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Sustainable Urban Energy Solutions: Investigating the Solar Potential of Vertical Façades Amidst Adjacent Buildings in Kuala Lumpur, Malaysia

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ABSTRACT

This article explores the impact of adjacent buildings on solar exposure for photovoltaic (PV) applications in high-rise urban areas in Malaysia. The rapid urbanization and population density in Malaysia's high-rise areas have increased energy demand, necessitating the exploration of alternative energy sources. Integrating PV systems into vertical façades offers a promising solution for maximizing energy generation in space-constrained urban environments. However, the efficacy of PV systems is influenced by adjacent buildings, including their arrangement, height, and orientation, which affect solar exposure and energy generation potential. Understanding these effects is crucial for optimizing PV system design and placement. This study aims to investigate the relationship between adjacent buildings and solar exposure for PV panels mounted on high-rise buildings in Malaysia. By examining these effects, the research provides valuable insights for urban planners, architects, and renewable energy practitioners involved in sustainable urban development. The findings will inform decisions regarding the integration of PV systems, promoting renewable energy adoption, and reducing the environmental impact of urban areas. The article also discusses Malaysia's climate, energy consumption, and solar radiation potential, emphasizing the need to harness solar energy in a country blessed with abundant sunlight. The challenges faced by current air conditioning systems and building-integrated photovoltaic (BIPV) applications in Malaysia are outlined, along with efforts to address them through energy-efficient systems and awareness campaigns. The research conducted simulations using a 3D model in Kuala Lumpur, Malaysia, considering different heights and distances of adjacent buildings. The software used for simulations was IES-VE, which offers various modules for energy consumption analysis. The results demonstrate how adjacent buildings affect the annual average energy for different scenarios, highlighting the importance of distance and height. The findings provide insights into the monthly average energy variations and emphasize the relationship between adjacent building height and average energy levels. Overall, this research contributes to the efficient utilization of vertical façades for harnessing solar energy in high-rise urban areas, supporting Malaysia's sustainable energy goals while ensuring urban environment liveability and resilience.

Keywords:
Solar exposure; solar energy; BIPV; sustainable solutions

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1. Introduction

The rapid urbanization and increasing population density in Malaysia's high-rise urban areas have led to a surge in energy demand. To address this challenge and reduce reliance on traditional energy sources, there is a growing interest in harnessing solar energy through photovoltaic (PV) applications [1,2]. Among the various architectural possibilities, integrating PV systems into vertical façades presents a promising solution for maximizing energy generation in space-constrained urban environments [3]. However, the efficacy of PV systems in high-rise urban areas is significantly influenced by several factors, with adjacent buildings playing a crucial role [4]. The arrangement, height, and orientation of neighbouring structures can significantly impact the solar exposure received by PV panels, ultimately affecting their energy generation potential. Understanding these effects is vital for optimizing the design and placement of PV systems, ensuring their optimal performance and viability as a sustainable energy solution [5].

In the context of Malaysia, a country blessed with abundant solar radiation, it becomes imperative to explore the relationship between adjacent buildings and solar exposure for PV applications in vertical façades [6]. Given the tropical climate and the increasing emphasis on energy efficiency, this study aims to investigate how the surrounding built environment influences the solar exposure of PV panels mounted on high-rise buildings in urban areas. By examining the effects of adjacent buildings on solar exposure, this research endeavours to provide valuable insights to urban planners, architects, and renewable energy practitioners involved in sustainable urban development [5]. Understanding the complex interplay between building layouts and solar exposure will enable informed decisions regarding the integration of PV systems, promoting the adoption of renewable energy and reducing the environmental impact of urban areas. This article delves into the significance of assessing adjacent buildings' impact on solar exposure for PV applications in high-rise urban areas, specifically in the Malaysian context. By shedding light on this crucial aspect, we can pave the way for the efficient utilization of vertical façades as a viable platform for harnessing solar energy, advancing the nation's sustainable energy goals while ensuring the liveability and resilience of urban environments.

1.1 Malaysia's Climate, Energy Consumption, and Solar Radiation

Solar radiation plays a crucial role in Malaysia's energy consumption and sustainability efforts. As a tropical country, Malaysia receives abundant sunlight throughout the year. The country's geographical location near the equator ensures a consistent solar radiation supply, making solar energy a viable and renewable resource for power generation [7,8]. According to Rababah *et al.,* [9], Malaysia's solar energy potential is estimated to be around 1022 kWh/m^2 in Kuala Lumpur This availability of solar radiation provides a significant opportunity to harness solar energy and reduce dependence on traditional energy sources. Energy consumption in Malaysia is driven by various factors, including population growth, industrialization, and the need for cooling in hot and humid climates. The extensive use of air conditioning systems contributes significantly to the country's energy demand. According to Tuck *et al.,* [2], residential and commercial sectors account for a substantial portion of electricity consumption, with cooling systems representing a significant share. The increasing demand for air conditioning, especially in urban areas and commercial buildings, poses a challenge to the country's energy infrastructure and sustainability goals [1]. Furthermore, Malaysia's equatorial climate with high temperatures and humidity necessitates the extensive use of air conditioning systems, contributing to increased energy consumption [10]. However, Malaysia's abundant solar radiation offers a promising opportunity to harness solar energy as a sustainable alternative [11]. As the country focuses on reducing its carbon footprint and promoting renewable energy, the adoption of solar power can help mitigate the energy demands associated with air conditioning systems, leading to a more sustainable future [11-13].

According to Asia-Pacific Economic Cooperation (APEC) [14], Malaysia is classified as an upper-middle-income economy characterized by a diversified range of economic activities, and it is anticipated to complete its transition into a high-income economy by the year 2024. As of 2020, the composition of the nation's Gross Domestic Product (GDP) is dominated by the services sector, which contributes nearly 59%, followed by manufacturing at 22%, mining and quarrying at 7%, agriculture at 7%, and construction at 5%. Notably, the energy sector has emerged as the pivotal driver of most economic endeavours within the Malaysian context. Over the past two decades, both total energy demand and supply within Malaysia have undergone substantial escalation, a trend predominantly attributed to the robust annual Gross Domestic Product growth rate of 5.4% since the year 2000. Concurrently, the generation of electricity has exhibited a slightly higher annual increase of nearly 5.6% spanning the years from 2000 to 2018. Malaysia is endowed with a significant repository of diverse energy resources, encompassing conventional sources such as oil, gas, and coal, alongside renewable alternatives. Geographically, approximately two-thirds of these energy reserves are situated in East Malaysia, with the remainder located in Peninsular Malaysia. Furthermore, the assessment of energy reserves as of the year 2020 reveals an estimated total of 32,696 petajoules (PJ) for gas and 16,713 PJ for oil. At the current rates of consumption, both gas and oil reserves are projected to be depleted within 12 and 13 years, respectively, a projection substantiated by the prevailing reserve-to-production (R/P) ratio.

Energy policies in Malaysia are formulated and disseminated through the collaborative efforts of various entities, including governmental ministries, regulatory bodies, and industry stakeholders. These policies, which encompass a series of strategic frameworks, have played a pivotal role in guiding the nation's energy planning and decision-making processes. Notable among these policies are the National Petroleum Policy of 1975, the National Energy Policy of 1979, the National Depletion Policy of 1980, the Four-Fuel Diversification Policy of 1981, the Five-Fuel Diversification Policy of 2000, the National Policy on the Environment of 2002, the National Biofuel Policy of 2006, the National Green Technology Policy of 2009, the National Policy on Climate Change of 2010, the National Renewable Energy Policy and Action Plan of 2010, the New Energy Policy of 2010, the National Energy Efficiency Action Plan spanning 2016 to 2025, the Green Technology Master Plan spanning 2017 to 2030, and the Nationally Determined Contribution articulated in 2019 [14].

In the year 2018, the energy consumption attributed to buildings constituted an approximate share of 13% in Malaysia's total energy demand, a proportion projected to ascend to around 19% by the year 2050. These escalating figures are attributed to the concurrent elevation of macroeconomic indicators, notably the expansion of population and Gross Domestic Product (GDP), which collectively propel energy requisites upwards across both temporal scenarios. Within the domain of building energy consumption, notable augmentations manifest because of several specific measures and initiatives. These encompass the implementation of the Efficient Management of Electrical Energy Regulations in 2008, the enforcement of Minimum Energy Performance Standards (MEPS), the execution of the Green Technology Master Plan spanning 2017 to 2030, advancements in technologies pertaining to heating systems resulting in a discernible 0.5% enhancement in energy efficiency by the year 2030 (as referenced), and the imposition of energy efficiency measures that restrain demand expansion to less than a twofold increase within the framework of the Carbon Neutrality context. A preeminent driver underpinning the energy demand attributed to buildings in Malaysia is electricity, predominantly harnessed for space cooling purposes. The climatic conditions within the nation are characterized by persistently warm and humid weather conditions throughout the year, with mean daily temperatures ranging between 24 to 33 degrees Celsius, as documented in 2019. Notably, the dominion of electricity as the primary energy source for buildings endures across the projection horizon, with its prevalence poised to rise from an 84% share in 2018 to 86% in 2050, as per the Reference (REF) scenario, and to a more pronounced 93% within the Carbon Neutrality (CN) scenario [14].

In the context of the CN scenario Figure 1, an instrumental strategy in achieving a reduction of a quarter in buildings' energy demand, relative to the REF trajectory, rests upon the facilitation of enhanced distribution and adoption of more energy-efficient electrical appliances. A commensurate imperative is the advancement of a more rigorous building code to foster the construction of edifices characterized by superior energy performance. Such endeavours transcend the purview of the National Energy Efficiency Action Plan spanning 2016 to 2025, embodying a more comprehensive strategy in the pursuit of energy demand mitigation within the building sector [14].

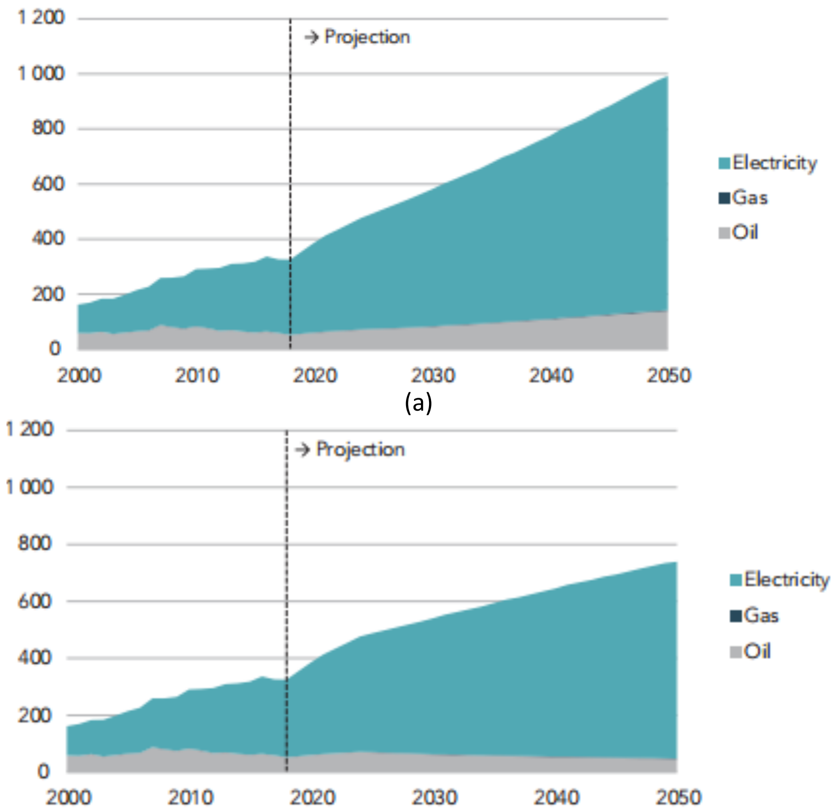


Fig. 1. (a) Buildings energy demand in REF, 2000-2050 (PJ), (b) Buildings energy demand in CN, 2000-2050 (PJ) [12]

1.2 Challenges that Face the Current Air Conditioning Systems and BIPV Applications in Malaysia

The current air conditioning systems in Malaysia face several issues that impact energy efficiency and sustainability. These issues are often exacerbated by the country's hot and humid climate and the increasing demand for cooling [15]. Meanwhile, building-integrated photovoltaic (BIPV) applications, which have the potential to contribute to renewable energy generation and reduce reliance on traditional power sources, also face challenges in their widespread adoption. One of the key issues with current air conditioning systems in Malaysia is their high energy consumption. Air conditioners account for a significant portion of electricity usage in both residential and commercial buildings [15-17]. The high demand for cooling, coupled with inefficient cooling systems and improper maintenance, leads to excessive energy consumption, and increases the strain on the power grid. Additionally, the use of conventional air conditioning systems contributes to greenhouse gas emissions and environmental degradation. Many air conditioners in Malaysia rely on fossil fuel-based electricity, which contributes to carbon emissions and exacerbates climate change [17]. This reliance on non-renewable energy sources hinders efforts to achieve sustainability and reduce the carbon footprint of the built environment.

In parallel, the adoption of building-integrated photovoltaic (BIPV) applications, which combine solar power generation with building elements, faces challenges in Malaysia [18,19]. BIPV systems have the potential to generate clean energy while serving as functional building components [20,21]. However, the integration of BIPV technologies into buildings requires careful design considerations, structural compatibility, and higher upfront costs [6]. These factors can hinder the widespread implementation of BIPV applications. Furthermore, the lack of awareness and limited knowledge about BIPV among stakeholders, including architects, developers, and policymakers, poses a significant challenge to its adoption in Malaysia [9]. There is a need for educational and promotional efforts to enhance understanding and highlight the benefits of BIPV systems in terms of energy savings, carbon reduction, and long-term cost-effectiveness.

To address these issues, efforts are being made to promote energy-efficient air conditioning systems and encourage the integration of BIPV technologies in Malaysia. The government has implemented various initiatives, such as energy efficiency labelling programs and building codes, to encourage the use of energy-efficient cooling systems [9]. Additionally, research and development in BIPV technologies, along with awareness campaigns and capacity building, are essential to drive the adoption of BIPV applications, the current air conditioning systems in Malaysia face challenges related to energy consumption and environmental impact, while the adoption of BIPV applications is hindered by design considerations, cost factors, and limited awareness. However, with supportive policies, increased awareness, and technological advancements, it is possible to improve the energy efficiency of air conditioning systems and promote the wider integration of BIPV in Malaysia's built environment.

Happle's *et al.,* [22] study underscores that investigations into urban solar dynamics should encompass not only the interplay between urban configuration and climatic factors but also incorporate the localized context of grid electricity composition. Our findings substantiate that the integration of Building-Integrated Photovoltaics (BIPV) holds the potential to effectuate a reduction in carbon emissions within Southeast Asian urban locales, with anticipated reductions spanning approximately 15% to 50%. For optimal outcomes, maximal utilization of solar energy generation necessitates the activation of the complete rooftop area and an approximate range of 40% to 100% of the building facades. Crucially, our study establishes that the efficacy of BIPV implementation transcends climatic and urban morphology considerations, as it emerges as particularly potent within nations characterized by high carbon-intensive grid electricity matrices. This assertion is consistent regardless of prevailing climatic conditions and urban layout [22]. Furthermore, our methodology offers a means to glean insights concerning the interface between urban design attributes and solar energy potential, furthering the cause of carbon emission reduction. It is advisable that forthcoming inquiries within the realm of energy economics embrace a comprehensive approach that integrates the local cost framework of electricity tariffs and BIPV installation expenses. Moreover, a holistic appraisal should extend to encompass both localized and global life cycle impacts, encompassing facets such as embodied energy, resource depletion, and ecotoxicity.

Zainuddin *et al.,* [23] conducted an evaluation of the roadmap initiatives implemented by the Government of Malaysia (GoM) with the aim of elucidating the pivotal contributions in advancing the solar photovoltaic (PV) sector, tracing its evolution from its initial pilot projects in the 1980s to the present day. Malaysia stands poised to excel in harnessing solar energy, owing to its geographical positioning that ensures consistent and elevated solar irradiation levels throughout the year, characterized by only marginal monthly fluctuations. The imperatives of environmental considerations and economic motivations should serve as primary impetuses driving the adoption of solar energy. By capitalizing on boundless solar resources, a diminution in reliance on finite and non-renewable energy sources, notably fossil fuels, can be achieved, concurrently yielding lucrative returns for investors. The GoM has demonstrated a commendable commitment to refining incentive frameworks, perpetually addressing their shortcomings, and thereby optimizing the nation's capacity to tap into solar energy potential [23]. Ultimately, the potency of an initiative is determined by its capacity to offer maximal financial gains for investors. The trajectory of the solar PV roadmap in Malaysia is emblematic of successful solar PV advancement, underscoring the instrumental role undertaken by the GoM in sustaining the momentum of solar PV development, ultimately elevating the solar PV sector to a position of promise within Malaysia's energy landscape.

Arnaout and Ii [24] conducted an analysis of the performance attributes inherent to a proposed Building-Integrated Photovoltaic (BIPV) system intended for the Heriot-Watt University Malaysia building, with a strategic focus on harnessing the potential of the building's curved roof structure. In their study, an innovative simulation methodology was introduced to assess the solar energy capacity and compute the electrical energy yield across various configurations of the proposed system. This methodology was then applied to the curved roof segment of the Heriot-Watt University Malaysia Building situated in Putrajaya, Malaysia. The application of Time-of-Flight (TOF) analysis revealed that the roof segment, even at its highest tilt on the western side, exhibits noteworthy energy potential due to the distinctive radiation dynamics prevalent in tropical regions, wherein the diffuse solar radiation component assumes significance. A comprehensive comparative evaluation was performed among eight distinct configurations of the roof-integrated system, with a primary emphasis on energy considerations. The outcomes of the study divulged that the deployment of CdTe Thin film modules sourced from First Solar emerged as the most prolific energy producer, yielding an impressive energy output of 1240 MWh/year [24]. This corresponded to a substantial 53% reduction in the electricity expenditure. In contrast, the scenario characterized by flexible laminates modules, chosen for their aesthetic attributes, generated a comparatively modest energy output of 596 MWh/year. Evidently, the study underscores that while the employment of flexible thin film technology in BIPV applications holds merit, further advancements in efficiency are requisite to rival the performance of their non-flexible silicon counterparts, which presently exhibit superior energy generation capabilities.

2. Methodology

In the pursuit of sustainable urban development and efficient energy utilization, the integration of renewable energy sources has emerged as a compelling solution. Among these, harnessing solar energy through photovoltaic (PV) applications in high-rise buildings offers great promise in densely populated urban areas. As such, this research sets out to explore the crucial role of adjacent buildings in shaping solar exposure for PV applications in a high-rise urban context, focusing on Kuala Lumpur, Malaysia. To comprehend the intricate relationship between adjacent buildings and solar exposure, a conceptual 3D model of a high-rise building in Kuala Lumpur was simulated. The primary objective is to investigate how adjacent buildings impact the solar exposure experienced by PV systems mounted on the main building's vertical façade. Two key parameters were identified to delve into this relationship: the height of the adjacent buildings and the distance between them and the main building. Figure 2 shows the flowchart for this research.

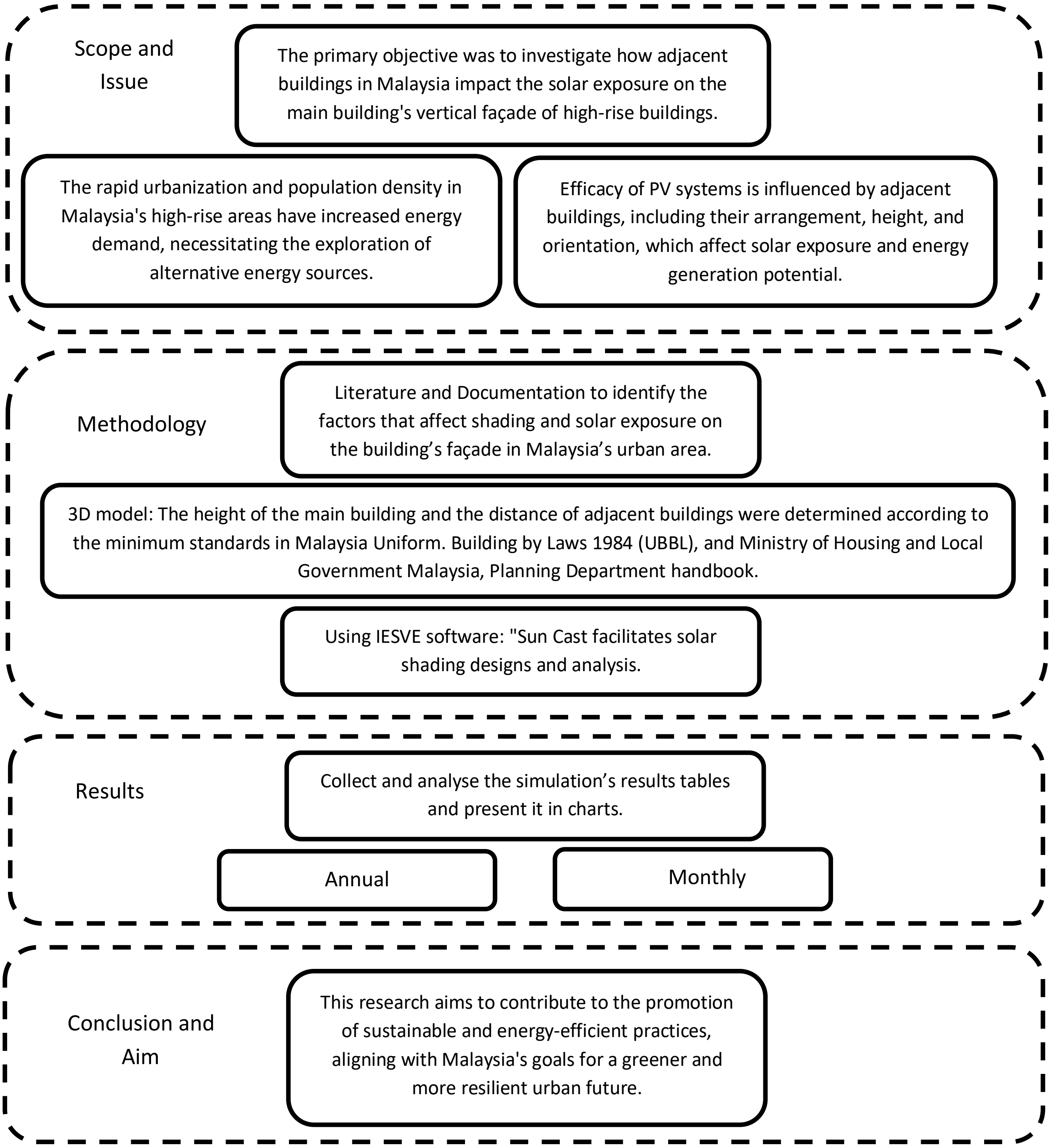


Fig. 2. Research Flowchart

To ensure the model's accuracy and relevance, the height of the main building and the minimum distance from adjacent buildings were aligned with Malaysia's Uniform Building by Laws 1984 (UBBL) and the Ministry of Housing and Local Government's Planning Department handbook. The conceptual 3D model depicted a main building towering at 61 meters (equivalent to 20 stories), with a minimum distance of 30 meters between it and the surrounding adjacent buildings. In a comprehensive effort to evaluate various scenarios, the research proposed multiple combinations of adjacent building heights and distances. The scenarios were meticulously laid out, ranging from 5 to 30 stories in height and distances from 30 to 50 meters from the main building. Figure 3 and Table 1 presented an overview of the diverse scenarios, forming the basis for conducting simulations and analyses. This research endeavour seeks to shed light on the complex dynamics between adjacent buildings and solar exposure for PV applications in high-rise urban environments. The insights gained from this investigation hold the potential to inform urban planners, architects, and renewable energy practitioners in optimizing the design and placement of PV systems. Ultimately, this research aims to contribute to the promotion of sustainable and energy-efficient practices, aligning with Malaysia's goals for a greener and more resilient urban future.

Fig. 3. Different scenarios of adjacent building heights and distances

Table 1
The proposed scenarios for the height and distance of the adjacent buildings

Distance between Main Building and Adjacent Buildings	Scenario 1 (UBBL – 30m)	Scenario 2 (35m)	Scenario 3 (40m)	Scenario4 (45m)	Scenario 5 (50m)
Adjacent Buildings Stories	5	5	5	5	5
	10	10	10	10	10
	15	15	15	15	15
	20	20	20	20	20
	25	25	25	25	25
	30	30	30	30	30

2.1 Model's Parameters

This research was conducted by simulating a conceptual 3D model for a high rise building in Kuala Lumpur, Malaysia, to identify how adjacent buildings affect the solar exposure on our 3D model. This research focuses on how adjacent buildings affect the solar exposure on the main building, therefore, the authors identified two main parameters which are the height of the adjacent buildings and the distance between the adjacent buildings and the main building. The height of the main building and the distance of adjacent buildings were determined according to the minimum standards in Malaysia Uniform Building by Laws 1984 (UBBL), and Ministry of Housing and Local Government Malaysia, Planning Department handbook (Kementerian Perumahan dan Kerajaan 'Tempatan Malaysia, Jabatan Perancangan Bandar Dan Desa, Semenanjung Malaysia). According to the mentioned the height of the main building in the 3D model was 61m (20 stories) and the minimum distance between the main building and adjacent buildings was 30m.

2.2 Software (IESve) and Parameters

IES-VE, which stands for Integrated Environmental Solutions-Virtual Environment, is a software utilized for virtual energy consumption simulations. It encompasses a collection of interconnected applications presented through a Common User Interface (CUI). This integration allows for seamless data transfer among the applications due to the presence of a centralized Integrated Data Model (IDM). Within IES-VE, several modules are available, each addressing different aspects of building energy consumption [25,26].

For instance, "SunCast" facilitates solar shading designs and analysis, "Radiance" enables lighting simulation, "ApacheSim" focuses on thermal simulation, and "ModelIT" assists in importing 3D building geometry from CAD programs. The user interface of the IES-VE application is depicted in the accompanying image. Furthermore, IES-VE offers a range of toolkits that enhance its capabilities. These include climate metrics and climate index, which enable the analysis of climate data specific to the building's location. The results are presented through informative graphical outputs that illustrate the impact of climate on energy consumption [27]. These analysed climate data outputs are then combined with additional inputs to optimize the utilization of natural resources like wind, sunlight, and water in the building's design. In addition, the "low/zero carbon technologies analysis" toolkit empowers users to identify and incorporate modules related to renewables, low-carbon solutions, and green power. This toolkit allows users to assess the potential benefits of these technologies in terms of energy and carbon reductions. For instance, Figure 8 showcases a table extracted from the primary panel of IES-VE, illustrating the annual "site energy," "source energy," and "CO_2 emissions" per unit area for each zone within a typical residential building model [25].

The key features of the IES-VE application encompass:

(i) The schematic geometry wizard, which offers a simplified approach to building geometry and design parameters.
(ii) The solar algorithm, which facilitates the tracking of the sun's path across contiguous and non-contiguous zones within the building.
(iii) The HVAC systems wizard, which streamlines the configuration of HVAC systems in a user-friendly manner, is typically achieved in five straightforward steps or fewer.

IES-VE Sun Cast equations according to the software official website

(i) Solar Energy Analysis:
 (a) Summate the hourly solar flux values.

$$\sum(W/m^2) => Wh\ /\ m^2 \tag{1}$$

 (b) Convert the value to kWh/m².

$$Wh/m^2 \div 1000 \tag{2}$$

 (c) Optionally then convert the value to kWh.

$$kWh/m^2 \times Area \tag{3}$$

(ii) Solar Exposure Analysis:
 (a) Summate the hourly percentage area values.

$$\sum(\%\ Area) => Hours \quad (4)$$

(b) Optionally then convert the value to % available.

$$(Hours\ \div Avialabil\ Hours) \times 100 \quad (5)$$

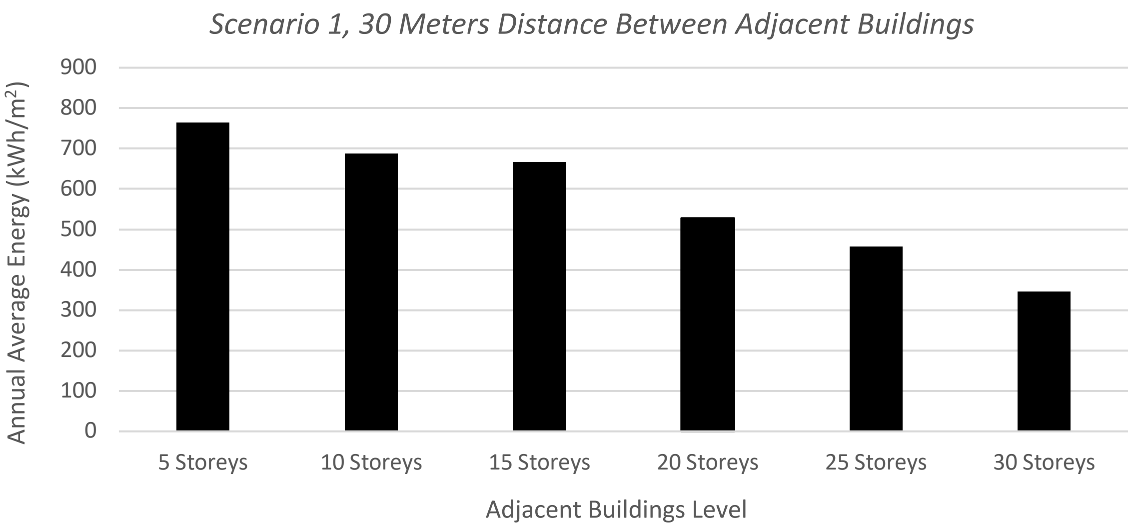
3. Results

This research performed a total of 30 simulation tests for all the proposed scenarios in IESve using the sun cast tool that provided by the software, which helped in having a better understanding of how adjacent buildings play a major role in determining the potential of using BIPV in vertical façade of high-rise buildings in Malaysia.

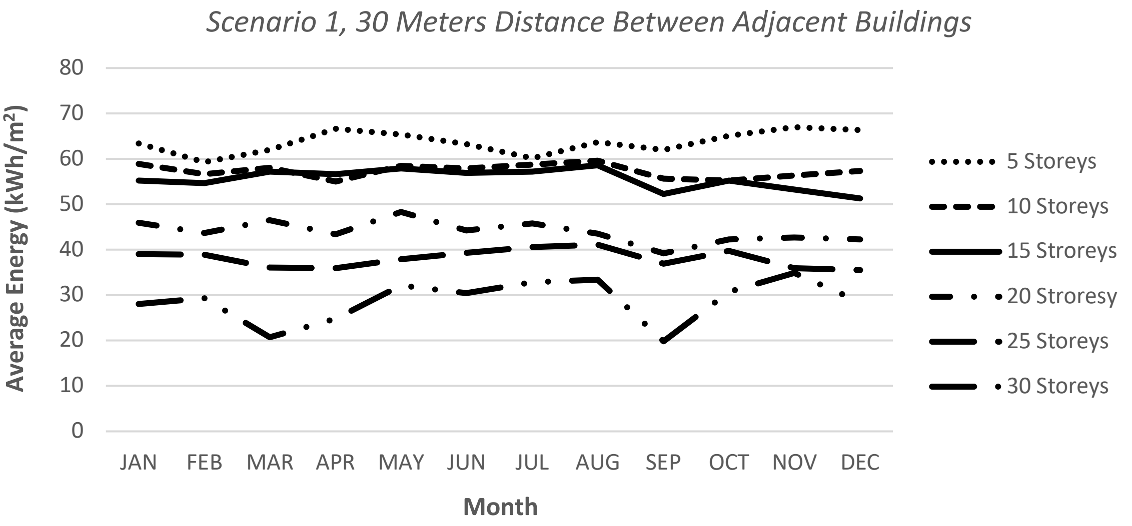
3.1 Scenario 1, 30 Meters Distance between Adjacent Buildings

The research entails a comprehensive investigation and comparative analysis conducted through simulations. The obtained results are visually depicted in Figure 4 to Figure 8, highlighting the variations in average energy patterns resulting from alterations in the distances between adjacent buildings. Furthermore, it is crucial to acknowledge the influential role played by the height of these adjacent buildings in shaping the observed patterns.

Figure 4(a) presents the annual average energy (kWh/m^2) for the six cases regarding the hights of the adjacent building, which is obvious from Figure 4(a) the amount of average energy is decreasing when moving to the higher floors and that can be seen in Table 2. Moreover, Figure 4(b) exemplifies this relationship, where the average energy attains its peak when the adjacent buildings consist of 5 stories. During this configuration, the average energy range fluctuates between 59.28 kWh/m² in February and 66.98 kWh/m² in November. Conversely, increasing the height of the adjacent buildings leads to a subsequent decrease in the average energy levels. For instance, when these structures comprise 15 stories, the average energy range spans from 51.29 kWh/m² in December to 58.59 kWh/m² in August. Similarly, when the adjacent buildings reach a height of 30 stories, a noticeable gap emerges within the range of average energy. Specifically, the lowest point is recorded at 19.83 kWh/m² in September, while the highest point reaches 33.42 kWh/m² in August.



(a)

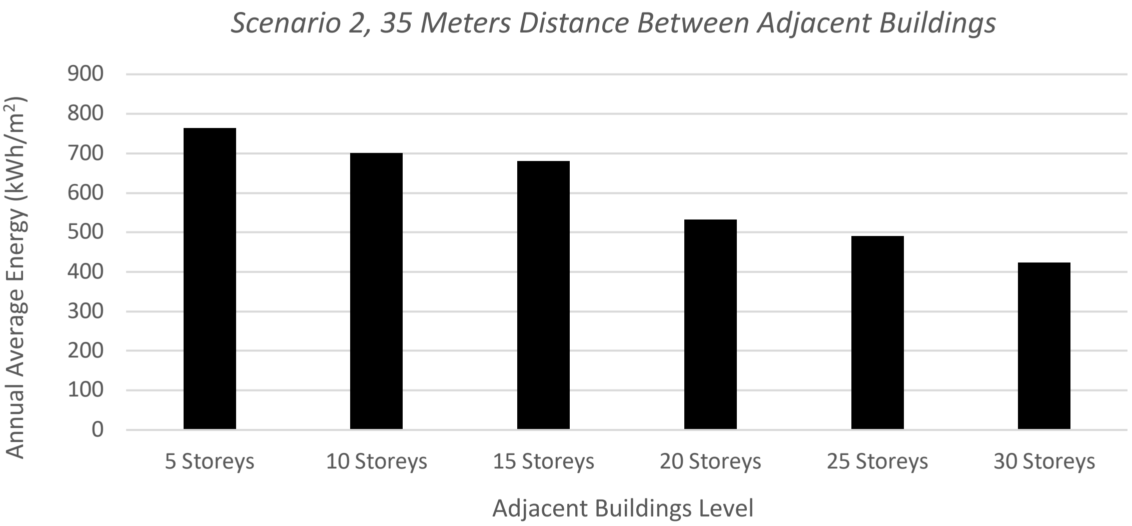


(b)

Fig. 4. (a) The annual average energy (kWh/m^2) for scenario 1, (b) the monthly average energy for scenario 1

3.2 Scenario 2, 35 Meters Distance between Adjacent Buildings

Figure 5(a) shows the annual Average Energy (kWh/m^2) for the scenario when the distance is 35m between the adjacent buildings, and from the chart, it's obvious that when the level of the building is increasing the annual energy is decreasing, Meanwhile, Figure 5(b) illustrates a distinct pattern, wherein the average energy readings exhibit minimal disparities between adjacent buildings standing at 10 and 15 stories. In the case of 10-story structures, the average energy range spans from 54.65 kWh/m² in September to 63.9 kWh/m² in May. Similarly, for adjacent buildings of 15 stories, the average energy range fluctuates between 52.26 kWh/m² in September and 62.4 kWh/m² in June. Interestingly, when the adjacent buildings consist of 5 stories, the energy readings remain consistent across the months. Furthermore, when the adjacent buildings reach heights of 20 and 25 stories, they demonstrate virtually identical energy readings in October, registering at 47.3 kWh/m² and 46.66 kWh/m² respectively.



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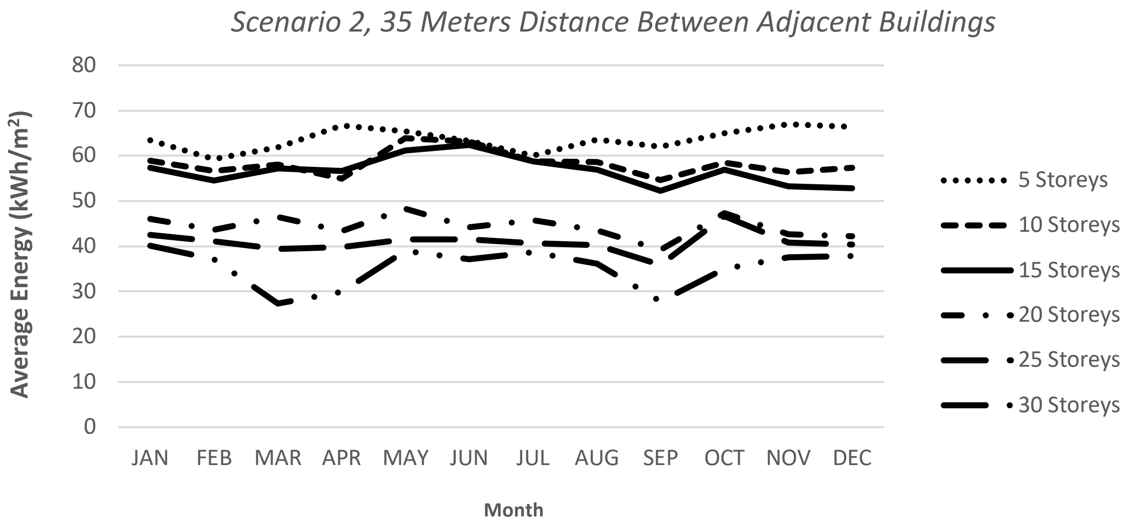


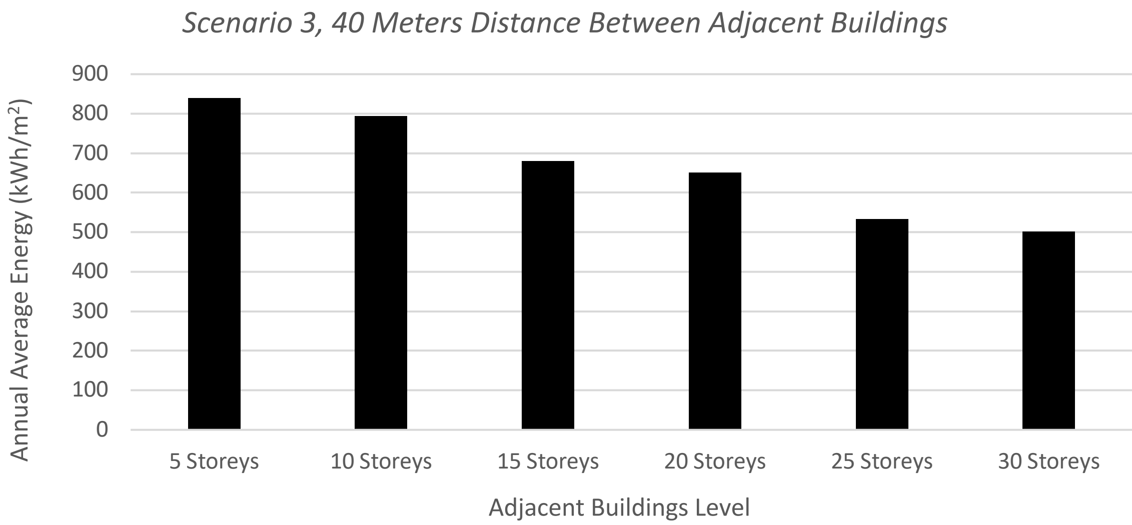
(b)

Fig. 5. (a) The annual average energy (kWh/m^2) for scenario 2, (b) the monthly average energy for scenario 2

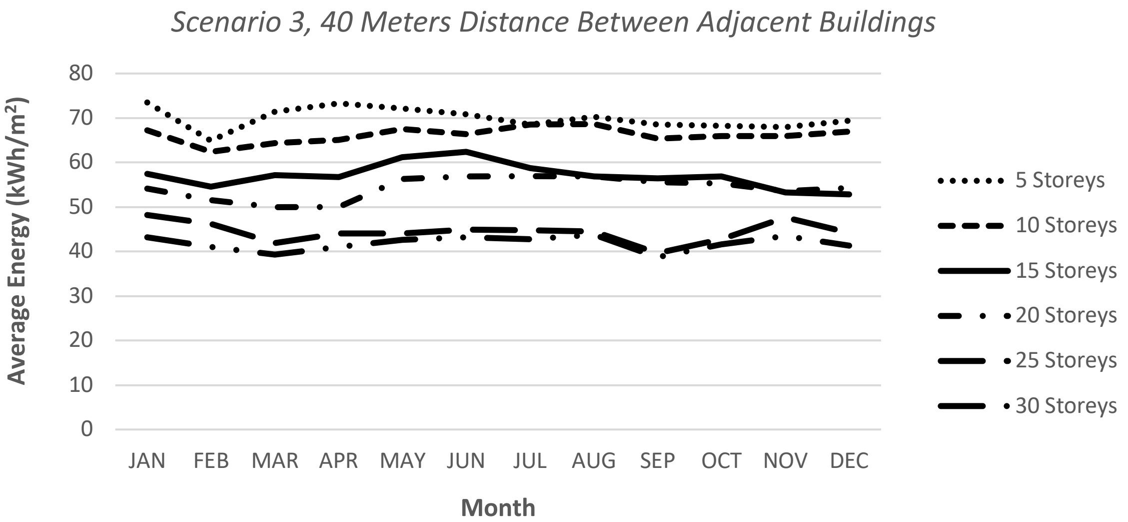
3.3 Scenario 3, 40 Meters Distance between Adjacent Buildings

Figure 6(a) shows almost the same reading as Figure 5(a) with a slight increase in the readings, On the other hand, Figure 6(b) also shows a different pattern, but the noticeable here is the readings started to increase for all cases. The average range for the readings was as follows:

(i) 5 stories: 64.9 kWh/m^2 - 73.49 kWh/m^2
(ii) 10 stories: 62.4 kWh/m^2 - 68.64 kWh/m^2
(iii) 15 stories: 52.84 kWh/m^2 - 62.4 kWh/m^2
(iv) 20 stories: 50.03 kWh/m^2 - 56.93 kWh/m^2
(v) 25 stories: 39.63 kWh/m^2 - 48.2 kWh/m^2
(vi) 30 stories: 38.72 kWh/m^2 - 43.77 kWh/m^2



(a)

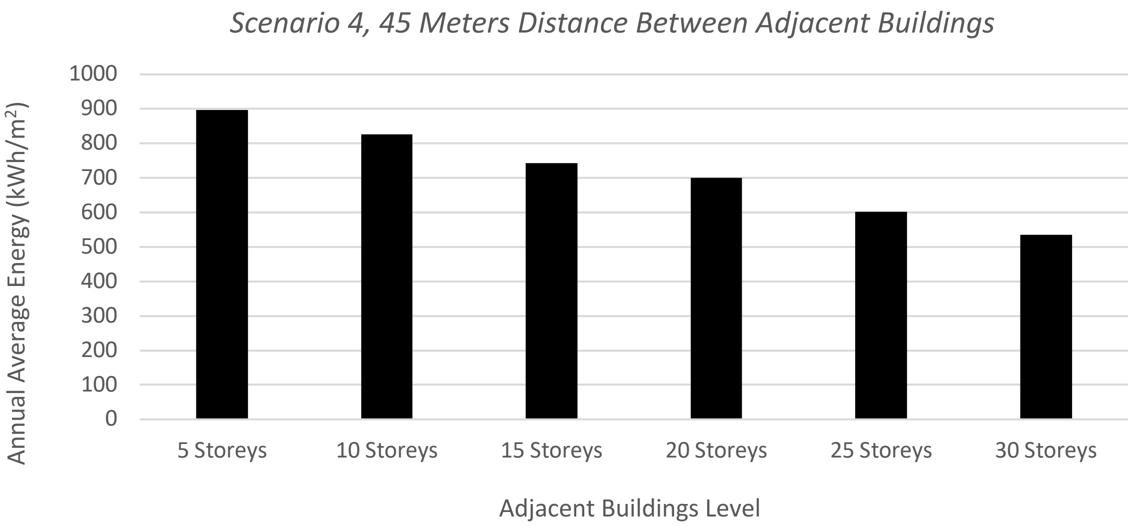


(b)

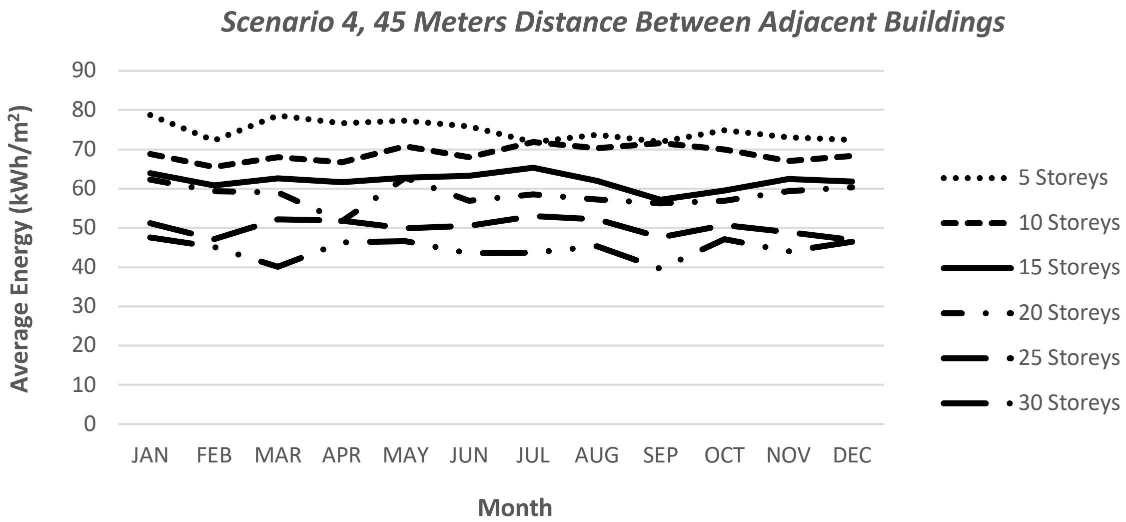
Fig. 6. (a) The annual average energy (kWh/m^2) for scenario 3, (b) the monthly average energy for scenario 3

3.4 Scenario 4, 45 Meters Distance between Adjacent Buildings

Figure 7(a) illustrates the annual average energy (kWh/m^2) for six different cases pertaining to the heights of adjacent buildings, with a fixed distance of 45m between the buildings. The results clearly indicate that greater spacing between adjacent buildings leads to higher energy yields. Furthermore, Figure 7(b) provides a more detailed representation of this relationship, highlighting that the average energy reaches its maximum when the adjacent buildings consist of five stories. During this configuration, the average energy fluctuates between 71.85 kWh/m² in July and 78.74 kWh/m² in January. In contrast, an increase in the height of the adjacent buildings results in a subsequent decrease in the average energy levels. For example, when these structures comprise 30 stories, the average energy range spans from 39.57 kWh/m² in September to 47.55 kWh/m² in January. These findings demonstrate the significant impact of adjacent building height and spacing on energy performance, emphasizing the importance of thoughtful urban planning and design to optimize energy efficiency in the built environment.



(a)

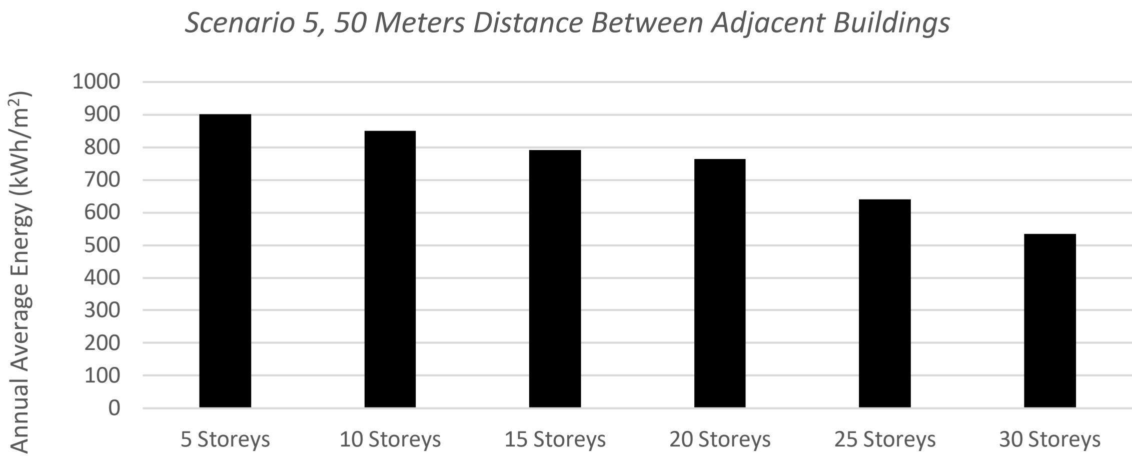


(b)

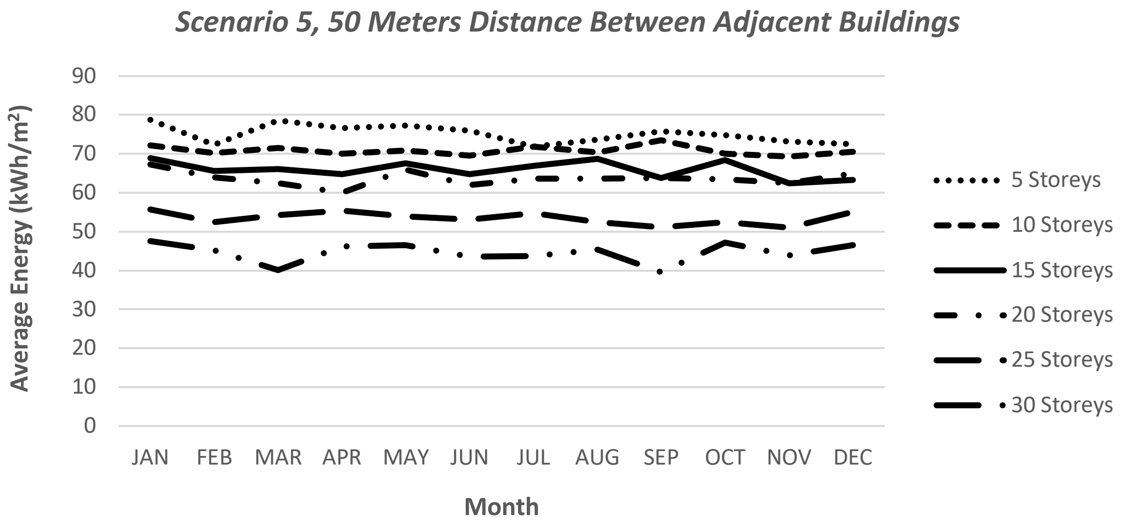
Fig. 7. (a) The annual average energy (kWh/m^2) for scenario 4, (b) the monthly average energy for scenario 4

3.5 Scenario 5, 50 Meters Distance between Adjacent Buildings

Like Figure 7, Figure 8 presents an analysis of the annual and monthly average energy (kWh/m^2) for six distinct scenarios involving varying heights of adjacent buildings. The study focuses on a fixed distance of 50m between the buildings. Notably, Figure 8(b) provides a more comprehensive depiction of this relationship, specifically emphasizing the peak in average energy when the adjacent buildings consist of five stories. During this configuration, the average energy displays seasonal fluctuations, with values ranging from 71.85 kWh/m² in July to 78.74 kWh/m² in January.



(a)



(b)

Fig. 8. (a) The annual average energy (kWh/m²) for scenario 5, (b) the monthly AVG energy for scenario 5

Conversely, an upward adjustment in the height of the adjacent buildings leads to a corresponding decrease in the average energy levels. For instance, in the case where these structures encompass 30 stories, the average energy range varies from 39.57 kWh/m² in September to 47.55 kWh/m² in January.

3.6 Results Summary

Additionally, the outcomes of the last two scenarios are depicted in Table 2, where the distances between the main building and adjacent structures are 45m and 50m, respectively. Notably, it becomes evident that an increased separation between the main building and adjacent buildings results in higher average energy levels, even when the adjacent buildings surpass the height of the main building. This finding substantiates the research's proposition that the application of Building-Integrated Photovoltaic (BIPV) modules on the vertical façade remains feasible, even if the surrounding buildings exhibit greater heights, as long as the distance between the building and its immediate surroundings is at least 40m or greater.

Table 2
The results of the simulation for all proposed scenarios, which, the annual average energy (kWh/m²) for the four vertical elevations of the main building

Adjacent Buildings Level	Distance between Main Building and Adjacent Buildings (m)/Annual Average Energy (kWh/m²)				
	(UBBL – 30m)	(35m)	(40m)	(45m)	(50m)
5 stories	764.01	764.01	839.37	897.11	901.11
10 stories	688	699.78	794.47	826.83	849.66
15 stories	666.38	680.44	680.44	743.17	791.1
20 stories	527.63	532.65	651.405	700.56	763.53
25 stories	456.93	490.63	532.99	601.95	641.2
30 stories	345.5	423.64	502.18	535.27	535.27

4. Conclusions

This research has provided extensive simulations and analyses of diverse scenarios, yielding valuable insights into the substantial influence exerted by neighbouring buildings on the solar exposure and energy generation potential of Building-Integrated Photovoltaic (BIPV) systems incorporated into the vertical façades of high-rise structures in Malaysia. The findings offer a discernible connection between the configuration, elevation, and proximity of adjacent buildings and the average energy yields generated by the BIPV systems. The research establishes that augmenting the separation distance between the main building and adjacent edifices culminates in a noteworthy elevation in average energy outputs, even in instances where the neighbouring structures exceed the height of the principal building. This revelation bears significance for various stakeholders within the built environment, each of whom can leverage these insights to enhance their respective contributions:

(i) Architects and Urban Planners: The research outcomes offer architects and urban planners' vital guidance in optimizing the design and placement of BIPV systems. By strategically arranging buildings and considering adequate separation distances, they can ensure that BIPV modules are effectively positioned for optimal solar exposure and energy generation potential.
(ii) Renewable Energy Practitioners: The insights gained are pivotal for renewable energy practitioners as they orchestrate the integration of BIPV systems. By accounting for adjacent buildings, their heights, and the recommended separation distances, they can make informed decisions to maximize energy production, thereby contributing to sustainable energy solutions.
(iii) Policy and Regulation Authorities: Regulatory bodies responsible for formulating and enforcing building codes and standards, such as the Uniform Building By-Laws (UBBL) in Malaysia, can consider incorporating guidelines based on these findings. This could ensure that BIPV system installation aligns with urban planning and energy efficiency goals while adhering to established building regulations. The practical applications of these insights are well-contained within the accepted boundaries of UBBL in Malaysia, emphasizing the necessity for building professionals to work within existing legal frameworks.

Importantly, the research underscores that even if adjacent buildings surpass the height of the main structure, an increased separation distance can lead to elevated average energy levels. This underscores the feasibility of BIPV module integration on vertical façades, particularly when the gap between buildings exceeds 40 meters. In sum, this research establishes the pivotal role played by adjacent buildings in determining the solar exposure and energy generation capabilities of BIPV systems within Malaysia's high-rise urban environments. These insights should be seamlessly integrated into urban development strategies, architectural designs, and renewable energy planning. By optimizing the integration of BIPV systems in line with these findings, Malaysia can effectively tap into its abundant solar resources, reduce reliance on conventional energy sources, and contribute to a more ecologically conscious and sustainable future for its high-rise urban landscapes.

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