertex 3 X-coordinate {m}
!    10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,         !- Vertex 3 Z-coordinate {m}
!    20.000000000000,        !- Vertex 4 X-coordinate {m}
!    10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;         !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    71DD34,                 !- Name
!    Wall,                   !- Surface Type
!    Exterior Wall,          !- Construction Name
!    South Zone,             !- Zone Name
!    Adiabatic,              !- Outside Boundary Condition
!    ,                       !- Outside Boundary Condition Object
!    SunExposed,             !- Sun Exposure
!    WindExposed,            !- Wind Exposure
!    ,                       !- View Factor to Ground
!    4,                      !- Number of Vertices
!    20.000000000000,        !- Vertex 1 X-coordinate {m}
!    10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,         !- Vertex 1 Z-coordinate {m}
!    20.000000000000,        !- Vertex 2 X-coordinate {m}
!    10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,         !- Vertex 2 Z-coordinate {m}
!    10.000000000000,        !- Vertex 3 X-coordinate {m}
!    10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,         !- Vertex 3 Z-coordinate {m}
!    10.000000000000,        !- Vertex 4 X-coordinate {m}
!    10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;         !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    E81186,                 !- Name
!    Roof,                   !- Surface Type
!    Exterior Roof,          !- Construction Name
```

```
!    South Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    30.000000000000,         !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    3.000000000000,          !- Vertex 2 Z-coordinate {m}
!    20.000000000000,         !- Vertex 3 X-coordinate {m}
!    10.000000000000,         !- Vertex 3 Y-coordinate {m}
!    3.000000000000,          !- Vertex 3 Z-coordinate {m}
!    10.000000000000,         !- Vertex 4 X-coordinate {m}
!    10.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    62203C,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    South Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    10.000000000000,         !- Vertex 1 X-coordinate {m}
!    10.000000000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    10.000000000000,         !- Vertex 2 X-coordinate {m}
!    10.000000000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    0.000000000000,          !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    South Wall,              !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    South Zone,              !- Zone Name
!    Outdoors,                !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    30.000000000000,         !- Vertex 3 X-coordinate {m}
!    0.000000000000,          !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    30.000000000000,         !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    FFE892,                  !- Name
!    Floor,                   !- Surface Type
```

```
!    Exterior Floor,          !- Construction Name
!    West Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    NoSun,                   !- Sun Exposure
!    NoWind,                  !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    10.000000000000,         !- Vertex 1 X-coordinate {m}
!    10.000000000000,         !- Vertex 1 Y-coordinate {m}
!    0.000000000000,          !- Vertex 1 Z-coordinate {m}
!    10.000000000000,         !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    20.000000000000,         !- Vertex 4 Y-coordinate {m}
!    0.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    DA9951,                  !- Name
!    Roof,                    !- Surface Type
!    Exterior Roof,           !- Construction Name
!    West Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    20.000000000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    3.000000000000,          !- Vertex 2 Z-coordinate {m}
!    10.000000000000,         !- Vertex 3 X-coordinate {m}
!    0.000000000000,          !- Vertex 3 Y-coordinate {m}
!    3.000000000000,          !- Vertex 3 Z-coordinate {m}
!    10.000000000000,         !- Vertex 4 X-coordinate {m}
!    10.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    West Wall,               !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    West Zone,               !- Zone Name
!    Outdoors,                !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    20.000000000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    20.000000000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    668E3E,                  !- Name
```

```
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    West Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    10.000000000000,         !- Vertex 1 X-coordinate {m}
!    10.000000000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    10.000000000000,         !- Vertex 2 X-coordinate {m}
!    10.000000000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    20.000000000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    20.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    762918,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    West Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    10.000000000000,         !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    10.000000000000,         !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    10.000000000000,         !- Vertex 3 X-coordinate {m}
!    10.000000000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    10.000000000000,         !- Vertex 4 X-coordinate {m}
!    10.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    7151B6,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    West Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    10.000000000000,         !- Vertex 3 X-coordinate {m}
!    0.000000000000,          !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    10.000000000000,         !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
```

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!    CEA751,                 !- Name
!    Floor,                  !- Surface Type
!    Exterior Floor,         !- Construction Name
!    East Zone,              !- Zone Name
!    Adiabatic,              !- Outside Boundary Condition
!    ,                       !- Outside Boundary Condition Object
!    NoSun,                  !- Sun Exposure
!    NoWind,                 !- Wind Exposure
!    ,                       !- View Factor to Ground
!    4,                      !- Number of Vertices
!    0.000000000000,         !- Vertex 1 X-coordinate {m}
!    20.000000000000,        !- Vertex 1 Y-coordinate {m}
!    0.000000000000,         !- Vertex 1 Z-coordinate {m}
!    0.000000000000,         !- Vertex 2 X-coordinate {m}
!    -10.000000000000,       !- Vertex 2 Y-coordinate {m}
!    0.000000000000,         !- Vertex 2 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 3 X-coordinate {m}
!    0.000000000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,         !- Vertex 3 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 4 X-coordinate {m}
!    10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    0.000000000000;         !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    DBDADA,                 !- Name
!    Wall,                   !- Surface Type
!    Exterior Wall,          !- Construction Name
!    East Zone,              !- Zone Name
!    Adiabatic,              !- Outside Boundary Condition
!    ,                       !- Outside Boundary Condition Object
!    SunExposed,             !- Sun Exposure
!    WindExposed,            !- Wind Exposure
!    ,                       !- View Factor to Ground
!    4,                      !- Number of Vertices
!    0.000000000000,         !- Vertex 1 X-coordinate {m}
!    20.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,         !- Vertex 1 Z-coordinate {m}
!    0.000000000000,         !- Vertex 2 X-coordinate {m}
!    20.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,         !- Vertex 2 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 3 X-coordinate {m}
!    10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,         !- Vertex 3 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 4 X-coordinate {m}
!    10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;         !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    48142A,                 !- Name
!    Wall,                   !- Surface Type
!    Exterior Wall,          !- Construction Name
!    East Zone,              !- Zone Name
!    Adiabatic,              !- Outside Boundary Condition
!    ,                       !- Outside Boundary Condition Object
!    SunExposed,             !- Sun Exposure
!    WindExposed,            !- Wind Exposure
!    ,                       !- View Factor to Ground
!    4,                      !- Number of Vertices
!    -10.000000000000,       !- Vertex 1 X-coordinate {m}
!    10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,         !- Vertex 1 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 2 X-coordinate {m}
!    10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,         !- Vertex 2 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 3 X-coordinate {m}
!    0.000000000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,         !- Vertex 3 Z-coordinate {m}
!    -10.000000000000,       !- Vertex 4 X-coordinate {m}
!    0.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;         !- Vertex 4 Z-coordinate {m}
!
```

```
! BuildingSurface:Detailed,
!    8B65C5,                  !- Name
!    Roof,                    !- Surface Type
!    Exterior Roof,           !- Construction Name
!    East Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -10.000000000000,        !- Vertex 1 X-coordinate {m}
!    10.000000000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    -10.000000000000,        !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    3.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    3.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    20.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    F508AE,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    East Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -10.000000000000,        !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    -10.000000000000,        !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    East Wall,               !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    East Zone,               !- Zone Name
!    Outdoors,                !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    20.000000000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    20.000000000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
```

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!
! BuildingSurface:Detailed,
!    DCDB4E,                  !- Name
!    Floor,                   !- Surface Type
!    Exterior Floor,          !- Construction Name
!    Core Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    NoSun,                   !- Sun Exposure
!    NoWind,                  !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    3.996592000000,          !- Vertex 1 X-coordinate {m}
!    4.015921000000,          !- Vertex 1 Y-coordinate {m}
!    0.000000000000,          !- Vertex 1 Z-coordinate {m}
!    3.996592000000,          !- Vertex 2 X-coordinate {m}
!    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 3 X-coordinate {m}
!    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 4 X-coordinate {m}
!    4.015921000000,          !- Vertex 4 Y-coordinate {m}
!    0.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    FF003C,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    Core Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -6.003408000000,         !- Vertex 1 X-coordinate {m}
!    -5.984079000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 2 X-coordinate {m}
!    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    3.996592000000,          !- Vertex 3 X-coordinate {m}
!    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    3.996592000000,          !- Vertex 4 X-coordinate {m}
!    -5.984079000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    EA7F7B,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    Core Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    3.996592000000,          !- Vertex 1 X-coordinate {m}
!    -5.984079000000,         !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    3.996592000000,          !- Vertex 2 X-coordinate {m}
!    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    3.996592000000,          !- Vertex 3 X-coordinate {m}
!    4.015921000000,          !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    3.996592000000,          !- Vertex 4 X-coordinate {m}
!    4.015921000000,          !- Vertex 4 Y-coordinate {m}
```

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!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    98104C,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    Core Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -6.003408000000,         !- Vertex 1 X-coordinate {m}
!    4.015921000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 2 X-coordinate {m}
!    4.015921000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 3 X-coordinate {m}
!    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 4 X-coordinate {m}
!    -5.984079000000,         !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    Core Roof,               !- Name
!    Roof,                    !- Surface Type
!    Exterior Roof,           !- Construction Name
!    Core Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    0.0,                     !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -6.003408000000,         !- Vertex 1 X-coordinate {m}
!    4.015921000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 2 X-coordinate {m}
!    -5.984079000000,         !- Vertex 2 Y-coordinate {m}
!    3.000000000000,          !- Vertex 2 Z-coordinate {m}
!    3.996592000000,          !- Vertex 3 X-coordinate {m}
!    -5.984079000000,         !- Vertex 3 Y-coordinate {m}
!    3.000000000000,          !- Vertex 3 Z-coordinate {m}
!    3.996592000000,          !- Vertex 4 X-coordinate {m}
!    4.015921000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    7BBFE0,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    Core Zone,               !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    3.996592000000,          !- Vertex 1 X-coordinate {m}
!    4.015921000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    3.996592000000,          !- Vertex 2 X-coordinate {m}
!    4.015921000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 3 X-coordinate {m}
!    4.015921000000,          !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    -6.003408000000,         !- Vertex 4 X-coordinate {m}
```

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!    4.015921000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    795B5E,                  !- Name
!    Floor,                   !- Surface Type
!    Exterior Floor,          !- Construction Name
!    North Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    NoSun,                   !- Sun Exposure
!    NoWind,                  !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    20.000000000000,         !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    0.000000000000,          !- Vertex 1 Z-coordinate {m}
!    10.000000000000,         !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    -10.000000000000,        !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    0.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    North Wall,              !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    North Zone,              !- Zone Name
!    Outdoors,                !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    0.0,                     !- View Factor to Ground
!    4,                       !- Number of Vertices
!    20.000000000000,         !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    20.000000000000,         !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    -10.000000000000,        !- Vertex 3 X-coordinate {m}
!    0.000000000000,          !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    -10.000000000000,        !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    996064,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    North Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -10.000000000000,        !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    -10.000000000000,        !- Vertex 2 X-coordinate {m}
!    0.000000000000,          !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    0.000000000000,          !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
```

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!    0.000000000000,          !- Vertex 4 X-coordinate {m}
!    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    403F94,                  !- Name
!    Roof,                    !- Surface Type
!    Exterior Roof,           !- Construction Name
!    North Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    -10.000000000000,        !- Vertex 1 X-coordinate {m}
!    0.000000000000,          !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    3.000000000000,          !- Vertex 2 Z-coordinate {m}
!    10.000000000000,         !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    3.000000000000,          !- Vertex 3 Z-coordinate {m}
!    20.000000000000,         !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    31AE50,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    North Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    ,                        !- View Factor to Ground
!    4,                       !- Number of Vertices
!    0.000000000000,          !- Vertex 1 X-coordinate {m}
!    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    0.000000000000,          !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    10.000000000000,         !- Vertex 3 X-coordinate {m}
!    -10.000000000000,        !- Vertex 3 Y-coordinate {m}
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    10.000000000000,         !- Vertex 4 X-coordinate {m}
!    -10.000000000000,        !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
! BuildingSurface:Detailed,
!    123456,                  !- Name
!    Wall,                    !- Surface Type
!    Exterior Wall,           !- Construction Name
!    North Zone,              !- Zone Name
!    Adiabatic,               !- Outside Boundary Condition
!    ,                        !- Outside Boundary Condition Object
!    SunExposed,              !- Sun Exposure
!    WindExposed,             !- Wind Exposure
!    0.0,                     !- View Factor to Ground
!    4,                       !- Number of Vertices
!    10.000000000000,         !- Vertex 1 X-coordinate {m}
!    -10.000000000000,        !- Vertex 1 Y-coordinate {m}
!    3.000000000000,          !- Vertex 1 Z-coordinate {m}
!    10.000000000000,         !- Vertex 2 X-coordinate {m}
!    -10.000000000000,        !- Vertex 2 Y-coordinate {m}
!    0.000000000000,          !- Vertex 2 Z-coordinate {m}
!    20.000000000000,         !- Vertex 3 X-coordinate {m}
!    0.000000000000,          !- Vertex 3 Y-coordinate {m}
```

```
!    0.000000000000,          !- Vertex 3 Z-coordinate {m}
!    20.000000000000,         !- Vertex 4 X-coordinate {m}
!    0.000000000000,          !- Vertex 4 Y-coordinate {m}
!    3.000000000000;          !- Vertex 4 Z-coordinate {m}
!
!
!
! HVACTemplate:Thermostat,
!    Constant Setpoint Thermostat,  !- Name
!    ,                        !- Heating Setpoint Schedule Name
!    20,                      !- Constant Heating Setpoint {C}
!    ,                        !- Cooling Setpoint Schedule Name
!    25;                      !- Constant Cooling Setpoint {C}
!
!
!
! HVACTemplate:Zone:IdealLoadsAirSystem,
!    South Zone,              !- Zone Name
!    Constant Setpoint Thermostat;  !- Template Thermostat Name
!
! HVACTemplate:Zone:IdealLoadsAirSystem,
!    West Zone,               !- Zone Name
!    Constant Setpoint Thermostat;  !- Template Thermostat Name
!
! HVACTemplate:Zone:IdealLoadsAirSystem,
!    East Zone,               !- Zone Name
!    Constant Setpoint Thermostat;  !- Template Thermostat Name
!
! HVACTemplate:Zone:IdealLoadsAirSystem,
!    North Zone,              !- Zone Name
!    Constant Setpoint Thermostat;  !- Template Thermostat Name
Output:VariableDictionary,
    IDF;                     !- Key Field


!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:CONSTRUCTIONS ===========

Output:Constructions,
    Constructions,           !- Details Type 1
    Materials;               !- Details Type 2


!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:TABLE:SUMMARYREPORTS ===========

Output:Table:SummaryReports,
    AllSummary,              !- Report 1 Name
    AllSummaryAndMonthly;    !- Report 2 Name


!-   ===========  ALL OBJECTS IN CLASS: OUTPUTCONTROL:TABLE:STYLE ===========

OutputControl:Table:Style,
    HTML,                    !- Column Separator
    JtoKWH;                  !- Unit Conversion


!-   ===========  ALL OBJECTS IN CLASS: OUTPUT:VARIABLE ===========

Output:Variable,
    *,                       !- Key Value
    Ideal Loads Zone Total Cooling Energy,  !- Variable Name
    Monthly,                 !- Reporting Frequency
    Hours of Operation Schedule;  !- Schedule Name

Output:Variable,
    *,                       !- Key Value
    Zone Lights Electric Consumption,  !- Variable Name
    Monthly,                 !- Reporting Frequency
    Hours of Operation Schedule;  !- Schedule Name

Output:Variable,
```

```
*,                   !- Key Value
PV Generator DC Energy,  !- Variable Name
Monthly;                 !- Reporting Frequency
```

APPENDIX C – LCA Unit Process Raw Data

Photovoltaic Laminate (a-Si)

	Name	Location	Unit	Photovoltaic laminate, a-Si, at plant
product	photovoltaic laminate, a-Si, at plant	US	m2	1.00E+0
technosphere	electricity, medium voltage, at grid	US	kWh	4.82E+01
	light fuel oil, burned in industrial furnace 1MW, non-modulating	RER	MJ	5.89E+00
infrastructure	photovoltaic module factory	GLO	unit	4.00E-06
water	tap water, at user	RER	kg	3.97E+01
manufacturing	wire-drawing, copper	RER	kg	6.68E-02
	sheet rolling, steel	RER	kg	9.64E-01
materials	aluminium alloy, AIMg3, at plant	RER	kg	1.43E-02
	copper, at regional storage	RER	kg	6.68E-02
	steel low-alloyed, at plant	RER	kg	9.64E-01
	brazing solder, cadmium free, at plant	RER	kg	2.62E-03
	soft solder, Sn97Cu3, at plant	RER	kg	9.71E-03
	polyethylene, HDPE, granulate, at plant	RER	kg	1.10E+00
	packaging film, LDPE, at plant	RER	kg	3.10E-01
	polyvinvlflouride film, at plant	US	kg	1.23E-01
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	kg	3.58E-02
	synthetic rubber at plant	RER	kg	6.76E-02
coating	silicon tetrahydride, at plant	RER	kg	3.58E-03
	indium, at regional storage	RER	kg	8.94E-04
	cadmium telluride, semiconductor-grade, at plant	US	kg	8.94E-04
	phosphoric acid, fertiliser grade, 70% in H2O, at plant	US	kg	7.50E-05
auxiliaries	oxygen, liquid, at plant	RER	kg	4.85E-04
	hydrogen, liquid, at plant	RER	kg	2.18E-02
packaging	polyethylene, LDPE, granulate, at plant	RER	kg	1.84E-02
transport	transport, lorry > 16t, fleet average	RER	tkm	8.49E-02
	transport, transoceanic freight ship	OCE	tkm	9.07E+00
	transport, freight, rail	RER	tkm	1.50E+00
disposal	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	kg	3.00E-02
	disposal,rubber, unspecified, 0% water, to municipal incineration	CH	kg	6.76E-02
	disposal, polyvinvyfluoride, 0.2% water, to municipal incineration	CH	kg	1.23E-01
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	kg	3.46E-01
	treatment, glass production effluent, to wastewater treatment, class 2	CH	m3	3.97E-02
emission air	heat, waste	-	MJ	1.74E+02

Inverter (2500W)

	Name	Location	Unit	inverter, 2500W, at plant
product	inverter, 2500W, at plant	RER	unit	1.00E+0
technosphere	electricity, medium voltage, production UCTE, at grid	UCTE	kWh	2.12E+01
	aluminium, production mix, cast alloy, at plant	RER	kg	1.40E+00
	copper, at regional storage,	RER	kg	5.51E+00
	steel, low-alloyed, at plant	RER	kg	9.80E+00
	styrene-acrylonitrile copolymer, SAN, at plant	RER	kg	1.00E-02
	polyvinylcholride, at regional storage	RER	kg	1.00E-02
electronical components	printed wiring board, through-hole, at plant	GLO	m2	2.25E-01
	connector, clamp connection, at plant	GLO	kg	2.37E-01
	inductor, ring core choke type, at plant	GLO	kg	3.51E-01
	integrated circuit, IC, logic type, at plant	GLO	kg	2.80E-02
	transistor, wired, small size, through-hole mounting, at plant	GLO	kg	3.80E-02
	diode,glass-, through-hole mounting, at plant	GLO	kg	4.70E-02
	capacitor, film, through-hole mounting, at plant	GLO	kg	3.41E-01
	capacitor, electrolyte type, > 2cm height, at plant	GLO	kg	2.56E-01
	capacitor, tantalum-, through-hole mounting, at plant	GLO	kg	2.30E-02
	resistor, metal film type, through-hole mounting, at plant	GLO	kg	5.00E-03
	sheet rolling, steel	RER	kg	9.80E+00
processing	wire drawing, copper	RER	kg	5.51E+00
	section bar extrusion, aluminium	RER	kg	1.40E+00
	metal working factory	RER	unit	8.97E-09
infrastructure	corrugated board, mixed fibre, single wall, at plant	RER	kg	2.50E+00
packaging	polystyrene foam slab, at plant	RER	kg	3.00E-01
	fleece, polyethylene, at plant	RER	kg	6.00E-02
	transport, lorry >16t, fleet average	RER	tkm	2.30E+00
transport	transport, freight, rail	RER	tkm	7.11E+00
	transport, transoceanic freight ship	OCE	tkm	3.63E+01
	heat, waste	-	MJ	7.63E+01
emission air, high pop dens.	disposal, packaging cardboard, 19.6% water, to municipal incineration	CH	kg	2.50E+00
disposal	disposal, polystyrene, 0.2% water, to municipal incineration	CH	kg	3.10E-01
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	kg	6.00E-02
	disposal, plastic, industrial electronics, 15.3% water, to municipal incineration	CH	kg	0.00E+00
	disposal, treatment of printed wiring boards	GLO	kg	1.70E+00

Façade Construction (Integrated at Building)

	Name	**Location**	**Unit**	**façade construction, integrated, at building**
product	façade construction, integrated, at building	RER	m2	1.00E+0
technosphere	aluminium, production mix, wrought alloy, at plant	RER	kg	3.27E+00
	section bar extrusion aluminium	RER	kg	3.27E+00
transport	transport, lorry > 16t, fleet average	RER	tkm	1.64E-01
	transport, freight, rail	RER	tkm	6.54E-01
	transport, van <3.5ft	RER	tkm	3.27E-01
Energy use for mounting	screws		kwh/m2	2.00E-02
	aluminium profile mounting		kwh/m2	2.00E-02

Electrical Installation (Photovoltaic Plant)

	Name	**Location**	**Unit**	**façade construction, integrated, at building**
product	electric installation, photovoltaic plant, at plant	CH	unit	1.00E+0
technosphere	copper, at regional storage	RER	kg	1.47E+01
	brass, at plant	CH	kg	2.00E-02
	zinc, primary, at regional storage	RER	kg	4.00E-02
	steel, low-alloyed, at plant	RER	kg	8.60E-01
	nylon 6, at plant	RER	kg	2.30E-01
	polyethylene, HDPE, granulate, at plant	RER	kg	1.76E+01
	polyvinylchloride, bulk polymerised, at plant	RER	kg	2.13E+00
	polycarbonate, at plant	RER	kg	2.00E-01
	epoxy resin, liquid, at plant	RER	kg	2.00E-03
manufacturing	wire drawing, copper	RER	kg	1.47E+01
	transport, lorry 20-28t, fleet average	CH	tkm	2.15E+00
	transport, freight, rail	CH	tkm	1.34E+01
disposal	disposal, plastic, industrial electronics, 15.3% water, to municipal incineration	CH	kg	2.02E+01
	disposal, building, electric wiring, to final disposal	CH	kg	6.00E-02

Photovoltaic Module (Micromorph)

	Name	**Unit**	**photovoltaic module, micromorph, at plant**
product	photovoltaic module, micromorph, at plant	-	-
	electricity	kWh/kWp	369
	compressed dry air	l/kWp	80883
	water supply	m3/kWp	0.27
	solar glass, low-iron	kg/kWp	192
	gas supply	kg/kWp	49.93
	wrapping	kg/kWp	1.2

APPENDIX D – Contractors' Quotation for Glazing

SPACE CONSTRUCTION

3 PHENG GECK AVENUE SINGAPORE 348198
TEL: 6483 1201 FAX: 6482 9646
EMAIL: scspacecon@gmail.com

SC/1004/13 17 April 2013

Mr Ng Poh Khai
Solar Energy Research
Institute of Singapore ng_khai@hotmail.com

Dear Sir

<u>RE : COSTING FOR WINDOWS/CURTAIN WALL</u> **(SIZE : 30MR X 3MH)**

1.	Supply only single-glazed windows (6mm thick clear glass)	@ $ 60/m²
2.	Supply of aluminum framing for single-glazing windows	@ $ 270/m²
3.	Installation of single-glazed windows on a 30m x 3m building façade.	@ $ 70/m²
4.	Supply of double-glazed windows (6/5/6 clear glass)	@ $ 130/m²
5.	Supply of aluminum framing for double-glazing windows	@ $ 350/m²
6.	Installation of double-glazed windows on a 30m x 3m building façade.	@ $ 120/m²

** **Items Excluded :** Hositing of glass/aluminium frame
Scaffolding

<u>Conditions</u>

a)	Date of Completion	:	6 months from date of confirmation/deposit receive. We need 5 days to mobilise our men.
b)	Term of Payment	:	40% deposit, progressively upon job completed on site full payment upon completion.
c)	Validity Date of Pricing	:	3 weeks from date of this letter.
d)	Defect Liability Period	:	12 months from date of completion.

Awaits your early reply.

Yours faithfully
SPACE CONSTRUCTION

NG HIAN HOCK

....
Client's Signature &
Date of Confirmation

M. S. KONG CONTRACTS SERVICE PTE LTD.

KMS/1859/13

16 April 2013

Mr Ng Poh Khai
Solar Energy Research
Institute of Singapore

ng_khai@hotmail.com

Dear Sir

RE : COSTING FOR WINDOWS/CURTAIN WALL (SIZE : 30mr X 3MH)

We would like to quote the following :

1.	Supply of single-glazed windows (6mm thick clear glass)	@ $ 50/m²
2.	Supply of aluminum framing for single-glazing windows	@ $ 250/m²
3.	Installation of single-glazed windows on a 30m x 3m building façade.	@ $ 80/m²
4.	Supply of double-glazed windows (6/5/6 clear glass)	@ $ 120/m²
5.	Supply of aluminum framing for double-glazing windows	@ $ 280/m²
6.	Installation of double-glazed windows on a 30m x 3m building façade.	@ $ 100/m²

**** Subject to GST**

Conditions

a)	Date of Completion	:	6 months from date of confirmation/deposit receive. We need 5 days to mobilise our men.
b)	Term of Payment	:	40% deposit, progressively upon job completed on site full payment upon completion.
c)	Validity Date of Pricing	:	3 weeks from date of this letter.
d)	Defect Liability Period	:	6 months from date of completion.
***	**Items Not Included**	-	**Scaffolding** **Crane / Hoisting**

Awaits your early reply.

Yours faithfully
M.S. KONG CONTRACTS SERVICE PTE LTD

....
Client's Signature &
Date of Confirmation

PETE KONG

Blk 1002 Toa Payoh Industrial Park
#01-1425 Singapore 319074
~~3 PHENG GECK AVENUE, SINGAPORE 348198~~ TEL: 6483 1201 FAX: 6482 9646 EMAIL: mskong@singnet.com.sg

Ref : TBC/Q2013-149

Date : 2nd May 2013

Thiam building construction

QUOTATION

Ng Poh Khai (Mr)
Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore (NUS)
7 Engineering Drive 1
Block E3A, #06-01
Singapore 117574

Dear Sir,

Re : Quotation for Aluminium window works

Reference is made to the above mentioned. We are pleased to submit herewith the quotation for your kind consideration & approval:-

S/no	Description	Rate	
1	Supply of single glazed window (6 mm Side hung)	30.00	per m^2
2	Supply of single -glazed framing for single-glazing window (casement)	100.00	per m^2
3	Installation of single-glazed window on a 30 m x 3 m building facade	50.00	per m^2
4	Supply of double glazed window (6+6+6)	120.00	per m^2
5	Supply of aluminium framing for double glazed window	120.00	per m^2
6	Installation of of a double glazed window on a 30 x 3 m facade	60.00	per m^2

Terms & condition :

- 7% GST to be added accordingly

Thank you

Yours faithfully,

Toh Kai Thiam
Director

Thiam Building Construction Pte Ltd
No. 10, Admiralty Street #06-85 North Link Building
Singapore 757695. Tel: 6752-8878 Fax: 6752-5755
Email: thiam@tbcpl.com.sg Business Reg. No.: 1996-09217-K

Ng Poh Khai

From: christophe.inglin <christophe.inglin@phoenixsolar.sg>
Sent: Monday, 15 April, 2013 11:42 PM
To: Ng Poh Khai
Cc: André Nobre
Subject: RE: Contact - SERIS PhD student

Hi Poh Kai

For CTO, the figures we have as our costs:
CTO, 200 panels, 42kWp (really depends on the spacing between cells)
Overall area: 28.1m x 20.3m = 570.43 sqm

Lump sum costing for:
1. UV weather proof structure silicon: $13'500
2. Glass cushion foam 6mm: $1'890
3. Modified aluminium capping (trunking): $7'300
4. Manpower with tooling and accessories: $27'793

Total cost from glass installer: $50'000 with $483 – discount

The main con paid for the underlying canopy structure, so we do not know its cost.

For CREATE, things are more complicated still. We kept costs down by sharing facilities with YKK, the glazing contractor. For example, the gondola costs SGD8k, and we shared this equally with YKK, with each of us paying SGD4k

Create Tower Block, 72 panels (@1.6 x 1.6 m), on 17th storey building.

1. Provision of space for (trunking): Free (we run along the mullion for this portion, else we need to add trunking cost, est. $50/m running vertically for supply and install)
2. Protection (during handling and construction): $2'500 (supply and install)
3. Supply of UV rated stopper, cable tie, cable tie holders: $1'200
4. Gondola: Approx. $8'000 for two months (inclusive of installation, endorsement, dismantling, each relocation will be charged at approx. $500).< two months, same price. > two months, weekly charges apply. We paid $4'000 as we shared this with YKK who installed the panels for us. Only use them for approx. 2 weeks including weekends.
5. Wiring, laying of cables, crimping of connectors, AC isolator, installing inverter, DC and AC trunking : $8'500
6. DC junction boxes, SPDs, terminal blocks, labelling: $700
7. Standard glass installation cost: we don't have this cost since YKK installed this under the maincon directly.

To answer your question below on how much it costs to install BIPV on all four facades of a building 30x30 x 3m high, you need first to talk to a glazing contractor, and agree on the BIPV type to install. Then:

1) deduct cost of conventional glazing and add cost of BIPV laminates. Assuming 100W/m2 c-Si laminates, you are looking at 36kWp system size. If a-Si, then perhaps 12kWp.
2) add cost of electrical work. If the building is properly designed, we can assume very roughly something like SGD1.50-3.00/Wp for cabling + trunking, inverters, labour.

Annual maintenance is not much different from a rooftop PV system. You need annual inspection and testing at the inverters. Cleaning in line with window cleaning regime (likely every 3-4 years). It gets expensive only if you need to replace a defective BIPV laminate, for which you need the specialist glazing contractor.

A big problem is how badly a BIPV facade works in Singapore, because the facade is seldom uniformly illuminated. You are aware that partial shading messes up system yields.The best thing is probably to use power maximisers or micro inverters. But since these are transformerless, they exclude a-Si, some CIGS modules and c-Si modules with SunPower cells. These all need to be grounded, hence no TL inverters. You can only use c-Si laminates or FSLR CdTe (but they are not really in BIPV form because front glass is not tempered.

Please see what use you can make of the above numbers, and then discuss where we can help get more detail.

Best regards

Christophe

From: christophe.inglin [mailto:christophe.inglin@phoenixsolar.sg]
Sent: Monday, 15 April, 2013 10:48
To: 'Ng Poh Khai'
Cc: 'André Nobre'
Subject: RE: Contact - SERIS PhD student

Hi Poh Khai

thanks for your reminder! We have two projects to draw from:
CTO has a 42kWp BIPV canopy, using c-Si
CREATE has 13kWp of semi-transparent a-Si facade

(Another one is Tampines Grande, but it is too long ago to be relevant)

The same Project Manager did both projects, but he has been on an overseas project for several weeks and just returned today. I spoke with him and can get you some figures by this evening or tomorrow.

The challenge is to get meaningful costing for a properly designed building, where BIPV is part of the original design mandate and the architect, client and main con all understand how BIPV works. That has never happened in Singapore yet. Instead, such projects face death by multiple tenders, where each sub contractor tries heroically to cut costs on his scope of work, regardless of the consequences for the bigger picture.

For the canopy, we have a pretty clear idea of the costs. For the facade, we will try to express the costs as the increment to installing a non-PV facade. That means things like mast crawler are already