EFFECTIVENESS OF SEMI-TRANSPARENT PHOTOVOLTAIC APPLICATION AT HIGHRISE VERTICAL FACADE IN MALAYSIAN URBAN AREA

HAITHAM ESAM MAHMOUD RABABAH

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by

HAITHAM ESAM MAHMOUD RABABAH

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$I_{d_i r}$	The direct solar flux (W/m2) incident on the surface.
θ	The angle of incidence.
β	The inclination of the surface.
α	The solar altitude.
$NOCT$	Nominal cell temperature
L	The luminance.
I	Incident solar irradiance, with adjustment for shading and degradation.
E	illuminance.
DF	Daylight Factor.
Cf	Correction factor for orientation.
A	Panel area.
ρ_g	The solar reflectance (albedo) of the ground.
η_r	PV module nominal efficiency
η_p	Generation efficiency
β_p	Temperature coefficient for module efficiency
f_s	Degradation factor
f_e	The electrical conversion efficiency
f_d	Shading factor.
T_r	Reference temperature (25C)
T_c	Cell temperature.
T_{aNOCT}	20°C.
L_z	The luminance at the zenith (cd/m2).
I_{unsh}	Unshaded solar irradiance.

$I_b eam$	The solar flux (W/m2) was measured perpendicular to the beam.
I_{NOCT}	800 W/m2 or 1000 W/m2 as indicated in the input.
I_{sd_iff}	The diffuse sky solar flux (W/m2) incident on the surface.
I_{hd_iff}	The diffuse sky solar flux (W/m2) on the horizontal plane.
I_{gd_iff}	The diffuse ground solar flux (W/m2) incident on the surface.
Ev	Eval glare.
$(\delta - \delta_s)$	The angle between the panel normal's declination and the solar

LIST OF ABBREVIATIONS

BIPV	Building Integrated Photovoltaics
STPV	Semi-transparent Photovoltaics
FIT	Feed-in Tariff
PV	Photovoltaics
ROI	Return of Investment
TNB	Tenaga Nasional Berhad
WWR	Window-to-Wall Ratio
CdTe	Cadmium Telluride
IESve	Integrated Environmental Solution Virtual Environment
GWh	Gigawatt Hour
MWh	Megawatt Hour
lx	Lux
CO_2	Carbon Dioxide
KLCC	Kuala Lumpur City Centre
DF	Daylight Factor
SDG	Sustainable Development Goal
SHGC	Solar Heat Gain Coefficient
SAM	Sistem Advisor Model
NREL	National Renewable Energy Laboratory
HIT-si	Heterojunction Intrinsic Thin-film
BIM	Building Integrated Modeling
DSF	Double Skin Facade
GBI	Green Building Index

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KEBERKESANAN PENGGUNAAN FOTOVOLTAIK LUT CAHAYA PADA FAKAD BANGUNAN TINGGI SECARA VERTIKAL DI KAWASAN BANDAR MALAYSIA

ABSTRAK

Kajian ini bertujuan untuk menggandakan fakad vertikal bangunan dalam kawasan bandar tinggi Malaysia bagi menghasilkan tenaga boleh diperbaharui, menangani cabaran ruang terhad untuk pemasangan solar tradisional. Khususnya memberi tumpuan kepada seting bandar Kuala Lumpur, kajian menggunakan teknik pemodelan dan simulasi yang canggih untuk menilai potensi pendedahan solar dan mengoptimumkan penempatan panel fotovoltaik (PV). Objektif utama adalah meneroka kelayakan dan keberkesanan penggunaan permukaan vertikal untuk pengeluaran tenaga solar. Dengan menumpukan kepada kawasan tertentu yang merangkumi bangunan tinggi di Kuala Lumpur. Dengan menggunakan perisian Revit untuk membangunkan model 3D konseptual dan perisian IESve untuk simulasi, kajian memberi tumpuan kepada faktor-faktor seperti bangunan bersebelahan, kesan teduhan, dan jarak untuk menentukan impak mereka terhadap pendedahan solar. Penemuan menunjukkan pemasangan panel PV berpotensi mengurangkan kos elektrik sebanyak 42.67%. Selain itu, kajian menekankan kebolehgunaan ekonomi pendekatan ini, dengan anggaran bahawa panel PV mempunyai Purata Pulangan Pelaburan (ROI) antara 6.7% dan 11%, bergantung kepada nisbah panel PV kepada tingkap, integrasi inovatif ini menjanjikan pulangan yang signifikan bagi pemilik bangunan. Secara keseluruhan, kajian ini menandakan langkah yang menjanjikan ke arah pembangunan bandar yang mampan, menunjukkan potensi fakad vertikal dalam menyumbang kepada matlamat tenaga boleh diperbaharui sambil meningkatkan landskap bandar.

EFFECTIVENESS OF SEMI-TRANSPARENT PHOTOVOLTAIC APPLICATION AT HIGHRISE VERTICAL FACADE IN MALAYSIAN URBAN AREA

ABSTRACT

This research endeavours to leverage the vertical facades of buildings within Malaysia's high-rise urban areas to generate renewable energy, addressing the challenge of limited space for traditional solar installations. Specifically focusing on the urban setting of Kuala Lumpur, the study employs sophisticated modelling and simulation techniques to assess solar exposure potential and optimise the placement of photovoltaic (PV) panels. The primary objective is to explore the feasibility and effectiveness of utilising vertical surfaces for solar energy production, by concentrating on a specific area encompassing high-rise buildings in Kuala Lumpur. By using Revit software for developing a conceptual 3D model and IES VE software for simulations, the study focused on factors such as neighbouring buildings, shading effects, and distances to ascertain their impact on solar exposure. The findings highlighted that installing PV panels have the potential to reduce electricity costs by 42.67%. Moreover, the research underscores the economic viability of this approach, with an estimation that PV panels have an average Return on Investment (ROI) between 6.7% and 11%, depending on the ratio of PV panels to windows, this innovative integration promises significant returns for building owners. Overall, the research signifies a promising step towards sustainable urban development, demonstrating the potential of vertical facades in contributing to renewable energy goals while enhancing the urban landscape.

CHAPTER 1

INTRODUCTION

1.1.Introduction

Chapter 1 is the first chapter of this research, which highlights an overview of the whole thesis and gives some insights into the main issues that this research is trying to tackle and seeks the appropriate methods and solutions. Moreover, chapter 1 starts with a review of the current situation of Highrise buildings, with a specific focus on the city of Kuala Lumpur, Malaysia then spotting the issues in the problem statement section to help in determining the main issues and problem, and that helps in addressing the correct questions that should be asked. Furthermore, identifying the research question drew the right path for this research to formulate the research objectives for this study. Subsequently, this chapter discussed a brief of literature review, methodology, scope and limitations, and conceptual framework, which are discussed in detail in the following chapters.

1.2.Background of the Study

Addressing the energy sector's social, environmental, and economic issues requires establishing sustainable energy systems. Remarkably, up to 40% of the world's energy is currently consumed by buildings; this percentage is expected to increase to 50% by 2030 (S. R. Aldhshan, K. N. Abdul Maulud, W. S. Wan Mohd Jaafar, O. A. Karim, & B. J. S. Pradhan, 2021). Cities such as Kuala Lumpur face significant environmental challenges with energy efficiency (Yin, & Abdullah, 2020). Nevertheless, their massive social housing construction projects fall short of adequately addressing these urgent problems (Sahabuddin & Gonzalez-Longo, 2019). Malaysia is one of the top consumers of primary energy in Asia (Aldhshan et al., 2021). Tropical cities, with a distinct combination of warmth and humidity, are especially important in this respect. Because of the constant rise in temperature throughout the year, these regions' main energy consumption is related to the requirement for cooling structures (Wang et al., 2022). More than half of the energy is used for space cooling alone, far more than is needed for appliances, lighting, ventilation, and other uses (Wang et al., 2022). In most commercial and high-rise residential buildings where lowering cooling energy costs is vital, an integrated approach for controlling solar radiation transmission must be implemented (Athienitis, Barone, Buonomano, & Palombo, 2018). Semi-transparent photovoltaic windows, rather than reflecting, tinted, or fritted windows, can be used to minimise solar heat gains and create solar power (Kapsis & Athienitis, 2015). Because of the rising economic and population densities in Southeast Asian countries, most of the residents live in high-rise buildings (Mirrahimi et al., 2016).

High-rise buildings are the product of fast urbanisation in densely populated areas to reduce land shortages. The fast-growing economies and population are more than twice as crowded as cities in Europe and five times denser than cities in North America and Australia (Wang et al., 2020). Furthermore, given the significance of high-rise buildings in terms of finance, sustainability, the environment, and quality of life, the construction industry may be regarded as one of the most important components of environmental sustainability (Y. Wang et al., 2020). High-rise buildings are deemed sustainable if their social, economic, and environmental implications on the community are adequately addressed and contribute to the long-term progress of society (Savvides, 2018). Social sustainability refers to people's ability to meet present demands as well as the requirements of future generations (Y. Wang et al., 2020). Semi-transparent Photovoltaics (STPV) modules have been employed as part of the façade recently for energy efficiency reasons. The usage of STPV proved to influence energy consumption for heating, cooling, and lighting, as well as thermal and visual comfort within the building (Didoné & Wagner, 2013). Now, STPV systems do not need extra space to be installed compared to traditional PV panels because they integrate into the building envelope and are part of it (Didoné & Wagner, 2013).

1.3.Problem Statement

In tropical climates, building design relies heavily on natural daylight. This approach provides the most efficient daylight illuminance for buildings throughout the day (Mirrahimi et al., 2023). Orient daylight openings to control direct sunlight while providing sufficient illumination from high-quality sources (Mirrahimi et al., 2023). Moreover, insufficient daylighting in a building may decrease productivity for both people and the building itself (Zulkarnain, Mohd Salleh, & Abdul Aziz, 2021). Excessive solar openings can cause heating and increase energy consumption. Insufficient daylighting is often caused by attempts to reduce exposure to sunlight, which leads to increased artificial lighting energy use and decreased productivity and comfort for users (Zulkarnain et al., 2021). Moreover, daylight harvesting can save energy in lighting by 20 to 87% (Shamri et al., 2022).

Malaysia's tropical environment provides sufficient daylight throughout the year. The intermediate sky provides sufficient daylight (over 20,000 lx) between 09:00 and 17:00 hrs (Sern, Liou, & Fadzil, 2022). Offices usually only need 300–400 lx. This means that tropical countries have a great chance to utilise renewable energy sources because of the abundance of daylight (Sern et al., 2022). A more visually appealing setting might also boost occupant productivity (Lim, Ahmad, & Ossen, 2013). Moreover, people, especially office workers, are recognised to gain psychologically from daylight. In addition to raising employee productivity, it fosters a healthier atmosphere that lowers absenteeism (Heng, Lim, & Ossen, 2020). Furthermore, compared to electric lighting, it is more efficient in producing light because it generates less heat for the same amount of light. This can reduce a building's cooling load by up to 15% (Heng et al., 2020). Natural light is the most effective light source for visual comfort, visual appeal, and energy efficiency (Al-Ashwal, Hassan, & Lim, 2023). Malaysia is in a tropical location with sufficient daylight availability, which may meet the required lighting during the day (Al-Ashwal et al., 2023). Moreover, the lack of natural light and the usage of artificial lighting throughout the day have resulted in high power consumption rates in many Malaysian office buildings (Y. Li & Solaymani, 2021). Furthermore, Aaditya and Mani (2013) addressed that the orientation, exterior walls, surface finishes, window area, glass type, external shading and roofing are the key elements that lead to the building's heat gain. Thus, that will influence increasing cooling loads, leading to an increase in energy consumption (Aaditya & Mani, 2013).

Building energy and indoor environmental performance is crucial in modern society, where up to 40% of the world's energy is currently consumed by buildings (Aldhshan, et al., 2021) and people spend most of their time indoors (Chen, et al., 2019). Recently, energy consumption in developed and developing countries has increased rapidly, which can be attributed to the large number of electrical devices that have been developed; additionally, this increase in energy consumption has become a significant issue that the economies in these countries are dealing with (Didoné, Wagner, & Buildings, 2013). Moreover, commercial building energy consumption in developed countries is rapidly increasing; moreover, buildings utilise massive amounts of energy to alter the illumination and interior temperature of living spaces using artificial lighting and air-conditioning devices. Furthermore, windows are the most critical feature in any structure since they have the highest rate of heat loss or gain, but they are also directly tied to light and visual comfort. As a result, new glazing technologies (passive and active windows) are being developed to minimise energy demands while improving building interior environments (Martín-Chivelet et al., 2018).

Buildings use between 20% and 40% of total world energy (Hannon & Bolton, 2021), with high-rise buildings having the largest cooling loads and consuming the most energy (Walker, 2017). Furthermore, buildings with twenty or more storeys require around two and a half times the energy of mid-rise buildings (Yang et al., 2019). Furthermore, the increase in cooling loads in high-rise structures may be attributed to internal heat gain because of artificial lighting, equipment, and so on, as well as the usage of big glazing systems (Yuan, Vallianos, Athienitis, & Rao, 2018). Because of the limitation of land and the rapid growth of the population, many high-rise structures have been built. According to reports, there are 142 cities with more than one hundred high-rise buildings, for example, New York City has the most high-rise buildings with 6034 buildings in 2019. Furthermore, the number of high-rise buildings is rapidly increasing, particularly in cities with significant economic growth (Qiu & Yang, 2020).

Malaysia is one of the countries with the highest energy consumption rate (Shamri et al., 2022), which is related to significant economic development in the residential and commercial sectors, which consume nearly half of the total electricity generated (Shamri et al., 2022). Malaysia's urban growth is accelerating (Mustafa et al., 2019a), and with all these developments, energy consumption is one of the problems that Malaysia is facing (Loo et al., 2020). Buildings in Malaysia emit the greenhouse effect, which contributes more than 40% of carbon emissions (Shamri et al., 2022). Moreover, residential buildings consume 24,709 gigawatt-hours (GWh) of electricity, while commercial buildings utilise up to 38,645 gigawatt-hours (GWh)(Aldhshan et al., 2021). Aldhshan et al. (2021) revealed that Malaysia’s buildings collectively account for 48% of the country's total electricity consumption (Aldhshan et al., 2021). Moreover, previous research in Singapore and Kuala Lumpur (Mostafavi, Tahsildoost, & Zomorodian, 2021) found outdoor air temperature variation of up to 2 ◦C between lower and upper levels in high-rise buildings. Height-related changes in the convective heat transfer coefficient led to significant changes in thermal loads and energy demand.

Recently, the world noticed the environmental effects of fossil fuels, as well as how burning fossil fuels contributes to climate change (Seng, Lalchand, & Lin, 2008). Furthermore, the rise in crude oil prices has forced Malaysia to confront a slew of social and economic issues. Malaysia had the third-largest energy demand in Southeast Asia in 2013, and one of the highest per capita consumption rates in the area (Baharum et al., 2018), due to the load demand, which necessitates the inclusion of extra equipment to effectively adjust the power output, increasing system complexity and resulting in high energy production costs (Chua, 2015).

1.4.Research Questions

From the mentioned earlier it concludes that, High-rise buildings in Malaysia face issues such as increasing cooling loads caused by the significant use of artificial lighting and air conditioning, as well as the crucial role of windows in thermal control and daylight availability. The environmental impact of fossil fuel-based energy sources exacerbates the issue, emphasising the importance of sustainable energy alternatives. Semi-transparent photovoltaic technology could integrate renewable energy generation with building facades. However, the impact of such technology on energy performance, indoor environmental quality, and overall sustainability needs further examination. Therefore, the research questions are as follows:

- How does integrating semi-transparent PV modules on high-rise building vertical façades and external shading affect daylighting performance within indoor environments?
- Is it preferable to use solar collecting systems to address the problem of high energy consumption for high-rise buildings in Malaysia?
- How cost-effective are semi-transparent PV modules in terms of payback period and return on investment when applied to high-rise building façades in Malaysia?
- How does incorporating semi-transparent PV technology into building vertical façades enhance sustainability, particularly regarding CO_2 emissions?

1.5.Research Aim and Objectives

This research aims to seek alternate methods and design considerations of using semi-transparent PV, which is integrated with the building's vertical façade, moreover, this research investigates the impact of applying Semi-transparent Photovoltaic technologies in the glazing system in buildings in Malaysia.

- To study the shading and daylighting effect of semi-transparent PV on building vertical façade.
- To estimate the electricity generation from semi-transparent PV on building vertical façade.
- To evaluate the cost, payback period and Return on Investment of semi-transparent glazing components on building façade in Malaysia.
- To assess the CO_2 emission associated with the adoption of semi-transparent PV technology in building vertical façades in Malaysia.

1.6.Research Scope and Limitations

This research focused on the integration of semi-transparent photovoltaic (PV) modules on vertical façades of high-rise buildings in Malaysia's Kuala Lumpur City Centre (KLCC). The study assessed the influence of these PV modules on daylighting performance, energy consumption, environmental sustainability, and economic viability. Using simulations with the IESve software, the investigators model multiple situations to provide extensive analysis of PV module performance. However, the research had several limitations. The 3D models used in the simulations were simplified, focusing solely on the building's footprint and basic façade lines, with no curving lines or curves.

1.7.Conceptual Framework

Based on Figure 1.1, the conceptual framework offers a structured approach to determine the feasibility and effectiveness of employing vertical facades for solar energy generation in Kuala Lumpur's high-rise urban zones, with an emphasis on economic, environmental, and architectural aspects. Vertical facades, renewable energy generation, solar exposure potential, photovoltaic (PV) panels, economic viability, environmental impact, and architectural integration are among the key themes under consideration. The primary variables to be investigated are solar exposure potential, installation height, PV panel efficiency, power generation from PV panels installed on high-rise vertical facades, return on investment (ROI), and payback period.

The research hypotheses are as follows: H1: PV panels put at the optimal heights on vertical facades generate more electricity than standard installations. H2: Monocrystalline PV panels will have a greater efficiency and ROI than other varieties. H3: Integrating PV panels into vertical facades will result in large CO_2 reductions and shorter payback periods. The study aims to look into the relationship between installation height, PV panel efficiency, and solar exposure potential. It will also investigate how integrating PV panels into vertical facades affects economic aspects like ROI and payback period. Furthermore, the investigation will look into the links between environmental benefits like lower CO_2 emissions and the architectural integration of PV panels.

Several assumptions and principles underpin this research. It is assumed that advanced modelling and simulation approaches accurately represent real-world solar exposure potential and energy generation. The idea is that incorporating PV panels into vertical facades can be a viable solution to the problem of limited space for typical solar installations in high-rise urban settings.

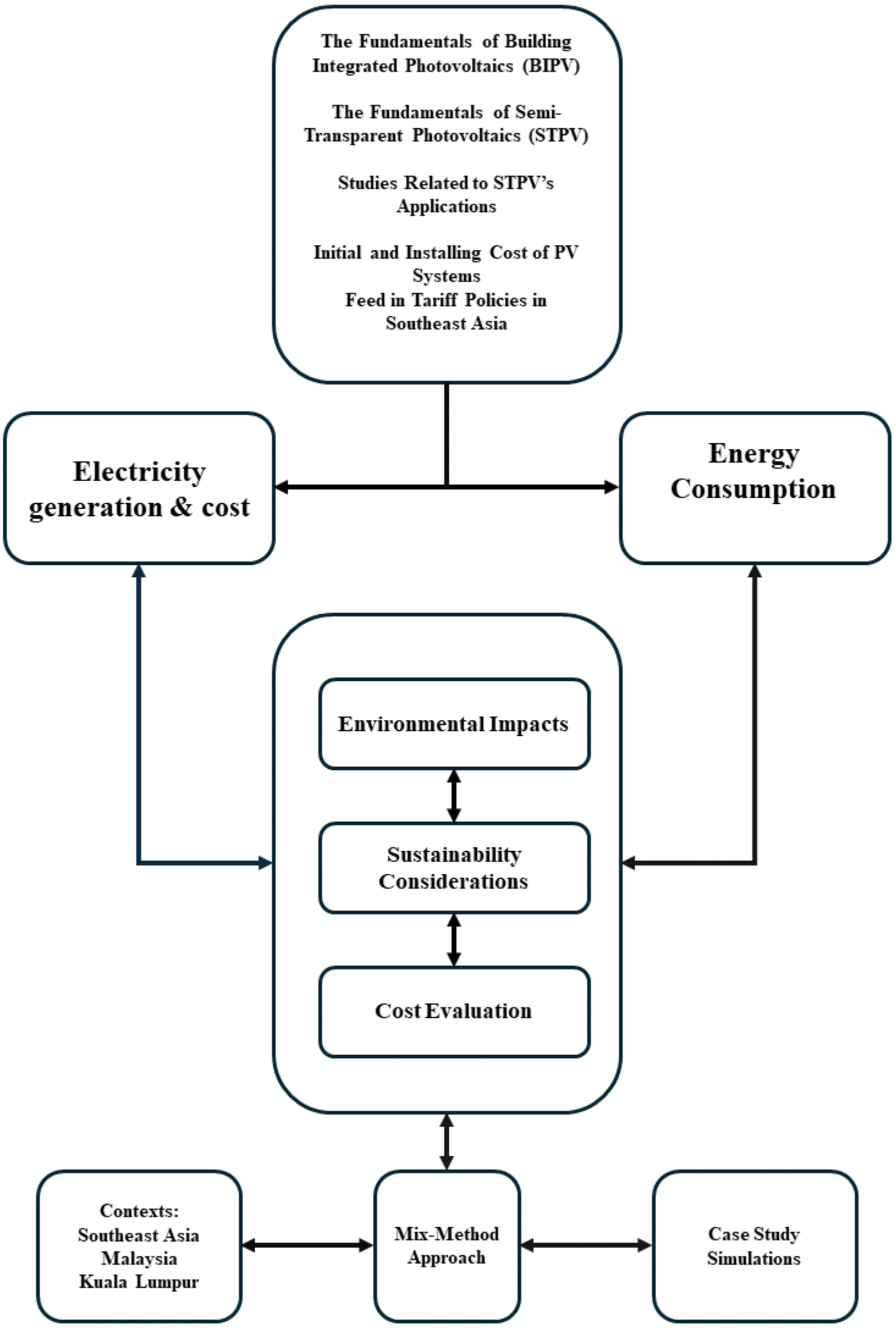

Figure 1.1. Conceptual Framework.

1.8. Overview of Research Methodology

The methodology described the approach taken to investigate the integration of semi-transparent photovoltaic (PV) modules in Malaysian high-rise buildings. The study is to evaluate the daylighting performance, energy consumption, environmental impact, and economic viability of these PV modules within the building facades. The study is divided into phases, each focusing on a particular topic area, and employing a mixed-method strategy that combines quantitative and qualitative methods. The qualitative component conducted a thorough literature analysis to build a theoretical framework, while the quantitative conducted simulations with advanced software and economic assessments to offer empirical support.

The focus is on high-rise buildings in Malaysian urban areas, which were chosen due to their high solar irradiation and the necessity for sustainable construction. Case studies are used to validate procedures and outcomes. Simulations are performed using the Integrated Environmental Solutions Virtual Environment (IESve) software, which properly models building performance such as solar radiation, energy usage, and daylighting. Semi-transparent PV modules are chosen for their transparency, efficiency, and visual appeal, to achieve both energy generation and architectural integration. The chapter also examined the impact of adjacent buildings, shade, and distance on sun exposure using a variety of simulated scenarios. The performance of the PV modules is evaluated in terms of energy generation, efficiency, and durability. Moreover, daylighting performance is evaluated to establish its impact on indoor lighting conditions, with an emphasis on daylight factor (DF) and glare. Furthermore, an economic study determined the cost viability, payback period, ROI, and long-term financial benefits of installing semi-transparent PV modules. This thorough methodology provided a complete framework for understanding the integration and performance of semi-transparent PV modules in high-rise buildings by systematically addressing each study objective to assess the technology's potential benefits and challenges.

1.9.Significant of Research

The significance of this research lies in its exploration of semi-transparent photovoltaic (STPV) materials as a potential glazing component for the vertical façades of high-rise office buildings in the bustling urban environment of Kuala Lumpur's Golden Triangle area. This investigation aligns with Malaysia's Renewable Energy (RE) Policies, including the Renewable Energy Policies (2011), Sustainable Energy Development Authority (SEDA) (2011), and the Feed-in Tariff Scheme (2011), which emphasise the promotion and utilisation of renewable energy sources. Furthermore, this research is closely linked to the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). By applying STPV technology to high-rise vertical facades, the study addresses the pressing need for sustainable and environmentally responsible solutions in urban areas. The introduction of STPV as a glazing material for high-rise buildings in Malaysia represents an innovative approach to meeting energy demands while reducing carbon emissions. This research contributes to the diversification of renewable energy sources and offers architects and urban planners an alternative to conventional building materials. Additionally, the integration of STPV with existing vertical facades holds the potential to enhance the energy efficiency and sustainability of urban structures, aligning with the broader objectives of sustainable urban development.

Ultimately, this research not only pioneers the application of STPV technology in the urban context of Malaysia but also provides architects and policymakers with valuable insights into more sustainable design considerations. By exploring the feasibility and benefits of STPV integration in high-rise buildings, this study offers a pathway towards more environmentally conscious and energy-efficient urban development, which is crucial for achieving the outlined Sustainable Development Goals and advancing Malaysia's commitment to renewable energy adoption.

1.10. Thesis Outline

This thesis has five main chapters as follows:

Chapter 1 serves the purpose of furnishing a comprehensive overview of the thesis' contents. Within this chapter, we expound upon the contextual background of contemporary energy issues and the problem statement, specifically within the domain of photovoltaic façades in urban areas. This exposition is undertaken to elucidate the overarching research objectives pursued in this study. Furthermore, the chapter is devoted to delineating the scope and constraints inherent to the research under consideration.

Chapter 2, This chapter endeavours to elucidate the foundational concept and conduct an extensive literature review concerning the subject matter of photovoltaic systems integrated into vertical façades, as well as the core principles of Building-Integrated Photovoltaic (BIPV) systems. This investigation encompasses a comparative analysis of prior academic works pertinent to this domain, thereby identifying gaps in existing research. Additionally, this chapter offers a comprehensive examination of contemporary policies and feed-in tariff frameworks within Malaysia, coupled with an exploration of the region's climatic conditions and their interplay with energy consumption patterns.

Chapter 3, This chapter is dedicated to delineating the research approach and methodologies employed in the pursuit of the study's objectives. It also addresses the validation procedures for simulation software. Within this chapter, this research provided an overview of the simulation program utilised in this research, elucidating the analytical aspects of the conceptual simulation tool. Additionally, this chapter furnishes details regarding the configuration of the base model for ten high-rise buildings located in the Golden Triangle area of Kuala Lumpur, Malaysia.

Chapter 4, this chapter is dedicated to the presentation of a study concerning solar exposure on the vertical façades of specific buildings. Within this context, an in-depth analysis is undertaken to determine the relationship between adjacent buildings and the distance parameter in the context of solar exposure assessment. Furthermore, the chapter delves into a comprehensive examination of the performance exhibited by photovoltaic (PV) modules belonging to various PV types. The performance evaluation of each PV module is predicated on power generation and daylight performance, categorised according to two distinct PV module ratios. Lastly, this chapter encompasses an evaluation of the economic costs associated with the PV modules and conducts an analysis of their carbon dioxide (CO_2) emissions.

Chapter 5, this chapter concluding chapter encapsulates the principal discoveries and contributions emanating from this thesis. It also acknowledges the limitations encountered during this research endeavour and proffers recommendations for future investigations.

CHAPTER 2

LITERATURE REVIEW

2.1.Introduction

The growing worldwide energy demand and the urgent need for sustainable energy solutions have encouraged substantial research and development in renewable energy technology. Solar energy, a valuable and renewable resource, has great promise for tackling these energy challenges. With its favourable geographical location and high solar irradiation, Malaysia offers a unique potential to harness solar energy. This chapter conducts a thorough literature assessment on the many aspects of solar energy utilisation, particularly in Malaysia. It goes into sun radiation, energy consumption, climate issues, air conditioning systems, and the use of Building Integrated Photovoltaics (BIPV) in Malaysian settings.

The first section explores the history of solar radiance, energy consumption, climate conditions, air conditioning systems, and the integration of BIPV applications in Malaysia. Understanding these characteristics is critical for optimising solar energy utilisation and increasing the efficiency of building energy systems. The following section discusses Semi-Transparent Photovoltaics (STPV), a promising technology that combines energy generation with aesthetic and practical advantages. STPV systems are especially useful in urban areas where building design and natural lighting are essential challenges. Building integrated Photovoltaics (BIPV) are explored in the third section, emphasising their dual role as building materials and energy sources. Integrating photovoltaic systems into building constructions not only reduces energy consumption but also promotes sustainable architecture practices.

Finally, the literature review discusses the economic aspects of solar systems, focusing on Life Cycle Costing (LCC) and Feed-in Tariff (FIT) policies. These financial systems are crucial for determining profitability and encouraging the use of solar technologies. FIT policies have a significant impact on stimulating renewable energy investments and assuring long-term economic benefits. This comprehensive review summarises current information and suggests significant topics for future research, to assist Malaysian researchers in developing and implementing successful solar energy solutions.

2.2. Background of Solar Radiance, Energy Consumption, Climate, Air Conditioning Systems and BIPV Applications in Malaysia

Within Malaysia's dynamic energy environment, the radiant power of the sun emerges as an important factor (Shamri et al., 2022). Malaysia, located in the tropical zone, receives a steady supply of sunshine throughout the year. Its tropical location guarantees a consistent stream of solar radiation, making solar energy a viable and sustainable energy source for the country. According to Rababah, Ghazali, and Mohd Isa's (2021) analysis, Kuala Lumpur had a solar energy potential of approximately 1022 kWh/m2. This includes increasing the usage of renewable energy while decreasing reliance on traditional energy sources (Rababah, Ghazali, & Mohd Isa, 2021).

Malaysia's energy demand is influenced by a variety of factors, including population increase, manufacturing, and the constant need for cooling (Shamri et al., 2022). The use of air conditioning systems is responsible for a considerable amount of the country's energy consumption. Tuck et al. (2020), highlighted that both commercial and residential buildings together contribute to a considerable share of power usage, with cooling systems playing an important role (Tuck et al., 2020). The growing demand for air conditioning, particularly in urban areas and commercial buildings, challenges Malaysia's power supply and sustainability goals (Anang, Azman, Muda, Dagang, Daud, et al., 2021). The country's climate, which is characterised by high temperatures and constant humidity, increases its reliance on air conditioning, increasing energy consumption issues. Nonetheless, Malaysia's accessible solar radiation provides an excellent opportunity to harvest solar energy as a sustainable alternative (Mahlia, et al, 2011). In the effort to reduce its carbon footprint and advocate for renewable energy, the adaptation of solar power holds the possibility of reducing the energy demands for air conditioning systems, so indicating a more sustainable approach. (Buonocore et al, 2020; Yau & Pean, 2014; Z. Zhang, Zhang, & Khan, 2020).

Malaysia's current air conditioning systems need adaptation for energy efficiency and sustainability. These challenges are visibly compounded by Malaysia's hot and humid climate, coupled with the rising need for cooling (Hussin, Lim, Salleh, & Sopian, 2018). Building-integrated photovoltaic (BIPV) applications are considered key contributors to renewable energy generation and the reduction of reliance on traditional power sources (Rababah et al., 2021).

The significant energy usage of Malaysia's existing air conditioning systems is a major issue. Cooling systems had a significant share of power consumption in both residential and commercial buildings (Ahamed et al., 2016; Hussin, Chin Haw, & Salleh, 2019; Hussin et al., 2018). The high demand for cooling, combined using inefficient cooling technologies and poor maintenance methods, results in high energy use. Furthermore, relying on traditional air conditioning systems contributes to greenhouse gas emissions and damage to the environment (Hussin et al., 2019).

Concurrently, the integration of Building-Integrated Photovoltaic (BIPV) applications (K. Goh, Yap, Goh, Seow, & Toh, 2015; K. C. Goh, Goh, Yap, Masrom, & Mohamed, 2017). BIPV systems, with their latent potential for clean energy generation, while functioning as useful building components, appeal as an innovative technology (N. M. Kumar, Samykano, & Karthick, 2021; Shukla, Sudhakar, Baredar, & Mamat, 2017). However, implementing it into buildings requires comprehensive design considerations, structural compatibility assessments, and upfront capital investments. (Ghazal et al, 2017). These factors, considered together, could limit the adoption of BIPV applications. Furthermore, the lack of understanding of BIPV among stakeholders, including architects, developers, and policymakers, is assumed to be a strong barrier to its adoption in Malaysia (Rababah et al., 2021). This urgently required educational efforts and promotional campaigns to increase understanding and highlight the many benefits of BIPV systems in terms of energy efficiency, carbon reduction, and long-term cost-effectiveness (Rababah et al., 2021).

Efforts are now continuing to address the challenges by introducing a new era of energy efficiency as well as extensive integration of BIPV technology in Malaysia. Governmental initiatives, such as energy efficiency labelling programs and building codes, have been established for the adoption of energy-efficient cooling systems (Rababah et al., 2021). Simultaneously, research and development efforts in BIPV technology, together with awareness initiatives, have the potential to accelerate the adoption of BIPV applications (Figure 2.1) (Płaczek-Popko, 2017). The existing air conditioning conundrum in Malaysia, characterised by energy consumption and negative environmental impacts, interacts with the BIPV adoption, characterised by design challenges, costs, and informational limitations (Debbarma, Sudhakar, & Baredar, 2017; Ghazali et al., 2017; Rababah et al., 2021).

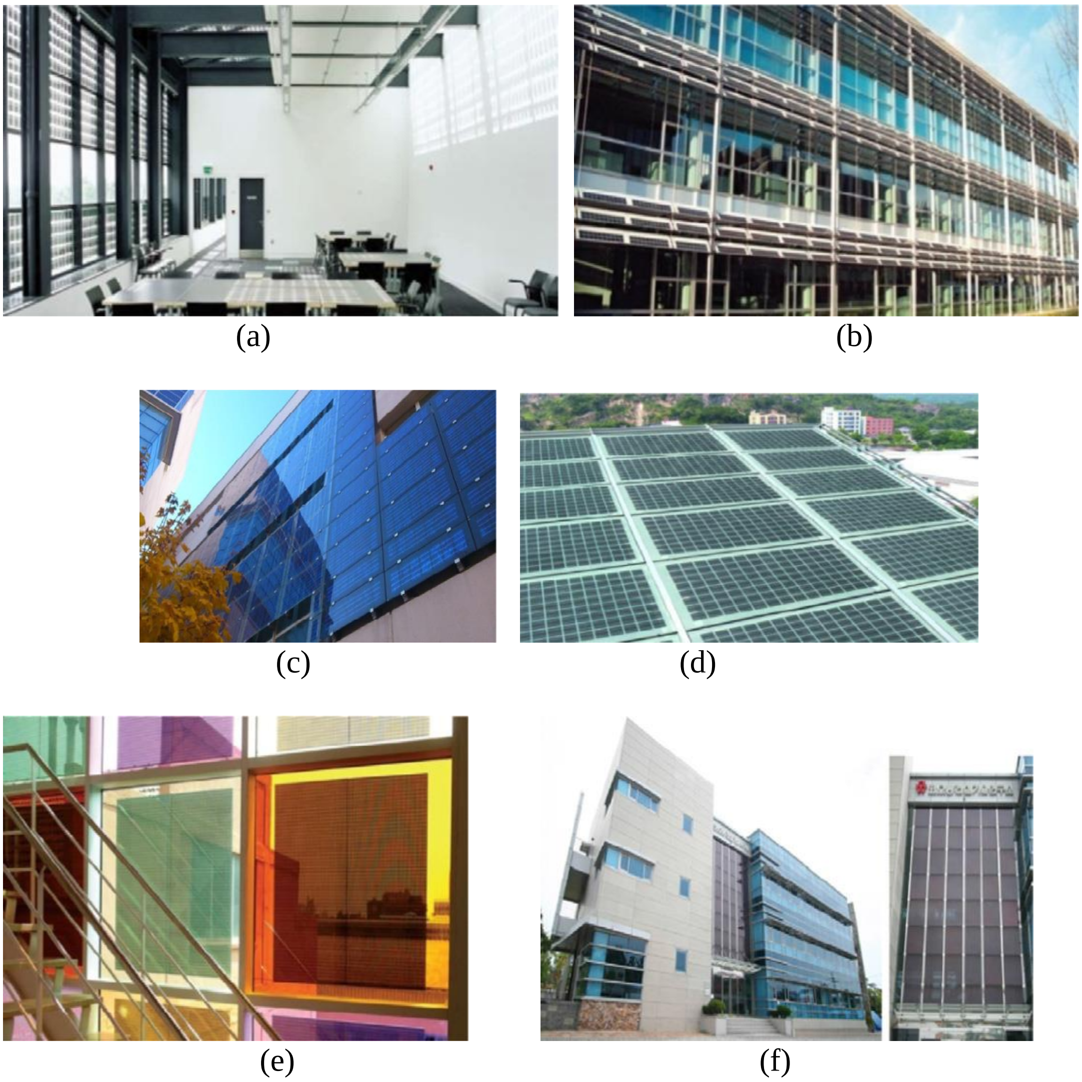

Figure 2.1. Examples of Building Integrated Photovoltaics (BIPV) Applications, (a) BIPV Skylight, (b) Shading Systems, (c) BIPV Solar Façade, (d) BIPV In-Roof Systems, (e) Semi Transparent Facades, and (f) Installation of BIPV system using transparent amorphous silicon thin film PV (Debbarma et al., 2017).

2.3. Semi-Transparent Photovoltaics (STPV)

Solar photovoltaic (PV) cells are frequently divided into three generations. The first generation includes "traditional" PV cells, which are produced from wafers of either single, steady silicon crystals (monocrystalline silicon cells) or many silicon crystals with separate grain boundaries (polycrystalline cells) (A. Kumar, Gawre, Sarkar, & Gosula, 2018). The second generation of PV cells, which are less expensive due to thin film technology, is slightly less efficient than the previous generation, necessitating greater surface area to generate the same amount of energy (Kumar et al., 2018). The third generation of PV cells uses organic components like small particles and polymers. This new generation of solar cells is being made from several unique materials other than silicon, such as nanotubes, silicon wires, solar inks produced using traditional printing press technology, organic dyes, and conductive polymers (Tak, al., 2017).

STPV integration with building facades reduces energy consumption by changing and has a significant impact on light transmission through the building's façade. as PVs replace an element of the building that is integrated into the building (Sun & Jasieniak, 2017). Numerous design solutions have evolved throughout the years in response to research on the integration of PV modules into a building's façade, to boost solar receptivity (Radhi, 2010).

The use of semi-transparent photovoltaic (STPV) systems in buildings has been found to greatly improve energy efficiency. Musameh, Alrashidi, Al-Neami, and Issa (2022) proved that STPV glazing systems can generate a net energy savings of 67% in façade buildings when the window-to-wall ratio (WWR) is 100% and the STPV glazing system is around 40%. This research emphasises the ability of STPV systems to substantially reduce energy usage in buildings. Similarly, Barman et al. (2018) achieved a maximum energy savings of 60.4% using the most efficient STPV module. These considerable savings are especially important for high-rise buildings, which can use STPV technology to achieve low or net-zero energy consumption. Overall, these studies show the significant energy-saving potential of STPV systems, making them a viable option for sustainable building design (Gerthoffer et al., 2017).

Moreover, Daylight performance is an important consideration in the integration of STPV systems since it directly affects occupant comfort and lighting energy consumption. Liu, Sun, Wilson, and Wu (2020) found that PV windows with higher transparency, notably 40% and 50%, achieve better lighting uniformity. This shows that increased transparency in STPV systems might successfully improve daylight in buildings, decreasing the demand for artificial lighting and so adding to the reduction of energy consumption. Kapsis, Dermardiros, and Athienitis (2015) found that STPV modules with 30% visible effective transmittance when integrated as the outer glass layer of a double-glazed low-e window, give sufficient daylight throughout the year for external office façades. This data demonstrates that the ideal transparency level for daytime performance may differ depending on specific building requirements and design considerations (Kang et al., 2015).

The thermal performance of STPV systems is another important factor that influences their overall energy efficiency (Fung & Yang, 2008). Peng, Lu, Yang, and Ma (2015) highlighted the importance of the solar heat gain coefficient (SHGC) and the U-value in assessing the energy performance of photovoltaic double-skin façades (PV-DSFs). Their research provided an ideal operation approach based on thermal performance to maximise energy efficiency, emphasising the importance of thermal characteristics in STPV system design. Wang et al. (2017) conducted an experimental study on the thermal performance of STPV windows in Hong Kong during the winter and discovered that the STPV may reach temperatures of up to 50°C under strong sun irradiation. This suggests the possibility of large thermal benefits, which could cut heating requirements during the winter. These studies illustrate that optimizing thermal performance is essential for enhancing the overall efficiency of STPV systems.

STPV systems' effectiveness is determined by a variety of elements, including glazing system type, façade orientation, and ventilation. Kapsis and Athienitis (2015) evaluated the impact of these parameters and discovered that, while façade orientation, WWR, and electrical lighting power density influence building end-use energy consumption, they have no significant effect on the selection of optimal STPV optical qualities. This conclusion implies that other factors, such as the type of glazing system, may play a larger impact. For example, Musameh et al. (2022) found that using clear double-glazing systems and Barman et al. (2018) found that low-e glass improved the overall performance of STPV systems. Additionally, Peng et al. (2015) emphasised the significance of an inward-openable clear glass window with a 400 mm airflow cavity for optimising thermal performance. These insights underscore the need for a holistic approach in integrating STPV systems, considering various design and operational factors to maximise their benefits.

Furthermore, the integration of STPV systems into buildings provides considerable benefits in terms of energy efficiency, daylight performance, and thermal performance. Studies regularly demonstrate significant energy savings, with appropriate transparency levels improving both daylight and thermal performance. The effectiveness of STPV systems is also influenced by the type of glazing system and other design elements, necessitating an exhaustive implementation approach. Continued research is required to improve these systems, investigate their long-term effects, and develop integration solutions for a variety of building types and climates. STPV technology has enormous potential for improving sustainable building design and producing massive energy savings.

Table 2.1. Summary of different studies regarding STPV

Author	PV Transparent Ratio (%)	Area of Focusing	Type of Glazing system	Glazing U- Value (W/m²K)
(Liu, Sun, Wilson, & Wu, 2020)	20%, 30%, 40%, 50%.	Window-integrated semi-transparent PV for building daylight performance	clear double-glazing systems and Low e glass.	1.812
(Musameh, Alrashidi, Al-Neami, & Issa, 2022)	10%, 20%, 30%, 40%.	Energy performance analytical review of semi-transparent photovoltaics glazing in the United Kingdom	Clear double-glazing systems	2.783, 1.812
(Barman, Chowdhury, Mathur, Mathur, & Society, 2018)	7%, 12.3%, 17.7%, 25.2%, 32.7%	The efficiency of window integrated based semi-transparent photovoltaic module	Low e glass	1.812
(Kapsis & Athienitis, 2015)	10%, 20%, 30%, 40%, 50%.	The potential benefits of semi-transparent photovoltaics in commercial buildings	Insulated double-Glazed Window Unit	0.301
(Peng, Lu, Yang, & Ma, 2015)	10%, 20%, 30%, 40%.	The thermal and power performances of a semi-transparent photovoltaic façade under different ventilation modes.	Inward-openable clear glass window and a 400 mm depth airflow cavity	In this paper's findings the U-value whereas follows 3.4, 3.8 and 4.6
(K. Kapsis, V. Dermardiros, & A. J. E. P. Athienitis, 2015)	10%, 20%, 30%, 40%, 50%.	Daylight performance of perimeter office façades utilizing semi-transparent	Low e coated glass	0.184

		photovoltaic windows.		
(Olivieri et al., 2014)	10%, 20%, 30%, 40%.	Energy saving potential of semi-transparent photovoltaic	Not mentioned	2.783
(M. Wang, Peng, Li, Lu, & Yang, 2017)	Not mentioned	Experimental study on thermal performance of semi-transparent PV window in winter in Hong Kong	Tempered glass	5.58

2.3.1. The substantial's of Semi-Transparent Photovoltaics (STPV)

The solar resource is the most widely distributed energy resource in the world, and photovoltaics are leading the integration of solar-based technology into buildings. Building-integrated photovoltaic (BIPV) systems not only allow for on-site sustainable energy generation but have also been shown to contribute to significant reductions in energy consumption (Romaní, Ramos, & Salom, 2022). PV systems were introduced to the Malaysian market in six prototype projects in the 1990s (San Ong & Thum, 2013). These prototypes use about 1500 kW/h each month. Furthermore, the lack of a feed-in tariff that ensures an acceptable payback time and initial capital cost of PV was a major challenge. As a result, the Malaysian government began to encourage the usage of PV systems and launched BIPV applications to demonstrate grid-connected rooftop PV systems to the general population. This grid-connected solar PV project, known as SURIA 1000, is still in the works and will eventually become a nationwide BIPV scheme (San Ong, & Thum, 2013).

Photovoltaic (PV) is the most developed and rapidly increasing solar energy conversion technology worldwide (Gorjian et al., 2022). In recent years, pioneering