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Building-Integrated Transparent Photovoltaic as a Strategy Towards Net-Zero Energy Building in the Tropics: Considerations, Approach, and Feasibility based on Energy Performance

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Abstract

Previous studies have found the potential of Building Integrated Photovoltaic (BIPV) implementation on vertical facades. The implementation was suggested for buildings with a minimum of 45 percent window-to-wall ratio (WWR). This number is quite challenging for tropical buildings where the suggested WWR ranges around 20 to 40 percent. Furthermore, the installation may appear less efficient due to the lower irradiance received on tropical vertical facades. Given the abundance of vertical facades in tropical high-rise buildings, there exists an opportunity to offset power reduction. Therefore, this study aims to determine the feasibility, influencing factors, and approach for installing building-integrated thin film transparent photovoltaics (BITPV) in tropical regions, focusing on energy production. The objective is achieved through a combination of literature review and simulation. Three layout configurations on three different geographical locations, which present a typical classroom module for school buildings, are observed. Treatment is applied based on orientation, WWR, and the cell coverage ratio. The feasibility is shown by at least 23 percent energy substitution promoted by several configurations. East is suggested for classrooms with 1:1 and 3:2 modules, while north is suggested for classrooms with 2:3 modules. For buildings with minimum WWR (20 percent), TPV installation with ≥40 percent cell coverage ratio (on the specified orientation) is suggested to achieve the mix-energy use target. Additionally, this study presents the influencing factors and design approach for BITPV to provide a comprehensive understanding of the subject.

Keywords: BITPV, cell coverage ratio, energy performance, orientation, WWR.

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INTRODUCTION

Nowadays, the application of building-integrated photovoltaic (BIPV) has reached significant numbers. Tabakovic et al (2017) described that two-thirds of all BIPV applications are implemented in new buildings, and one-third in existing buildings. Furthermore, the study describes that 50 percent of the installations are found on the vertical facade. Meanwhile, residential buildings, public infrastructure, showroom offices, universities and schools, and historical buildings are the five building typologies where BIPV is mostly applied.

Initiating the planning process for implementing BIPV should involve careful consideration of its numerous influencing factors. Previous research has examined certain factors to assess their impact on particular performance metrics. Sun et al (2019) used different climate contexts and various WWRs to observe their impact on energy performance and daylight conditions. Xiong et al (2022) and Zomer and Ruther (2017) observed the impact of shading on BIPV performance. Meanwhile, Toledo et al (2020) used various PV technologies to study their thermal behavior. Another study conducted by Amelia et al (2016) investigated the effects of operating temperature on the performance of PV panels. Since there are many factors influencing BIPV performance, this study conducted a literature review to systematically map the factors.

Studies conducted primarily in mid-to high-latitude areas have found the advantages of BIPV installation on a building's vertical facade (Hu et al. 2023; Xiong et al. 2022; Alrashidi, Ghosh, et al. 2020; Alrashidi, Issa, et al. 2020; Do et al. 2017). In low-latitude areas, the solar radiation received on the vertical plane tends to be lower than the one on a horizontal plane. This makes the use of vertical facade as BIPV and or BITPV (building-integrated thin film transparent photovoltaic) appear less efficient. However, the potential is found in high-rise buildings in the tropics (Mangkuto et al., 2023), as they possess a substantial area that can potentially compensate for power reduction. The development of transparent PV (TPV) technology adds another potential benefit by allowing the incorporation of daylight into buildings. The light-transmissive PV module combines opaque PVs and arranges them with a specific spacing on a transparent substrate region. The application of this type in pattern combinations, from opaque solar cells, and transparent, unoccupied areas, will generate different outputs (Lee et al. 2020). Furthermore, an important consideration for implementing BITPV in the tropics is the window-to-wall ratio (WWR). A previous study in a high-latitude area found that TPV has the potential for building with a minimum WWR of 45 percent (Sun et al. 2019). This number is quite challenging for building in the tropics, where the suggested WWR ranges within 20 to 40 percent (Gupta and Deb 2023; Pathirana, Rodrigo, and Halwatura 2019; Tong et al. 2019).

This study presents a simulation of several BITPV configurations, particularly on building's vertical facades, in the context of low-latitude areas. The gap between the cells is modified to assess the influence of the cell coverage ratio on energy production. WWR value is limited to 20 to 40 percent due to tropical building constraints. The study was conducted for university and school building typology. This building typology is chosen due to its relatively high energy demand, as evidenced by its high occupancy density and receptacle power density. Based on Standard 90.1 (ASHRAE 2016), the occupancy density of an educational facility reaches 7.0 m^2/person, and the receptacle power density reaches 5.4 W/m^2. Its occupancy density is the second highest (above office), and the receptacle power density is within the highest three among other building's typologies. Meanwhile, particularly in Indonesia, there are significant numbers of universities comprising both private and public universities. Most of the well-known universities are placed in multi-story buildings (mid- to high-rise), as seen in Figure 1.

Overall, this study presents a literature review to systematically map the influencing factors, as well as simulation to investigate certain factors in detail. The factors considered include the climate context, orientation, WWR, cell coverage ratio, and TPV's efficiency. The study on BITPV and certain factors is expected to create an optimum BITPV configuration. The energy performance, in terms of energy yield and energy substitution, is used as the indicator to present the feasibility of BITPV implementation for tropical buildings. The study concludes by presenting the approach for designing BITPV systems.

LITERATURE REVIEW

Related to sustainability, net-zero energy building (NZEb) is one of many buildings' concepts that is considered the next frontier in green building. It refers to a building that demonstrates high energy efficiency performance, while also being capable of annually producing energy from renewable sources, ideally matching, or exceeding the amount it consumes from the grid. The energy production can be classified into on-site production and off-site production. PV, with one of its implementation concepts called BIPV (building integrated photovoltaic), is considered a potential technology for NZEb to produce on-site renewable energy. Further opportunity to promote energy and daylight is provided by the development of transparent PV/TPV (Lee et al. 2020).

Based on previous studies, there are several tiers and considerations involved in designing architectural and

Figure 1: Multi-story School Buildings in Indonesia. Sources: htpps://www.ui.ac.id; htpps://www.itb.ac.id; https://art.maranatha.edu/facilities/; https://unpar.ac.id; https://www.ciputramakassar.ac.id/. Accessed January 3, 2024.

building concepts. Heerwagen (2003) described that architecture and building in general could typically begin with considerations such as, site development, building envelope, building layout, and development of building interior. Meanwhile, (Lechner 2014) described that there are three tiers in designing architecture: basic building design, passive systems, and mechanical systems. When it comes to BIPV or BITPV, more detailed factors must be considered as they significantly influence performance. The literature review here discusses and compares the influencing factors used in several related studies. The comparison is tabulated in Table 1, and the influencing factors are mapped in Figure 2.

Previous studies have described several factors that influence BIPV/BITPV performance: envelope configurations and operational setting-related variables (Wu, Ng, and Skitmore 2016); geophysical, technical, environment, and economic (Wijeratne et al. 2019); technical design options for BIPV modules, design options for electrical system, module-level aesthetic design options, as well as constructional integration (Kuhn et al. 2021); envelope-related parameters and PV-related parameters (Samarasinghalage et al. 2022). Other studies have employed a range of variables to assess specific impacts on performance. From the comparison presented in Table 1, it is evident that external influencing factors on BIPV/BITPV performance include climatic conditions and site selection (Feng et al. 2023; Fadlallah and Benhadji Serradj 2020; Sun et al. 2019; Wijeratne et al. 2019). The climatic and weather-related factors that need to be considered include solar irradiance, humidity, air velocity, air temperature, and rainfall. The availability of solar irradiance is the most important since PV uses solar energy to produce electrical energy. The higher the irradiance received the more energy will be produced. Generally, the solar irradiance decreases as the latitude of an area increases (McMullan 2018). Therefore, site selection will have a significant influence on BIPV performance.

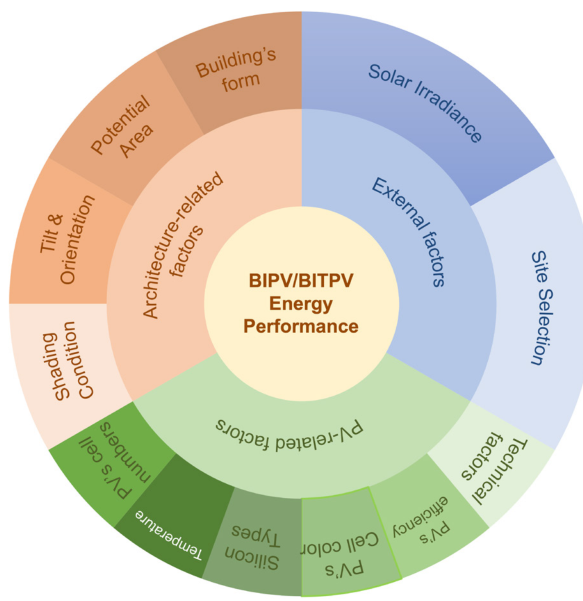

Figure 2: Influencing Factors of BIPV or BITPV.

Table 1: Previous BIPV-related Studies.

Research Title & Author(s) & Date	Research context	Approach	Variables	Objective	Findings
(Feng et al. 2023)	China	Simulation	Climate	To propose a comprehensive research framework.	Guidance for BIPV deployment in China.
(Xiong et al. 2022)	Changsha, Hunan Province	Simulation	Building shadow	To find the influence of building shadows on the semi-transparent PV glazing performance.	Building shadows decreases more to PV power generation and efficiency than solar radiation received.
(Samarasinghalage et al. 2022)	Canopy, roof, and cladding	Literature review Simulation	Envelope-related parameters (tilt, WWR, PV placement) PV-related parameters (PV product type)	To optimize BIPV based on: - Life cycle energy (LCE) - Life cycle cost (LCC)	Multi-objective optimization that works for early BIPV design decisions.
(Kuhn et al. 2021)	German BIPV Market	Literature review	Design options at: -material-level (color, texture) -module-level (front cover, front encapsulant, solar cell layer, etc. -facade-level (potential area, pattern, etc.) -building-level (orientation, modules positioning, shading) -environmental-level (shading)	To present a structured overview of BIPV systems and categorizes.	Design options for constructional integration of BIPV modules.
(Toledo et al. 2020)	Murcia, Spain	Experiment	PV technologies/ types (polycrystalline silicon, cadmium telluride, amorphous silicon, organic PV)	To study the thermal behavior of different PV technologies.	The correlation of temperature difference and in-plane irradiance is mostly independent of PV technology, but strongly dependent on orientation.
(Sreenath et al. 2020)	Kuantan Airport, Malaysia	Simulation	PV technologies/types (modules, absorption factor) Tilt and orientation	To assess the glare occurrence and its impact from proposed solar PV plant.	Glare mostly occurs between March to mid-October, mostly from 7 a.m. to 8 a.m. Green and yellow glare last up 10 & 30 minutes respectively in a year.
(Fadlallah and Benhadji Serradj 2020)	Sudan, Africa	Simulation	Location	To identify the optimal solar PV system by using a simulation named HOMER (hybrid optimization model for electric renewables).	Compared to diesel generators, the installation of PV systems will contribute to COE savings and avoid the generation of pollutants, Reducing the PV costs by 23% of its initial value has a significant impact on the cost of energy produced by PV plants.

Table 1 (continued): Previous BIPV-related Studies.

Research Title & Author(s) & Date	Research context	Approach	Variables	Objective	Findings
(Lee et al. 2020)	Worldwide	Observation Literature review	Performance (efficiency and visible transmittance), aesthetical factor, modularization and cell numbers, stability	To present the development of transparent photovoltaic (TPV).	The best candidate for commercialization of TPV is c-Si, the unit cell must be scaled up to a size of over 5’. Further research needs to be conducted on its modularization to maintain transparency.
(Sun et al. 2019)	China	Simulation	Climate WWR	To observe the impact of WWR on energy performance and daylighting conditions on BIPV under different climate zones.	PV windows are potential for buildings with relatively large WWR (³45%) and they offer better daylight performance.
(Wijeratne et al. 2019)	Worldwide	Data collection through extensive literature survey and worldwide search	Geophysical (city, weather, terrain) Technical (system components, building physics, grid, decommissioning, operation & maintenance, losses, construction &commissioning)	To propose a multidiscipline design platform that covers: - Economic & Environmental aspects	An integrated platform to provide cost-effective solutions for PV project development.
(Zomer and Rüther 2017)	Singapore Florianopolis	Simulation Manual calculation	Shading	To apply the simplified method for shading-loss analysis in BIPV systems, to estimate the influence of partial shadings on the BIPV performance.	The method is powerful for use with already installed PV systems or under investigation surfaces for PV installation, indicated by PR and annual energy yield values that are highly consistent with real PV system measurements.
(Wu, Ng, and Skitmore 2016)	Hongkong	Multi-objective optimization Simulation	Envelope-related variables (type of window, WWR, exterior wall insulation) Operational setting-related design variables (air temperature, air velocity, ventilation rate, RH)	To optimize building performance based on: - Energy costs - Occupant satisfaction (IEQ)	Model to be used in the conceptual design stages to determine appropriate operational settings to achieve the objective.
(Amelia et al. 2016)	Malaysia	Simulation Experiment	PV’s temperature	To investigate the effects of operating temperature on monocrystalline PV panel.	The most significant impact due to the PV’s temperature is on the output voltage. The operational quality of PV panel decreases with increasing panel temperatures.
(Tripathy, Sadhu, and Panda 2016)	Worldwide	Literature review	Latitude of an area, PV’s placement, efficiency, shadow, tilt and orientation angle	To review the life cycle assessment of BIPV modules	BIPV as a sustainable and future promising technology to create zero-emission buildings.
(Ubisse and Sebitosi 2009)	Africa	Simulation	Shading	To study the effect of shading on PV modules.	The use of appropriate bypass diode technology can minimize the impact of shading.

In addition to site selection, there are influencing factors related to architecture and the PV itself. Regarding architecture, BIPV needs to fulfill the aesthetic as well as functional requirements. To meet its functional requirements, the architecture-related factors such as S/V ratio, D/L ratio, WWR, the potential of PV placement, surface's tilt and orientation, as well as shading possibilities need to be considered. The S/V ratio and D/L ratio will indicate whether the building's form and its orientation tend to minimize or maximize the solar irradiance received (Samarasinghalage et al. 2022; Wijeratne et al. 2019; Markus and Morris 1980). For BIPV or BITPV, a building's form that maximizes the solar irradiance received is preferable. Window-to-wall ratio (WWR) is another factor related to architecture that will influence the works of PV (Wu, Ng, and Skitmore 2016; Samarasinghalage et al. 2022; Sun et al. 2019). Regarding TPV, higher WWR is preferable as it indicates a greater availability of potential installation area (Sun et al. 2019).

Potential PV placement in terms of BIPV refers to the horizontal surface/roof (0° ≤ angle of surface <80°) and vertical surface/wall (90°±10° or ±15° from horizontal) of the building (Kuhn et al. 2021). Here, the potential PV placement is further described in the facade and architecture-layer. It involves the decision of PV layout for different facade orientations and the roof, as well as determining whether the entire facade is covered with an equal PV pattern, or if facade different patterns are used on different parts of the building. Related to PV placement, determining the tilt and orientation angle on those potential surfaces is essential to optimize the solar irradiance received (Samarasinghalage et al. 2022; Sreenath et al. 2020; Taveres-Cachat et al. 2019). Sequentially, this will influence the power output, building aesthetics, and its impact on surrounding buildings. PVs integrated in various orientations can enhance the balance of supply and demand. Furthermore, BIPV design should consider the possibility of shading. Shadows, in this case, could result from topographic features, neighboring buildings (Wijeratne et al. 2019; Xiong et al. 2022), as well as self-shading (Kuhn et al. 2021; Samarasinghalage et al. 2022). PV installations can experience partial or complete shading leading to a reduction in electrical energy generation. Studies have measured this reduction to be between 10 to 30 percent in soft and hard shading conditions (Feng et al. 2023; Ubisse and Sebitosi 2009; Zomer and Rüther 2017).

Related to the PV itself, the ability to produce electrical energy is influenced by factors such as cell temperature, number of cells in a module, cell color, technical factors, silicon type, and efficiency. PV systems tend to achieve optimum performance when operating at 25°C and receiving 1000W/m² of solar radiation. The increase of temperature under real conditions, will decrease the PV efficiency and electrical energy output (Amelia et al. 2016). An air gap of ventilation is usually provided to maintain the PV's optimum temperature (Samarasinghalage et al. 2022). Kuhn, et al (2021) described that in the module-layer, the design should decide whether the modules will be uniformly covered by PV cells, or whether there will be certain gaps or spacing between cells. The decision will determine the cell coverage ratio and influence the number of cells. Hence, the number of cells will directly affect voltage production. As the number of cells increases, the voltage production will also increase (Lee et al. 2020; Roberts and Guariento 2009). Related to PV cells, dark colors are functionally preferable since they can minimize light reflection resulting in higher performance. Technically, other influencing factors in the module-layer are design options for the front cover, front encapsulant, solar cell layer, rear encapsulant, rear cover, and junction box. Furthermore, technical factors also relate to several issues, such as loss from wiring, soiling, and inverter. The loss from these technical factors will reduce the electrical energy production. Certain software could provide a prediction of system loss sources and amounts (Guittet and Freeman 2018; Damiri and Nugraha 2021).

The selection of PV types will influence the work of BIPV (Toledo et al. 2020; Sreenath et al. 2020). Three kinds of transparent PV technology can be found in the market: thin-film technology, selective light-transmission technology, and luminescent solar concentrator technology. Among these three, thin-film technology and selective light-transmission technology are the most developed (Lee et al. 2020). This kind of technology has reached over 12 percent efficiency and 20 percent average visible transmittance. Between these two, the light-transmissive PV module combines opaque PV cells arranging them with a certain spacing on a transparent substrate region. Applying this type in a combination of a pattern of opaque solar cells and transparent unoccupied areas will generate different outputs. Modifying the gap between the cells will influence the cell coverage ratio, which in turn affects light transmission, the number of cells, and TPV efficiency. Sequentially, these factors will impact energy production. The PV cell is available in the market in two size options (10x10 cm and 15x15 cm), with crystalline silicon known as the most efficient type. One of the well-known PV manufactures, Onyx Solar, offers several variants of TPV. However, for optimizing energy production, lower transparency TPV with higher efficiency is preferable. Technically, this TPV has 15 percent transmittance, 38 Wp/m² peak power, and 16 percent efficiency.

PV with higher efficiency will generate higher power output (Roberts and Guariento 2009; Tripathy, Sadhu, and Panda 2016). However, in terms of TPV, the

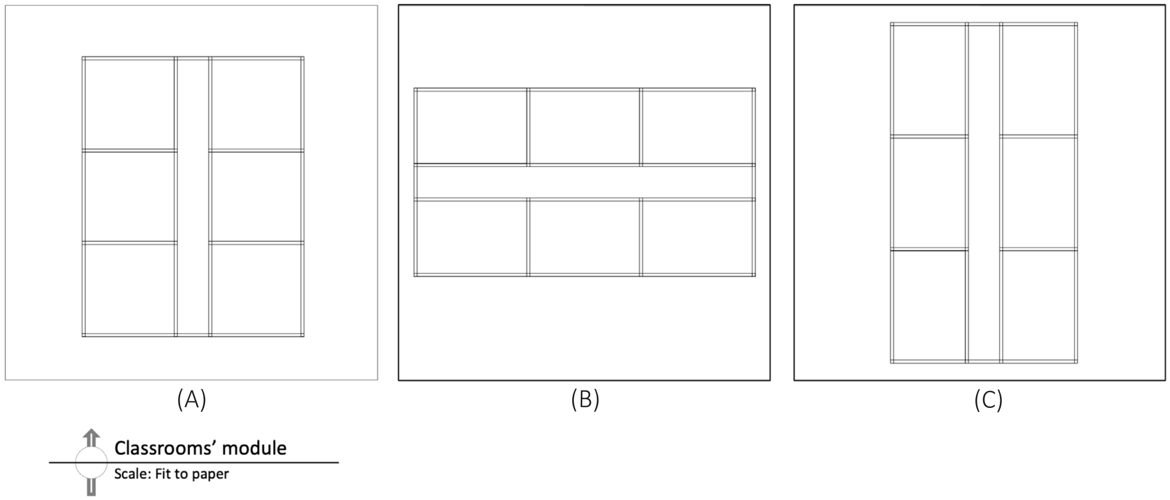

Figure 3: Class module A (1:1), B (2:3), and C (3:2).

efficiency will be inversely proportional to its ability to transmit daylight (Lee et al. 2020). The efficiency of PV is calculated based on the mathematical equation below.

η_m = ouput power / input power
= (Vmpp x Impp) / (G x A) (1)

where,

η_m = PV Efficiency
Output power = energy generated by a PV system
Input power = solar energy incident
Vmpp (volt) = voltage of *maximum power point*
Impp (Amp) = current of *maximum power point*
G (W/m²) = Solar radiation intensity/irradiance
A (m²) = PV area

Based on the mathematical equation above, the output power can be calculated if the PV efficiency and the irradiance are known. The mathematical equation can be seen below.

Output power = η_m x input power
= η_m x (GxA) (2)

where,

η_m = PV Efficiency
G (W/m²) = Solar radiation intensity/irradiance
A (m²) = PV area

METHODOLOGY

The literature review is conducted to systematically map the BIPV influencing factors. This research then employs simulation to generate data on PV energy production from various study settings, which are determined based on the orientation, WWR, and cell coverage ratio).

Site Selection

Multi-story buildings can be classified as low-rise (1-3 floors), mid-rise (4-8 floors), or high-rise (>9 floors) (McCombs 2015). Aside from this classification, school buildings themselves have a wide variety of layouts: linear, central corridor, and concentrated models. Hence, the classroom module varies from 1:1, 2:3, and 3:2. These variations indicate differences in building shape, which simultaneously have impact visual aesthetics, thermal performance, indoor air quality, and energy consumption (Montenegro et al. 2012). The study explains that the 1:1 module supports flexibility and coherence with certain educational models, while the rectangular shape is conducive to lighting and natural ventilation. The illustration of the class module is shown in Figure 3.

This research investigates the planning of BITPV installation in school buildings with various classroom modules. The area is set to be equal, approximately 216 m² – 216.09 m², intended to accommodate 30 students. Educational buildings, which aim for efficiency, typically have an energy utility index (EUI) ranging between 14.58-19.3 kWh/m².year ("Pedoman Pelaksanaan Konservasi Energi Dan Pengawasan Di Lingkungan Departemen Pendidikan Nasional" 2006; Fitriani et al. 2021). By using the minimum EUI rate, the energy needed for a classroom module used in this study ranges between 3149.28-3150.59 kWh/year. The energy demand for each module is tabulated in Table 2.

The geographical locations selected are 06°17 S, 106°73 E (Jakarta), 07°29 S, 112°63 E (Surabaya), and 05°15 S, 119°40 E (Makassar). These three locations represent capital cities in Indonesia, where educational facilities with high-rise building typology are found. Furthermore, the geographical location of the selected sites indicates the potential of solar radiation that can be used as the source of PV's energy. Glass cladding experiments are conducted on north, east, south, and west orientations. To investigate energy performance, the study focuses on the room's openings. The base case model is determined using Low-E glass for its 20 percent WWR. It is then treated using TPV with different WWR, orientation, and cell coverage ratio.

HelioScope Simulation Software

HelioScope is chosen as the tool to perform simulations on solar radiation received, as it can generate data of annual irradiance received in certain locations. The output is based on the consideration of PV placement and environmental conditions, including the climatic data, irradiance measurement, shading condition, reflection, and temperature predictions. It is a user-friendly, cloud-based software, that was validated in other studies (Fathi, Abderrezek, and Grana 2017; Guittet and Freeman 2018). The results of annual radiation received for each orientation in each geographical location are presented in Table 3-5.

The Study Setting

The pre-test, treatment, and post-test conditions of the study are presented in Table 6.

A – B – C represent the types of classroom modules respectively for 1:1, 2:3, and 3:2. The first percentage in the configuration's name represents the WWR, while the second percentage represents the cell coverage ratio. N – E – S – W represent the orientation respectively for north, east, south, and west. Figure 4a, b, c shows examples of the room's models, respectively for the base case, C30 to-S-30percent, and C30 to-S-40percent. The treatment resulted in eighty-four post-test models for each geographical location. The area for TPV installation, for each WWR, in each cell coverage ratio is tabulated in Table 7.

Method of Data Analysis

The performance of vertical facade integrated transparent photovoltaic will be measured based on energy performance. The energy produced by TPV configurations will be compared to the building's energy demand based on EUI. The result will then be compared to the target of mix-energy use issued by the Indonesian Government.

RESULTS AND DISCUSSION

In each orientation, HelioScope generates data of solar radiation received for each geographical location. The results are presented in Table 3-5 and resumed in Table 8.

Referring to equation (2), the number of solar radiations received is then multiplied by the cell area to generate the total solar radiation received for each of the post-test models. To calculate the electrical energy yield, the total solar radiation received is multiplied by the PV's efficiency (16 percent). The result is then compared to the module's energy demand and presented as a percentage of energy substitution. Table 9-11 illustrate the mathematical calculation for post-test models in A20%, B30%, C40% for all orientations and geographical locations, in a 50 percent cell coverage ratio. Results from all post-test models are presented in Figure 5-7.

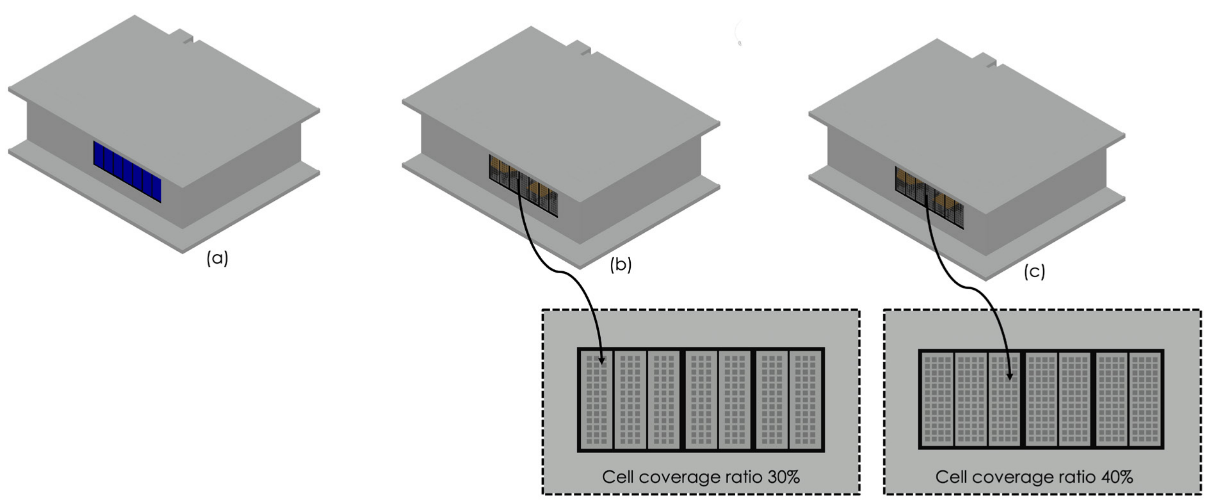

Figure 4: CAD for (a) Base-case Model with 30% WWR; (b) C30%-S-30%; (c) C30%-S-40%

Table 2: Energy Demand of Classroom Modules.

Configuration	L	W	A (LxW)	EUI	Energy Demand (AxEUI)
	m	m	m^2	kWh/m^2.year	kWh/year
1:1	14.7	14.7	216.09	14.58	3150.59
2:3	12.0	18.0	216.00	14.58	3149.28
3:2	18.0	12.0	216.00	14.58	3149.28

Table 3: Results of HelioScope for Jakarta.

Annual Production			
	Description	**Output**	**%Delta**
Irradiance (kWh/m²) – North Orientation	Annual global horizontal irradiance	1,736.2	
	POA Irradiance	858.7	-50.5%
	Shaded Irradiance	858.6	0.0%
	Irradiance after reflection	799.6	-6.9%
	Irradiance after soiling	783.6	-2.0%
	Total collector irradiance	783.6	0.0%
Irradiance (kWh/m²) – East Orientation	Annual global horizontal irradiance	1,763.2	
	POA Irradiance	996.9	-42.6%
	Shaded Irradiance	996.8	0.0%
	Irradiance after reflection	953.5	-4.3%
	Irradiance after soiling	934.4	-2.0%
	Total collector irradiance	934.4	0.0%
Irradiance (kWh/m²) – South Orientation	Annual global horizontal irradiance	1,736.2	
	POA Irradiance	660.4	-62.0%
	Shaded Irradiance	660.4	0.0%
	Irradiance after reflection	613.5	-7.1%
	Irradiance after soiling	601.2	-2.0%
	Total collector irradiance	601.2	0.0%
Irradiance (kWh/m²) – West Orientation	Annual global horizontal irradiance	1,736.2	
	POA Irradiance	947.9	-45.4%
	Shaded Irradiance	947.0	0.0%
	Irradiance after reflection	901.7	-4.9%
	Irradiance after soiling	883.7	-2.0%
	Total collector irradiance	883.7	0.0%

Table 4: Results of HelioScope for Surabaya.

Annual Production			
	Description	**Output**	**%Delta**
Irradiance (kWh/m²) – North Orientation	Annual global horizontal irradiance	1,782.1	
	POA Irradiance	962.3	-48.0%
	Shaded Irradiance	926.2	0.0%
	Irradiance after reflection	863.8	-6.7%
	Irradiance after soiling	846.5	-2.0%
	Total collector irradiance	846.5	0.0%
Irradiance (kWh/m²) – East Orientation	Annual global horizontal irradiance	1,782.1	
	POA Irradiance	1,017.5	-42.9%
	Shaded Irradiance	1,017.5	-42.9%
	Irradiance after reflection	973.8	0.0%
	Irradiance after soiling	954.4	-4.3%
	Total collector irradiance	954.4	-2.0%
Irradiance (kWh/m²) – South Orientation	Annual global horizontal irradiance	1,782.1	
	POA Irradiance	641.5	-64.0%
	Shaded Irradiance	641.4	0.0%
	Irradiance after reflection	595.4	-7.2%
	Irradiance after soiling	583.5	-2.0%
	Total collector irradiance	583.5	0.0%
Irradiance (kWh/m²) – West Orientation	Annual global horizontal irradiance	1,782.1	
	POA Irradiance	971.9	-45.5%
	Shaded Irradiance	971.8	0.0%
	Irradiance after reflection	924.3	-4.9%
	Irradiance after soiling	905.8	-2.0%
	Total collector irradiance	905.8	0.0%

Table 5: Results of HelioScope for Makassar.

Annual Production			
	Description	**Output**	**%Delta**
Irradiance (kWh/m²) – North Orientation	Annual global horizontal irradiance	1,770.9	
	POA Irradiance	871.2	-50.8%
	Shaded Irradiance	871.2	0.0%
	Irradiance after reflection	809.9	-7.0%
	Irradiance after soiling	793.7	-2.0%
	Total collector irradiance	793.7	0.0%
Irradiance (kWh/m²) – East Orientation	Annual global horizontal irradiance	1,770.9	
	POA Irradiance	1,010.2	-43.0%
	Shaded Irradiance	1,010.2	0.0%
	Irradiance after reflection	967.4	-4.2%
	Irradiance after soiling	948.0	-2/0%
	Total collector irradiance		0.0%
Irradiance (kWh/m²) – South Orientation	Annual global horizontal irradiance	1,770.9	
	POA Irradiance	648.0	-63.4%
	Shaded Irradiance	648.0	0.0%
	Irradiance after reflection	600.9	-7.3%
	Irradiance after soiling	588.8	-2.0%
	Total collector irradiance	588.8	0.0%
Irradiance (kWh/m²) – West Orientation	Annual global horizontal irradiance	1,770.9	
	POA Irradiance	983.1	-44.5%
	Shaded Irradiance	983.0	0.0%
	Irradiance after reflection	935.6	-4.8%
	Irradiance after soiling	916.9	-2.0%
	Total collector irradiance	916.9	0.0%

Table 6: The Study Setting.

Pre-test	Treatment	Post-test
A model with Low-E glass cladding facade on 1:1, 2:3, and 3:2 classroom's layout in three geographical locations in Indonesia.	BITPV configuration based on WWR (WWR 20%, 30%, 40%)	Configurations of BITPV: A20%-N-20% A20%-N-30% A20%-N-40% .
	BITPV configuration based on orientation (N, E, S, W)	A20%-E-20% A20%-E-30% . A30%-N-20% A30%-N-30% .
	BITPV configuration based on the ratio of TPV to transparent glass (20%, 30%, …, 80%)	A40%-N-20% . B20%-N-20% . C40%-W-30% C40%-W-40% C40%-W-50% C40%-W-60% C40%-W-70% C40%-W-80%

Table 7: Measurement of TPV Area.

Config. Names	Layout types	Length	Width	Height	Ori	Opening	TPV area in each cell coverage ratio						
		(m)	(m)	(m)		(m^2)	20%	30%	40%	50%	60%	70%	80%
A20%	1:1	14.7	14.7	4.0	All	11.76	2.35	3.53	4.70	5.88	7.06	8.23	9.41
B20%	2:3	12.0	18.0	4.0	N/S	14.40	2.88	4.32	5.76	7.2	8.64	10.1	11.5
					E/W	9.60	1.92	2.88	3.84	4.8	5.76	6.72	7.68
C20%	3:2	18.0	12.0	4.0	N/S	9.60	1.92	2.88	3.84	4.8	5.76	6.72	7.68
					E/W	14.40	2.88	4.32	5.76	7.2	8.64	10.1	11.5
A30%	1:1	14.7	14.7	4.0	All	17.64	3.53	5.29	7.06	8.82	10.6	12.4	14.1
B30%	2:3	12.0	18.0	4.0	N/S	21.60	4.32	6.48	8.64	10.8	13.0	15.1	17.3
					E/W	14.40	2.88	4.32	5.76	7.2	8.64	10.1	11.5
C30%	3:2	18.0	12.0	4.0	N/S	14.40	2.88	4.32	5.76	7.2	8.64	10.1	11.5
					E/W	21.60	4.32	6.48	8.64	10.8	13.0	15.1	17.3
A40%	1:1	14.7	14.7	4.0	All	23.52	4.70	7.06	9.41	11.8	14.1	16.5	18.8
B40%	2:3	12.0	18.0	4.0	N/S	28.80	5.76	8.64	11.5	14.4	17.3	20.2	23.0
					E/W	19.20	3.84	5.76	7.68	9.6	11.5	13.4	15.4
C40%	3:2	18.0	12.0	4.0	N/S	19.20	3.84	5.76	7.68	9.6	11.5	13.4	15.4
					E/W	28.80	5.76	8.64	11.5	14.4	17.3	20.2	23.0

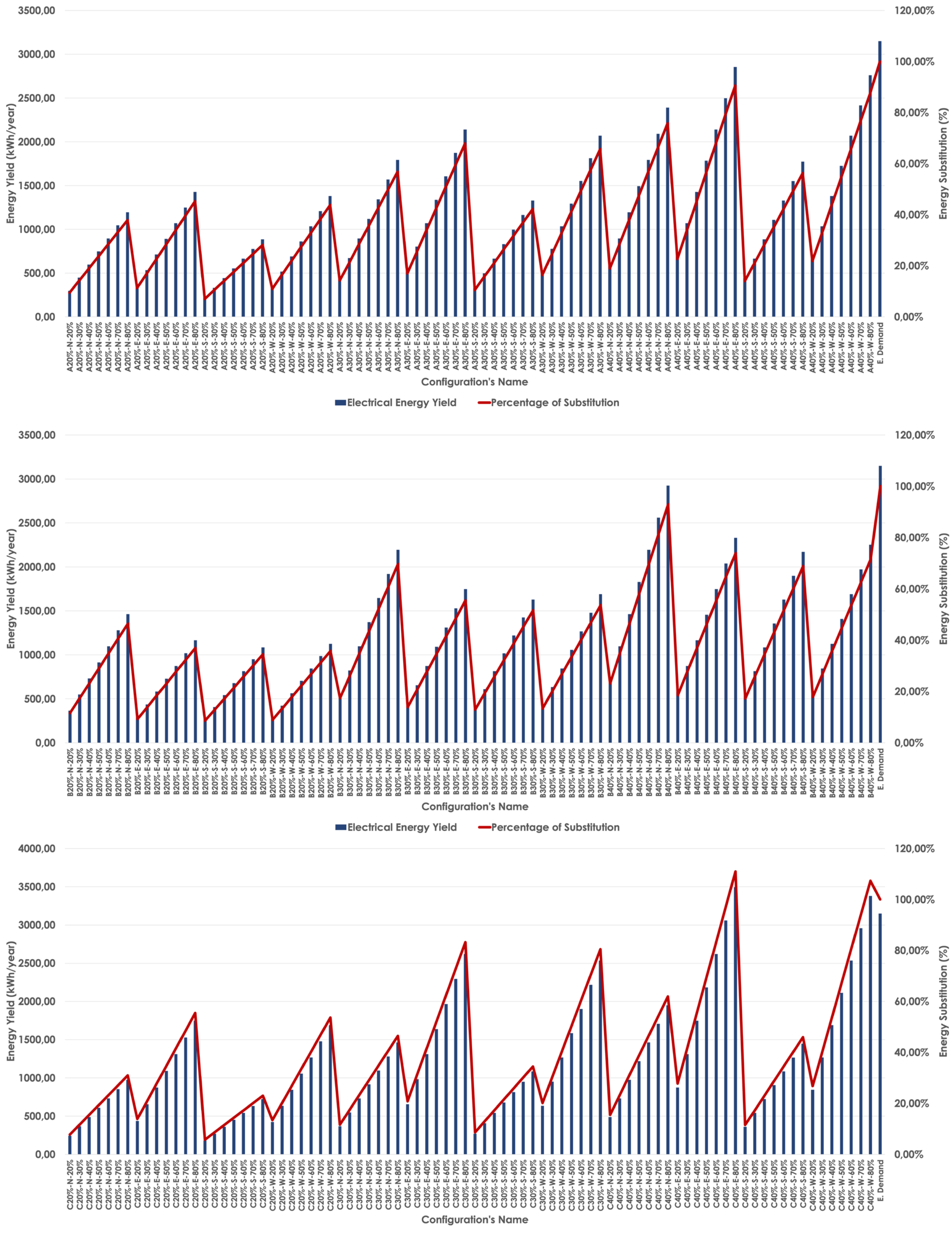

Figure 5: Energy Performance for Post-test Models – Makassar.

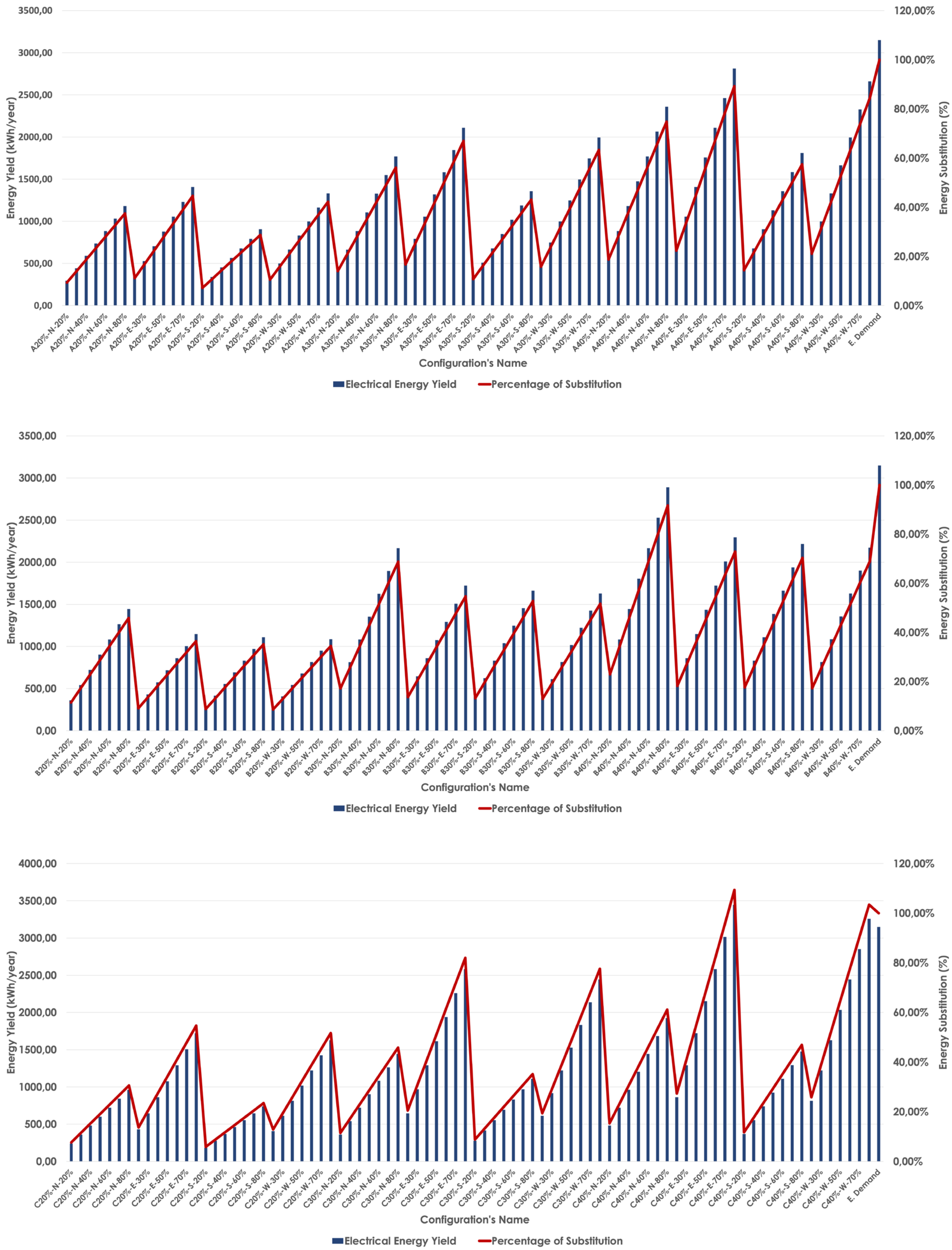

Figure 6: Energy Performance for Post-test Models – Jakarta.

Figure 7: Energy Performance for Post-test Models – Surabaya.

Table 8: Results of HelioScope Simulation.

Orientation	Solar radiation received (kWh/m².year)		
	Jakarta	Surabaya	Makassar
North (N)	783.6	846.5	793.7
East (E)	934.4	954.4	948.0
South (S)	601.2	583.5	588.8
West (W)	883.7	905.8	916.9

The simulation reveals that only a few models in all selected geographical locations can fully meet the energy needs of the classroom module. These models are identified within the 3:2 module, characterized by the highest WWR (40 percent) and cell coverage ratio (80%) when TPV is installed on east and west orientations. The utilization of high WWR and extensive cell coverage ratio warrants consideration in assessing thermal and daylight performance. However, many of the configurations can reach 23 percent of the mix-energy use targeted by the Indonesian government. As illustrated in Figure 5, in Makassar (05°15'S), a classroom with a module 1:1– 20 percent WWR reaches the target when the cell coverage ratio is set at ≥50% in N-E-W orientation and ≥70% in S orientation. Meanwhile, a classroom with a module 2:3–20 WWR achieves the target when the cell coverage ratio is set at ≥40%, ≥50%, ≥60% respectively for N – E – S and W orientation. Furthermore, for a classroom with a module 3:2 in 20%WWR, the target is reached when the cell coverage ratio and orientation are set in N-≥60%, E-≥40%, and W-≥40%. In this scenario, no configuration on the south orientation achieves the specified target.

For Jakarta (06°17'S), as illustrated in Figure 6, a classroom with a module 1:1 – 20% WWR reaches the target when the cell coverage ratio is set at ≥50% in N-E-W orientation and ≥70% in S orientation. A classroom with a module 2:3 - 20% WWR start to reach the target when the cell coverage ratio is set at 50% in the north and 60% in the east-south-east facade. It is then followed by other configurations with a higher cell coverage ratio in the specified orientation. Meanwhile, for the classroom with a module 3:2 in 20%WWR, the target is reached when the orientation and cell coverage ratio are set in N-≥70%, E-≥40%, S-≥80%, and W-≥40%.

Results for Surabaya (07°29'S) are illustrated in Figure 7. The same results with Makassar and Jakarta were found for a classroom in the 1:1 module. In a classroom with a 2:3 module – 20%WWR, the target is achieved starting in configuration with N-40%, E-50%, S-60%, and W-60%, followed by configuration in the specified orientation with a higher cell coverage ratio. In a classroom with 3:2 module-20%WWR, the target is reached in configuration with N-≥60%, E-≥40%, and W-≥40%. Similar to the one in Makassar, there is no configuration on south orientation that can reach the target in this case.

Within the same WWR and cell coverage ratio, the highest percentage of substitution was found when TPV simulated in the east, north, and east facade respectively for the 1:1 module, 2:3 module, and 3:2 module (illustrated in Figure 8). In terms of energy production, for the 1:1 module, the configurations suggested are

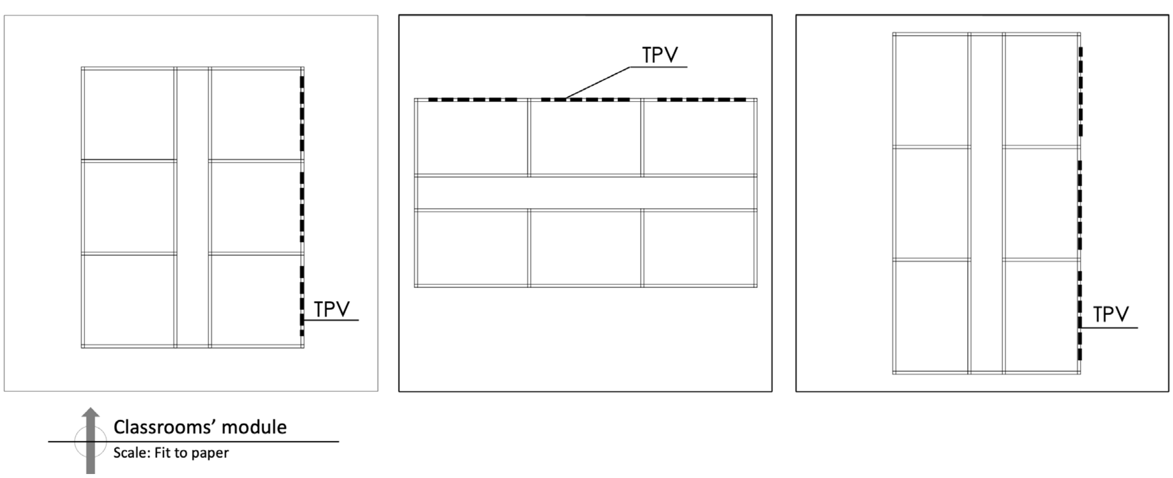

Figure 8: Suggested TPV Installation based on Energy Production.

Table 9: Calculation of Energy Substitution (Jakarta).

Configuration Names	Solar Radiation Received (kWh/m2.year)	TPV Area (m^2)	Total Solar Radiation Received (kWh/year)	Electrical Energy Yield (kWh/year)	Energy Substitution (%)
A20%-N-50%	793.7	5.88	4607.57	737.21	23.40%
A20%-E-50%	948.0	5.88	5494.27	879.08	27.90%
A20%-S-50%	588.8	5.88	3535.06	565.61	17.95%
A20%-W-50%	916.9	5.88	5196.16	831.38	26.39%
B30%-N-50%	793.7	10.80	8462.88	1354.06	43.00%
B30%-E-50%	948.0	7.20	6727.68	1076.43	34.18%
B30%-S-50%	588.8	10.80	6492.96	1038.87	32.99%
B30%-W-50%	916.9	7.20	6362.64	1018.02	32.33%
C40%-N-50%	793.7	9.60	7522.56	1203.61	38.22%
C40%-E-50%	948.0	14.40	13455.36	2152.86	68.36%
C40%-S-50%	588.8	9.60	5771.52	923.44	29.32%
C40%-W-50%	916.9	14.40	12725.28	2036.05	64.65%

Table 10: Calculation of Energy Substitution (Surabaya).

Configuration Names	Solar Radiation Received (kWh/m^2.year)	TPV Area (m^2)	Total Solar Radiation Received (kWh/year)	Electrical Energy Yield (kWh/year)	Energy Substitution (%)
A20%-N-50%	846.5	5.88	4977.42	796.39	25.28%
A20%-E-50%	954.4	5.88	5611.87	897.90	28.50%
A20%-S-50%	583.5	5.88	3430.98	548.96	17.42%
A20%-W-50%	905.8	5.88	5326.10	852.18	27.05%
B30%-N-50%	846.5	10.80	9142.20	1462.75	46.45%
B30%-E-50%	954.4	7.20	6871.68	1099.47	34.91%
B30%-S-50%	583.5	10.80	6301.80	1008.29	32.02%
B30%-W-50%	905.8	7.20	6521.76	1043.48	33.13%
C40%-N-50%	846.5	9.60	8126.40	1300.22	41.29%
C40%-E-50%	954.4	14.40	13743.36	2198.94	69.82%
C40%-S-50%	583.5	9.60	5601.60	896.26	28.46%
C40%-W-50%	905.8	14.40	13043.52	2086.96	66.27%

Table 11: Calculation of Energy Substitution (Makassar).

Configuration Names	Solar Radiation Received (kWh/m².year)	TPV Area (m²)	Total Solar Radiation Received (kWh/year)	Electrical Energy Yield (kWh/year)	Energy Substitution (%)
A20%-N-50%	783.6	5.88	4666.96	746.71	23.70%
A20%-E-50%	934.4	5.88	5574.24	891.88	28.31%
A20%-S-50%	601.2	5.88	3462.14	553.94	17.58%
A20%-W-50%	883.7	5.88	5391.37	862.62	27.38%
B30%-N-50%	783.6	10.80	8571.96	1371.51	43.55%
B30%-E-50%	934.4	7.20	6825.60	1092.10	34.68%
B30%-S-50%	601.2	10.80	6359.04	1017.45	32.31%
B30%-W-50%	883.7	7.20	6601.68	1056.27	33.54%
C40%-N-50%	783.6	9.60	7619.52	1219.12	38.71%
C40%-E-50%	934.4	14.40	13651.20	2184.19	69.36%
C40%-S-50%	601.2	9.60	5652.48	904.40	28.72%
C40%-W-50%	883.7	14.40	13203.36	2112.54	67.08%

E-≥50%, E-≥30%, and E-≥30% respectively for 20%-30%-40% WWR. For the 2:3 module: N-≥40%, N-≥30%, and N-≥20% respectively for 20%-30%-40% WWR can be suggested as the configurations that at least substitute 23% of non-renewable energy by the renewable one. For the 3:2 module, configurations that have at least 23% of energy substitution are E-≥40%, E-≥30%, and E-≥20%, respectively for 20%-30%-40% WWR.

Furthermore, the approach used to design BITPV in this study and its comparison with other architectural approaches in general is illustrated in Figure 9.

CONCLUSION

In general, architectural design, developed in three tiers: from the basic building design, passive systems, and mechanical systems (Lechner 2014). Another similar approach starts the architecture design from the site development, building envelope, building layout, and development of the building interior. In this study, basic building design and site development were primary considerations. However, the mechanical system that contributes to energy demand is suggested in the earlier stages. The EUI determination, presented here, influences the design of the building envelope.

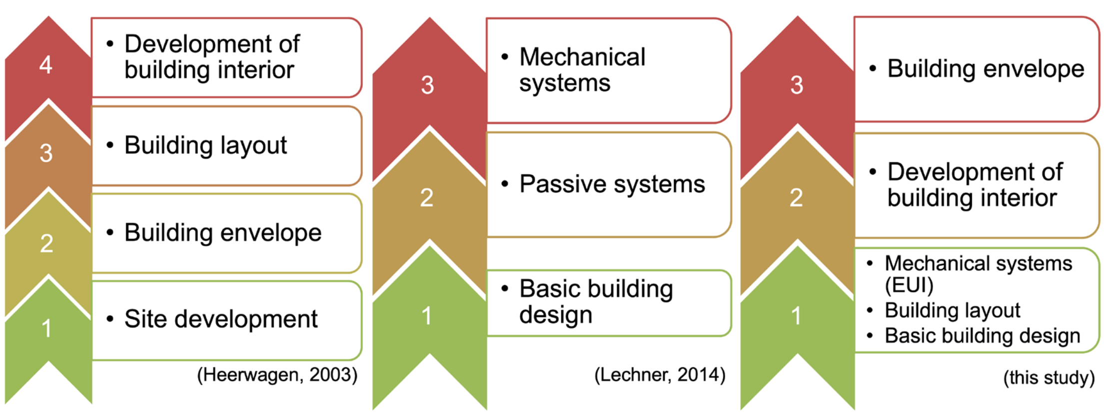

Figure 9: Comparison of Consideration and Approach.

Particularly, it is defined by the design of WWR, cell coverage ratio, glazing system, and orientation. Figure 2 illustrates the influencing factors, while Figure 9 depicts the comparison of the approaches.

Furthermore, this paper investigated the energy performance of building-integrated transparent photovoltaic for high-rise school buildings in the tropics. A previous study found that BITPV is suggested for buildings with ≥45% WWR (Sun et al. 2019). Meanwhile, buildings in the tropics are suggested to have WWR ranging from 20% to 40%. This study aims to find the feasibility of BITPV installation for these ranges of WWR. Several modules and geographical locations are used. Data analysed in this study is simulation-based data generated from HelioScope software, which is used to calculate the energy production and substitution. The result is compared to the mix-energy use target set by the Indonesian Government. Hence, it suggests that BITPV implementation is feasible in tropical buildings, despite the WWR limitation. The feasibility is shown by the number of energy substitutions promoted by several configurations that reach the minimum number of 23 percent. East is suggested for classrooms with 1:1 and 3:2 modules, while north is suggested for classrooms with 2:3 modules. The finding of east and north as the optimum orientation of BITPV is in line with the findings from other previous studies. The east facade is the optimum orientation for BITPV for energy performance due to its high solar irradiance. This vertical orientation received the highest incidence irradiance nominal throughout the year (Ghazali et al. 2017). Meanwhile, the north orientation is found as the optimum orientation on the 2:3 module, due to its larger potential area of TPV installation. The potential available area will affect the amount of solar radiation received. The larger the received area, the greater the amount of solar radiation received and sequentially will impact to greater electrical energy production (Susan and Wardhani 2020). Furthermore, installing TPV on the north facade is more profitable, as it allows TPV to capture solar radiation for the longest duration possible. (Bonifacius et al., n.d.). For buildings with a 20 percent WWR, experiments conducted across various layouts and geographical locations suggest that a cell coverage ratio of 40% to 50% (or higher) on the east and north orientations can be recommended to achieve the minimum energy substitution percentages set by the Indonesian Government. With every 10 percent increase in WWR, the suggested cell coverage ratio to meet the target tends to decrease by around 10 percent. Based on the optimal orientations identified for each type of classroom module, general layout plans featuring a central corridor for educational facilities in high-rise buildings in tropical regions are provided. These layout configurations are presented in Figure 8.

The context of this research is multi-story education facilities in the warm, humid climate areas. Part of the building observed is the vertical building envelope (wall). The building is assumed as a single building, with certain distances from any surrounding properties to optimize solar access, and the PV assumed to be used in this study is crystalline silicon, which has the highest efficiency. Hence, the findings are subject to the buildings that are relevant to the indicated building typologies. Furthermore, this study employed simulation as its method without validation. The actual energy performance can be monitored in future research using full-scale physical samples, in line with advancements in TPV technology. Ultimately, this study is anticipated to contribute to the industry by informing BITPV design practices, especially those implemented on the facades of tropical buildings.

AUTHORS' CONTRIBUTIONS

Susan Susan: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, validation, visualization, writing-original draft, writing-review & editing.

Safial Aqbar bin Zakaria: Conceptualization, supervision.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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