NOT ENOUGH SPACE IN YOUR CITY?
DEVELOPMENT OF FRAMEWORK FOR VERTICAL SOLAR PHOTOVOLTAIC ON BUILDING FACADE USING 3D MODELLING AND PSSCIENCE IN JAKARTA

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August, 2023

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

The gradual phasing down the coal induced the activity of climate technology to produce usable clean energy for replacing coal usage. However, most renewable technology, e.g., windmills and solar farm, require space to perform, which makes it not applicable in dense urban areas. Nevertheless, densely populated urban areas face challenges due to high populations that lead to high energy demands and land scarcity, which refrain from open space for performing energy transition activity. Acknowledge this issue; with the current research, the potential of Building Integrated Photovoltaic (BIPV) on tall building facades was evaluated. The study area is specifically located in the dense urban area of a developing country: in the Sudirman Central Business District of Jakarta, Indonesia.

The study demonstrates that BIPV holds significant promise for optimizing land use in areas with scarce resources while generating substantial energy and reducing CO_2 emissions. This conclusion is reinforced by feedback from decision-makers during participatory sessions conducted in Jakarta. Several analyses were conducted: sun irradiation, energy yield estimation, and environmental benefits for different facade orientations. The user interface was also developed to allow direct interaction to perform the BIPV simulation using a 3D geometry model on a map table during the participatory workshop involving nine different institutions. The participatory session to inform the stakeholder of BIPV's potential represents the novelty of this research. The feedback received during these sessions was evaluated based on usability and added value indicators.

The anticipated findings will be a starting point for BIPV enhancement in Indonesia to contribute to the country's efforts to combat climate change.

Keywords: BIPV, stakeholder participation, 3D model, map table, Jakarta.

ACKNOWLEDGMENT

"Pa, I did it! Your daughter finally fulfilled our last dream and her last promise to you"

This thesis, I fully dedicated to my late dad, my mother, my younger brother Bulip, my youngest sister Pijong, my old sister and her husband, also their energetic kids. Thank you for always being there support me and fully trust my decision without questioning it. Especially my mom, and our youngest, though she is a cry baby, she helps to take care of me when I could not even move an inch.

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The last I want to mentioned, Thanks to myself that you working this hard and still alive. The future me when you read back this thesis, you already be someone who her idea, voice, knowledge are being carefully respected by others. People will listened to you, despite you are woman. You will be involved in many important decision though you are a woman. Your idea will be heard, though you are a woman. The future me, I hope people see us as a human being, lets live a happy life start from today.

*ps: I am sorry if I miss out to mentioned someone's name, I might be forget (but you know my habit right :3)

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LIST OF ABBREVIATIONS

3D	Three-dimensional
ADB	Asian development bank
BAPV	Building Applied Photovoltaic
BIPV	Building Integrated Photovoltaic
BIM	Building Information Modeling
BP	British Petroleum
BPS	*Badan Pusat Statistik*
BRIN	*Badan Riset dan Inovasi Nasional*
CAD	Computer-Aided Design
CBD	Central Business District
CdtE	Cadmium Telluride
CGA	computer-generated architecture
CIS	Copper Indium Selenide
CO_2	Carbon Dioxide
COP26	Conference Of the Parties 26th
CTBUH	Council on Tall Buildings and Urban Habitat
c-Si	Crystalline Silicon
DSM	Digital Surface Model
EPW	Energy Plus Weather
IESR	Institute for Essential Services Reform
IPCC	Intergovernmental Panel on Climate Change
IPB	*Institusi Pertanian Bogor*
LoD	Level of Detail
GHG	Greenhouse Gas
GIS	Geoinformation Science
$GtCO_2$	Gigaton of Carbon Dioxide
Kementerian Bappenas	*Kementerian Perencanaan Pembangunan Nasional Republik Indonesia / Badan Perencanaan Pembangunan Nasional*
Kementerian BUMN	*Kementerian Badan Usaha Milik Negara*
Kementerian ESDM	*Kementerian Energi dan Sumber Daya Mineral*
NZEB	Nearly zero-emission building
PLN	*Perusahaan Listrik Negara*
PoC	Proof of Concept
PSS	Planning Support System
PV	Photovoltaic
rpk	rule package
SCBD	Sudirman Central Business District
SOL	Solar Out of Lidar
TMY	Typical Years
TWh	Terrawatt hour
UN	United Nation
UX	User Experience

1. INTRODUCTION

1.1. Background

Human-induced global warming is the core of climate change because human behavior in the way of living triggers the greenhouse gas (GHG) effect worldwide (P.R. Shukla J et al., 2022). As a result, the temperature rises up to 1.1 degrees Celsius in 2020, and about 2400 ± 240 ($GtCO_2$) carbon dioxide is emitted in a century (P.R. Shukla J et al., 2022). Concern about the impact of climate change, the united nation (UN) released the mitigation scenario in the IPCC report 6. One plan to reach zero net emissions by 2050 is the phasedown of coal usage and its replacement with clean energy (Bauer et al., 2018; Michael, 2022). However, cutting off coal usage is not easy to carry out, as it is a cheap energy source, and many countries rely on coal to support many fields, such as electricity power (P.R. Shukla J et al., 2022). It has become an important economic value in some developing countries (Peszko et al., 2020).

Indonesia is one example of a country that both exports and consumes a large amount of coal. The country is known as the biggest coal exporter and number seven in coal consumption in the world (British Petroleum, 2022). Based on (PLN, 2020), about 68 billion tons of coals are utilized for electricity support, and about 56% of the electricity supply comes from coal. It was estimated to be about 149.9 million tons of CO_2 from electricity coal power in 2021 (Kementerian ESDM, 2021b).

Concerned about the mass activity of CO_2 emission, Indonesia's president supported the Paris Agreement and the COP26 meeting in Glasgow (Kementerian ESDM, 2021a). To put into commitment, the Ministry of Energy and Mineral Resources has created a long-term strategy for low carbon and climate resilience (LTS-LCCR) to reach zero net carbon emission by 2060. Starting to reduce 29% of CO_2 in 2030, Indonesia focuses on building up the energy transition that will be dominated by solar power.

Located on the equator line, Indonesia has an annual average solarization of 12 hours per day (Arif Budiyanto & Nawara, 2017; Putranto et al., 2022). Based on Budiyanto & Lubis (2020) research comparing ten models to estimate solar radiation in Depok, Indonesia, the results show that the average global solar radiation is around 900 W/m^2 (Watt per meter square). Compared with the earth's solar radiation flux value (solar constant) of about 1367 W/m^2, the estimated amount of solar radiation illuminated in Indonesia by Budiyanto & Lubis (2020) research is considerably high. In addition, Indonesia's daily average solar time is regular ± 12 hours per day; this geographical condition brings great potential to utilize solar photovoltaic (PV) in the country (Sumarsono et al., 2022).

Acknowledging the promising prospect of clean energy from solar power, Indonesia's government has created three solar PV projects to achieve the renewable transition goal, where the two projects focus more on underdeveloped and rural areas, and the third project focuses on PV rooftops (Kementrian ESDM, 2021). Meanwhile, the most populated region is Jakarta city, with more than 10 million living in the city, with a population growth rate of about 9.2% in the last decade (BPS, 2020; BPS, 2022). The population will keep increasing in the future, as the population growth in the urban area of developing-country will be the most significant outgrowth (P.R. Shukla J et al., 2022). It is proven that the vast rising number of electricity consumption in urban areas for the past decade has increased by about 161% (Brito et al., 2017; P.R. Shukla J et al., 2022).

The third national project mentioned above is related to mounting PV on the building's rooftop that targets the city area, which might be a positive opportunity. However, for a city like Jakarta, with plenty of skyscraper buildings, the façade area is larger compared to the rooftop. The energy generated from the rooftop PV might not lighten up the energy consumption of the buildings (GSEP, 2018; Panagiotidou et al., 2021). At this moment, optimizing the solar PV potential on the building façade, a vertical PV, can be a prominent perspective to support the net-zero energy buildings and correspond to the land scarcity issue in the city area (Donn & Garde, 2014; Munari Probst et al., 2013; Scognamiglio & Garde, 2014). Therefore, most of the studies about vertical solar panels focus on the design part (Hamzah & Go, 2022), the technical part (Manoj Kumar et al., 2018), setting the decision criteria (Desthieux et al., 2018), or policy analysis (Hewitt et al., 2020). However, no prior study explains vertical solar panels in an interactive way through stakeholder engagement by performing a simulation for the decision-makers who are the primary actor in renewable energy activity. Informing decision-makers about the potential mitigation intervention to lessen the impact of climate change is important, as decision-makers decide the regulation pathway and the nation's project implementation. These informing activities can be assisted through stakeholder engagement.

This study aims to develop a framework that can be an aid to inform Indonesia's decision-makers about climate technology options for dense urban areas, namely vertical photovoltaic integrated into the building's façade. The analysis of this study requires the combination of multiple processes, starting with creating a three-dimensional model of the buildings in the study area, then the façade area is evaluated for BIPV installation. Followed by developing the user interface to enable stakeholders to interact with the model and run the simulation on the PSS tool, namely the map table touchscreen. The model and tool were presented to the decision-makers during the stakeholder participation workshop in Jakarta, Indonesia.

1.2. Problem statement

The rapid population expansion in the urban areas urges the high demand for electricity power (S. Freitas & Brito, 2019; Vahdatikhaki et al., 2022). It is predicted that by 2050, the urban areas will increase three times up to 211%, and about 85% of the world's population will live there (P.R. Shukla J et al., 2022; Ramírez-Moreno et al., 2021; Zhang et al., 2022). The significant population growth in urban areas is also due to the migration from rural areas to the city because of economic factors, which are likely to occur in developing countries (P.R. Shukla J et al., 2022; Teller, 2021).

One of the most populated developing countries is Indonesia, rated as the fourth inhabited country globally (World Bank, 2022). The state is also notable for being the second largest coal producer, and about 80% of the production is exported (British Petroleum, 2022). The revenue collected from coal production is estimated to be around 2.21 billion EUR (Arinaldo & Adiatma, 2019). These earnings boost the country's economic revenue and lead Indonesia into one of the biggest Southeast Asia economic markets (Martinez & Masron, 2020). Though Indonesia has a great deal of coal production, the country also supports the climate action plan in the international agreement and commits to attaining the National determined contribution (NDC), with the closest target to achieving a 23% clean energy mix that will be dominated by solar power in 2025 (Kementerian ESDM, 2021b).

Solar power becomes a powerful potential for accessing clean energy (Budiyanto & Lubis, 2020). With the help of PV technology, solar radiation will be captured and generated into electricity (Allouhi et al., 2022). Veldhuis & Reinders (2013) reviewed solar PV's perspective in Indonesia's urban, suburban, and villages area, and it is estimated that the total potential of solar PV energy production in Indonesia is 1492 TWh (Terrawatt hour). Moreover, the daily constant sun-irradiation time strengthens Indonesia's solar potential (Putranto et al., 2022; Veldhuis & Reinders, 2013). Even though Indonesia has enormous clean energy potential, such as solar energy potential, wind power, and hydropower, due to the unfamiliarity with renewable energy activity, the energy generated form the RE activities only reached 0.2% in 2021 (PLN, 2021). For this reason, to support the energy transition goals of solar power in Indonesia, this study focuses on informing decision-makers about the potential climate technology that can be applied in dense urban city areas.

However, applying climate technology in dense urban areas might face the constraint of land scarcity. Even though the city area is a suitable target to perform the energy transition, as the population growth and high electricity consumption fall in the city area, land availability is also another issue that must be considered. Additionally, acquiring land for renewable energy activities in Indonesia is difficult and time-consuming (Kementerian PUPR, 2022). Acknowledge all the difficulties; the climate technology that can optimize the area for renewable energy activity is potentially suitable for the dense city setting. Through this study, the framework for vertical solar photovoltaic using a 3D model and planning support system tool is developed and delivered to the decision-makers in Indonesia.

Nevertheless, stakeholder participation using the participatory support system tool will be an aid in achieving the study's goal mentioned above. However, even though energy transition is a trending topic worldwide, it is rarely heard in Indonesia society, leading to low social acceptance of renewable energy practices. Acknowledge this shortcoming; through this study, the concept of stakeholder participation with a map table as the tool to engage Indonesia’s decision makers to inform the developed framework with the topic of introducing the vertical solar panel is utilized during the stakeholder workshop in Jakarta.

1.3. Wicked problem analysis

According to the Asian development bank (ADB) and World Bank, Indonesia lags far behind in energy transition performance compared to other Southeast Asian countries. The issues of capacity to manufacture the technology, no competencies of development, and lack of innovation, hold back Indonesia from practicing energy transition (Asian Development Bank, 2020). Moreover, while executing the renewable energy project, Indonesia has not yet pursued the current digitalization system (World bank, 2021).

Apart from their incapability, the fast switchover scenario from coal to clean energy creates another issue for developing countries (Stockholm Environment Institute, 2021). It is because most developing countries are known for their rich fossil fuel source and have become reliant on their revenue (P.R. Shukla J et al., 2022; Peszko et al., 2020; Seto et al., 2016). According to Peszko et al. (2020), climate change goals significantly impact a country that depends more on fossil fuel industries.

Referring to British Petroleum (2021), Indonesia is positioned as the world's second-largest coal-producing country. This retaliates that the coal business in Indonesia is profitable and promising (Setyawati, 2020). Therefore, the coal industries are relatively close to the geo-politic situation, and some major shareholders play a role in the political layers (Setyawati, 2020).

As it is a prominent income for the country, the coal industry revenue contributes around 5% of Indonesia's GDP (Cui et al., 2018). However, the climate action goal of reaching zero net emissions implies that the state has to shut down the coal industries, which could cost excessive loss of the nation's income. The other concern that arises is the mass layoffs in the coal businesses. The coal companies might cut off their employees with the force of not producing coal anymore. Additionally, the transition into clean energy possibly increases the electricity price, leading to protests from the citizens.

The primary stakeholder in this study is the decision-makers because the study aims to support Indonesia's energy transition strategy. The current decision-makers position is likely a double-edged between performing the energy transition and phasedown the coal usage. Moreover, the situation on renewable energy could lead to a conflict of interest among the stakeholders affected and potentially arouse chaos. By all means, Indonesia's whole situation of energy transition action is considered a very wicked problem. The socio-economic-political factor: the high possibility of mass layoffs in the coal industry, the decrease in the nation's economic revenue, the geopolitical turbulence of the company's owner, technological incompetence to generate clean energy, the increase of electricity price because of the transition to the clean energy that led into huge protest. This research seeks to lessen the wickedness of filling the technology effectivity by analyzing the potential vertical solar PV on the building's façade.

1.4. Study area

The study area for the current research is Jakarta, Indonesia's capital city. Specifically, the scope of study area selected is at the Sudirman Central Business District (SCBD), as illustrated in Figure 1. The study area landscape is a mixed between offices, hotels, shopping malls, and apartments. SCBD is known as the Golden Triangle of Jakarta and is famous for its commercial zones (Puspitasari & Kwon, 2020). Stereotypically the SCBD territories are viewed as territories full of skyscraper buildings (see Figure 2).

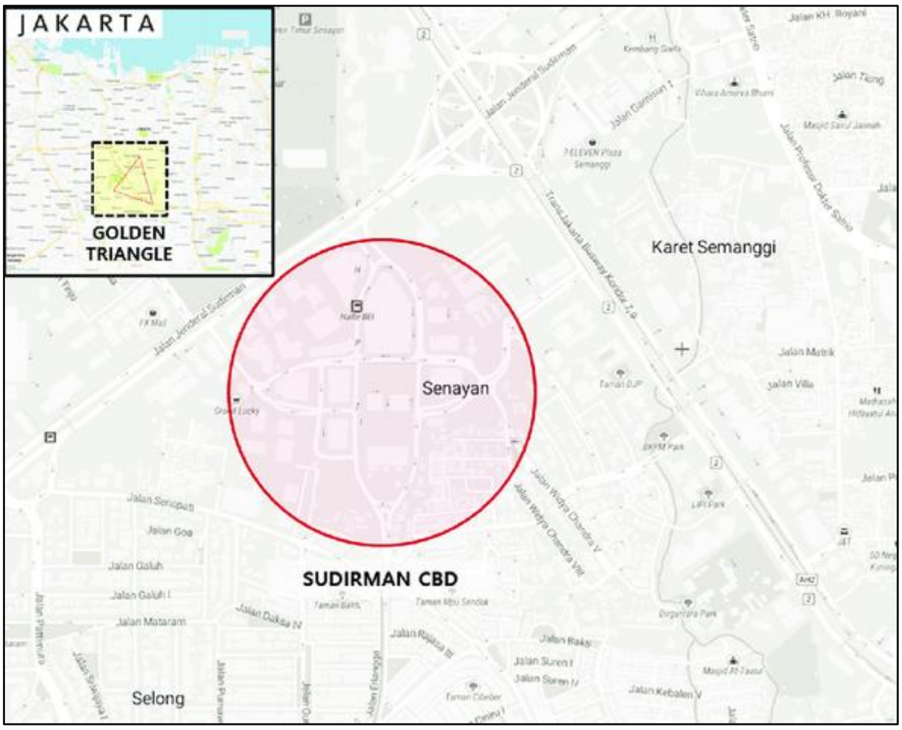

Figure 1 Potential study area: the golden triangle CBD Jakarta. Figure from : (Puspitasari & Kwon, 2020)

To address the focus of research on evaluating the dense urban setting area with skyscraper buildings, the SCBD area, which aligns with the aim, is chosen as the main study area (see Figure 2). Through the SCBD area as the study sample, the expected outcome serves as an example proof-of-concept of the BIPV evaluation of the dense urban situation in Jakarta, Indonesia.

Figure 2 Central business district Jakarta. Figure from: (SCBD[1], 2022)

1.5. Research objective (s) / research questions

The main objective of this study is: "to develop a framework for informing the stakeholders about vertical solar PV on building facades installation using 3D city modeling on a PSScience tool". To support the aim of the research, several sub-objectives and research questions are listed below:

[1] https://scbd.com/menu/page/home

1.5.1. Sub-objectives

The sub-objectives that will be covered in this study are:
1. To review the methods and software applications applied for solar potential analysis on the building's façade.
2. To develop a 3D city model for vertical PV simulation.
3. To evaluate the potential façade area for BIPV installations.
4. To develop the PSS map table tool design for vertical PV simulation.
5. To evaluate the stakeholder's feedback on the developed framework.

1.5.2. Research questions

The detailed research questions of the sub-objectives mentioned above are elaborate in this section:
Sub-Objective 1:
1. What potential existing tools can be applied to the study?
2. What are the datasets applicable to the study?
Sub-Objective 2:
1. Which method fits with the available datasets for BIPV assessment?
2. How to integrate the different datasets to develop a 3D model?
Sub-Objective 3:
1. What is the method to calculate the solar irradiation potential?
2. How much can CO_2 emission be reduced from a BIPV installation?
Sub-Objective 4:
1. How to design an interactive tool to demonstrate vertical PV simulation?
2. How will the stakeholders test the model with the map table tool?
Sub-Objective 5:
1. What is the stakeholder's review of the developed framework?
2. How to assess the usefulness and usability design of the model and tool?

1.6. Thesis structure

The thesis structure compiles six main chapters, annexes, and references. Each chapter corresponds to resolving the research objective and research questions. The overview flow for each chapter and more explanation will be described below:

Chapter 1: Introduction
Chapter one provides the research's background information and problem statement, including all the research objectives.
Chapter 2: Literature review
Chapter two mainly discussed the previous study, the research gap, and potential methods and datasets applicable to the study.
Chapter 3: Methodology
Chapter three describes the methods and concept theory applied in the research.
Chapter 4: Result
Chapter four explains the obtained results and the developed framework.

Chapter 5: Discussion
Chapter five discusses the study's findings, limitations, recommendations, and explanations for answering the sub-objectives.
Chapter 6: Conclusion
Chapter six explains the conclusion of the study.
Annexes
The supporting result and process not included in the main text are arranged here.

1.7. Summary

Section one briefly describes the research to comprehend the study's reason better. The research's objectivity is also presented, followed by explaining the thesis structure.

2. LITERATURE REVIEW

This chapter starts with an overview of previous studies to shape the state-of-art and research gap that will be filled in this study in section 2.1. Then continue reviewing potential existing methods and datasets that can be applied in this research (section 2.2). At the end of the chapter, the overall summary is provided.

2.1. Previous study – The research gap

Through its technological improvement, the PV module reaches a modest level to be integrated into the architectural façade structure, so be called vertical PV (Heinstein et al., 2013). Whereas the technology is part of Building integrated Photovoltaic or BIPV. The vertical solar panel is becoming one of the trends as a climate technology to help the global warming mitigation that does not require extra space; also a potential innovation to increase the electrical efficiency of buildings (S. Freitas & Brito, 2019; Panagiotidou et al., 2021; Probst & Roecker, 2012).

Acknowledgment of the potential of BIPV has encouraged the researchers to discuss building-integrated photovoltaics in several domains and concentrations. For instance, in terms of a suitable 3D model design approach, such study from Salimzadeh et al. (2018) developed a BIM model that focuses on creating classes of the surface of building envelopes, such as exterior walls, roofs, curtain walls, and windows, for surface solar simulation, which was used in later research Vahdatikhaki et al. (2022) to design PV modules. According to the author, such detailed attribute of the BIM model is necessity and helpful to select the PV modules. Additionally, they recommended applying the whole year period for solar simulations and continuing their study in the Vahdatikhaki et al. (2022) paper to develop the generative design of PV layout framework for tall buildings. In their findings, the BIM model in the level of detail (LoD) 350 is suitable for designing the new construction; meanwhile, for the existing building, it is preferable to the BIM model in LoD 400 or 500. Their research also shows that even the low radiation area can remain profitable for a certain period.

Other subsequent studies of BIPV in more detail in modules and systems. Manoj Kumar et al. (2018) study comparing the performances of building integrated photovoltaic (BIPV) and building applied photovoltaic (BAPV) with three different photovoltaic module cells technologies, namely: crystalline silicon (c-Si), Copper Indium Selenide (CIS) and Cadmium Telluride (CdtE) in Malaysia. The study concludes that CdTE sollar cells performed the best in terms of annual energy yield and losses compared to CIS and c-Si. Meanwhile, in comparison between BIPV and BIPV performances, BAPV has performed slightly better than BIPV. Martín-Chivelet et al. (2022) reviewed the energy behavior on BIPV systems performance, explaining the efficiency of BIPV performance depending on the module's electrical state, where electrical efficiency linearly decreases when the temperature increases. Moreover, the author mentioned that the main parameter of BIPV module efficiency is based on the degree of transparency and the module's color.

Even though there are plenty of studies of 3D façade analysis on high-rise buildings, there has not yet been any study in Indonesia. Most of the studies related to renewable energy topic in Indonesia are about the solar potential on a rooftop, sun irradiation analysis, or regarding policy based on energy transition (Budiyanto & Lubis, 2020; Fathoni & Boer, 2021; Fathoni & Setyowati, 2022; Ordonez et al., 2022; Saladin Islami et al., 2021; Setyawati, 2020; Setyowati & Quist, 2022; Sumarsono et al., 2022; Veldhuis & Reinders, 2013).

Additionally, most studies about BIPV mainly relate to technical and spatial analysis and never involve the stakeholder's point of view. To fill this research gap, stakeholders' participation will be involved in this study by using the PSS tool with informing driven tasks. The analysis result will be presented using the PSS tool, and the feedback from the stakeholders will be reviewed.

2.2. Solar radiation analysis for Building Integrated Photovoltaic

Acknowledge the potential of BIPV can be a strategy to mitigate the climate issue in an urban area; there are several studies available to assess the potential of BIPV on a building's facade.

One notable study by Catita et al. (2014) developed the Solar Out of Lidar (SOL) algorithm to estimate the solar potential energy on the roof and façade for urban areas. SOL algorithm specifically requires a digital surface model (DSM) from LiDar as input data. The author claims the developed method allows for analyzing the detailed solar potential for façade in individual units regardless of the façade orientation and obstacles.

In a separate investigation, (Salimzadeh et al., 2018) performed solar potential analyses on the roof and facade using the Revit-Dynamo software. Their study leveraged LiDAR data to construct a Building Information Modeling (BIM) representation of the building, achieving a three-dimensional model at the Level of Detail (LoD) 2. According to the author, LoD 200 is sufficient for PV panel planning and design, where the type and geometry of the building are known. Furthermore, Salimzadeh et al. (2018) extended their findings to identify the optimal locations for BIPV installation by integrating generative design optimization techniques.

Other subsequent studies by Brito et al. (2017) applied the Solar Out of Lidar (SOL) algorithm, initially developed by Catita et al. (2014), for analyzing PV potential on roofs and facades at the cityscape level using LiDAR and meteorological data. The researchers verified that local energy yield production could fulfill the total electricity demand from photovoltaic technology in daylight if the combination of roof and façade solar potential is fully exploited.

There have been studies focused on simulation and scenario, such J. de S. Freitas et al. (2020) chose the Rhinoceros and grasshopper-ladybug plugin to design and simulate potential solar availability on the façade with the input of Energy Plus Weather File (EPW) and a readymade 3D BIM model. While performed several simulations with various BIPV designs, the vertical design occupied more surface area, resulting in better energy balance and higher nominal power. In their study, the author discussed using the Rhinoceros and grasshopper-ladybug algorithm as effective, relatively easy to learn, and possibly performed with simplified geometries. However, the author also mentioned that the time requirement of the simulation processes ranged between 2 minutes to 6 hours, explaining that the larger surface areas required more simulation time. Quintana et al. (2021) combined Revit to create the 3D BIM model and the PVSITES toolkit to perform the solar analysis on the roof and façade with three buildings in different orientations and obstacles scenarios. In their research, tree obstruction does not significantly impact electricity production losses. Thus, the author stated that the applied toolkit is expected to fill the gap between building and energy performance modeling.

Meanwhile, Waibel et al. (2022) created a new plugin: HIVE, to perform the solar analysis and BIPV simulation. Described as a suitable tool for the early conceptual design stage, HIVE can support the geometry model with low-detail components. Moreover, Waibel et al. (2022) highlighted HIVE approach is to fill the gap of transfer knowledge with fast simulation time, which is befitting to help stakeholders understand the concept of energy-integrated building design Waibel et al. (2022).

Considering this study is presented to the stakeholders, which requires fast feedback and computational time of the simulation. Therefore, the HIVE tool is preferred to be used for the research. A detailed explanation of the tool applied can be seen in Chapter 4.6.

2.3. Stakeholder engagement with interactive planning support system tool

With the complexity of working with multiple actors, the planning support system (PSS) was introduced to engage stakeholders in various fields (Pelzer et al., 2014; Pelzer, Geertman, & van der Heijden, 2015). According to Geertman (2008), PSS is a geo-information technology instrument supporting specific task-based functions. It is important to note that PSS is developed based on mutual interest and cannot be used for other contexts without adaptation (Geertman J, 2020). Interactive PSS has been widely used to support energy transition activities which is the focus of this study. For instance, Flacke & De Boer (2017) developed an interactive PSS tool called COLLAGE to facilitate stakeholders providing the installation option of renewable energy to increase stakeholder awareness and address the social learning issue. Another research done by Hewitt et al. (2020) also applied the COLLAGE tool to support local-scale energy transition.

PSS tool is always designed on a specified goal-oriented approach and provides a concrete view of the goal with its ability to offer information and enlighten the process (Brömmelstroet, 2013; Geertman, 2008). In te Brömmelstroet (2017) paper explicitly points out PSS tool can be an aid to cope with wicked situations where there is no clear answer or solution by providing the support task.

Based on Vonk (2006), the PSS has three main support tasks: (1) Informing, (2) Communication, and (3) Analyzing. Each category has a different provision; in informing tasks, the approach is one-way interaction to provide the information to the users. Meanwhile, communication support has the function of offering two-way direct interaction between the stakeholders. Analyzing tasks allows PSS to solve problems by creating a model or design.

One example of an interactive instrumental tool of PSS is the map table, which has been adopted in some studies to facilitate the tasks mentioned above and enhance stakeholder interaction (Aguilar et al., 2020; Flacke et al., 2020). The map table is illustrated as a horizontal touch screen (see Figure 3) that allows stakeholders to stand around the tool, creating an interactive stakeholder engagement (Hewitt et al., 2020). This innovative approach promotes effective stakeholder engagement by providing advanced visual features like running simulations and manipulating 3D models. Through these advanced visualizations, the map table overcomes the limitations of paper-based participatory and provides more information for discussions.

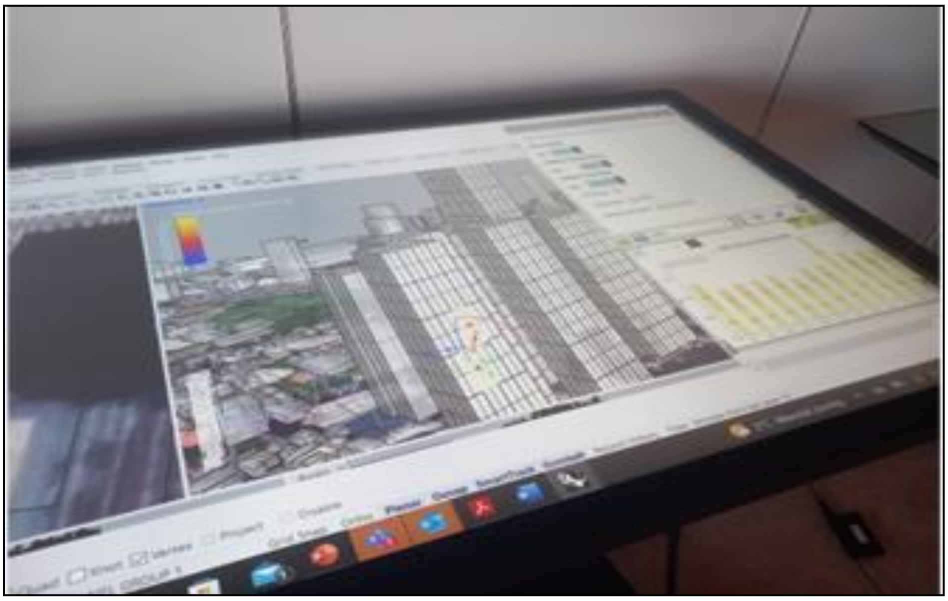

Figure 3 Output on map table (Figure Source: Author)

A typical stakeholder engagement using an interactive PSS tool is arranged with a PSS workshop (Flacke et al., 2020). The workshop possibly assists in controlled experiments where the specified user group tests the tool under certain conditions to evaluate the tool's usability and close to real-world stakeholders (Aguilar, 2022). In close to real-world stakeholder workshops, the set is more complex to implement, but it provides abundant information and added value from their expertise and experience (Aguilar, 2022).

The interactive stakeholder workshop using a map table fundamentally can be performed at different times (synchronous or asynchronous) and spaces (distributed or co-located (Aguilar et al., 2020; Isenberg et al., 2011; Maceachren & Brewer, 2004). These situations also deliberately describe as '*four meeting situations*': (i) co-located asynchronous: where it took the same location but different time, (ii) distributed asynchronous: occurring in different locations and time, (iii) co-located synchronous: when it is same location and time, and (iv) distributed synchronous: explained different location but same time setting (see Figure 4).

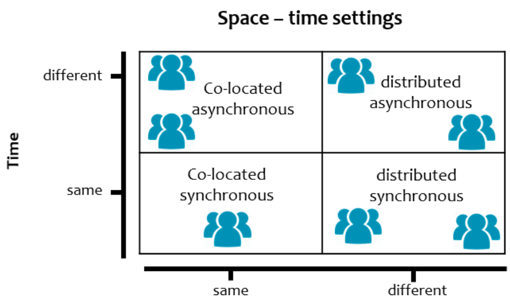

Figure 4 Workshop setting (Figure Source: Aguilar et al., 2020)

2.4. Stakeholder engagement activity in Indonesia

To find out the current participatory types in Indonesia, the author tried to find from the literature and discovered that the majority of the stakeholder participation is conducted using paper-based content (Sulistyawan et al., 2018), such as drawing maps on paper (Budisusanto et al., 2018). The only finding of participatory with digital PSS tool is through the papers published by the same author (Aguilar et al., 2021; Akbar, Flacke, Martinez, Aguilar, et al., 2020). They are using a map table to test the tool they developed: *Ogito*, with the participants from the village in Sumatera, Indonesia (see Figure 5) . In addition, (Akbar et al., 2019, 2021; Akbar, Flacke, Martinez, & van Maarseveen, 2020a, 2020b) research illustrated that the typical public participatory activity in Indonesia was similar to the classroom setting, where the participants only sit and listen without any interaction and active discussion.

Considering the target audience of this study is the decision-makers that focus on renewable energy activities in Indonesia, the detail information for each stakeholder can be found in section 3.5.1. The user experience (UX) is expected to be brought during the stakeholder engagement activity for this study.

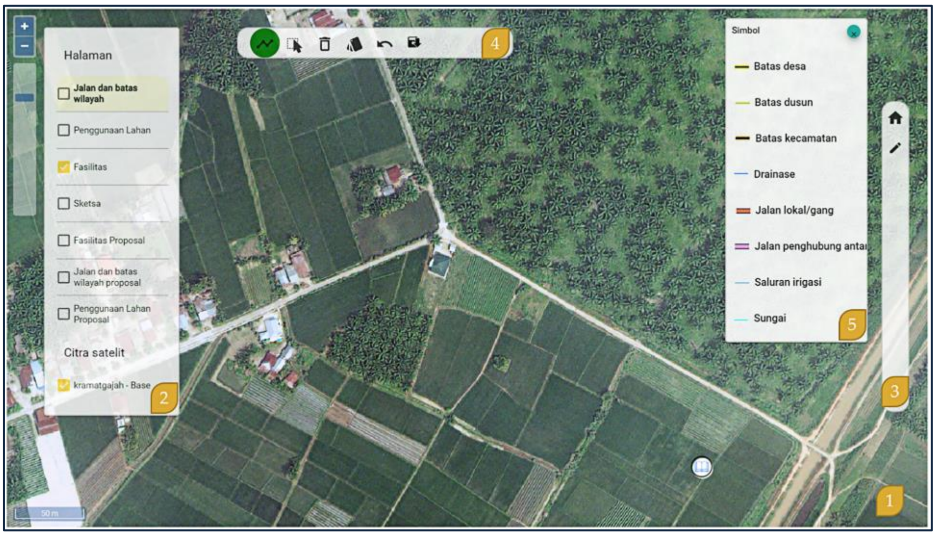

Figure 5 OGITO interface (Figure Source: Aguilar et al., 2021)

2.5. Summary

In this chapter, the author discusses how the current research gap will be addressed through this study, which includes exploring potential methods and datasets that can be applied to this research. Furthermore, this chapter provides an overview of stakeholder engagement using a planning support system tool called map table and highlights stakeholder engagement activity in Indonesia. The subsequent chapter will focus on describing the methodology applied in this study.

3. METHODOLOGY

This chapter substantively explains the methodology conducted of the developed framework. The methodology is structured into five phases corresponding to this study's sub-objectives representing developed framework stages. The activities start with pre-processing that focus on reviewing the potential methods and datasets collection, then continue with phase two to develop the 3D model, followed by phase three to evaluate the area of the building's façade for BIPV installation. Afterward, the PSS tool is designed to allow human-computer interaction on the map table, and the last phase is where the model and tool are developed and evaluated by the decision-makers in Indonesia. Figure 6 highlights each phase that is represented in different colors and numbers. The upcoming sub-section explains the methods of each phase, starting with Phase-1 until Phase-5.

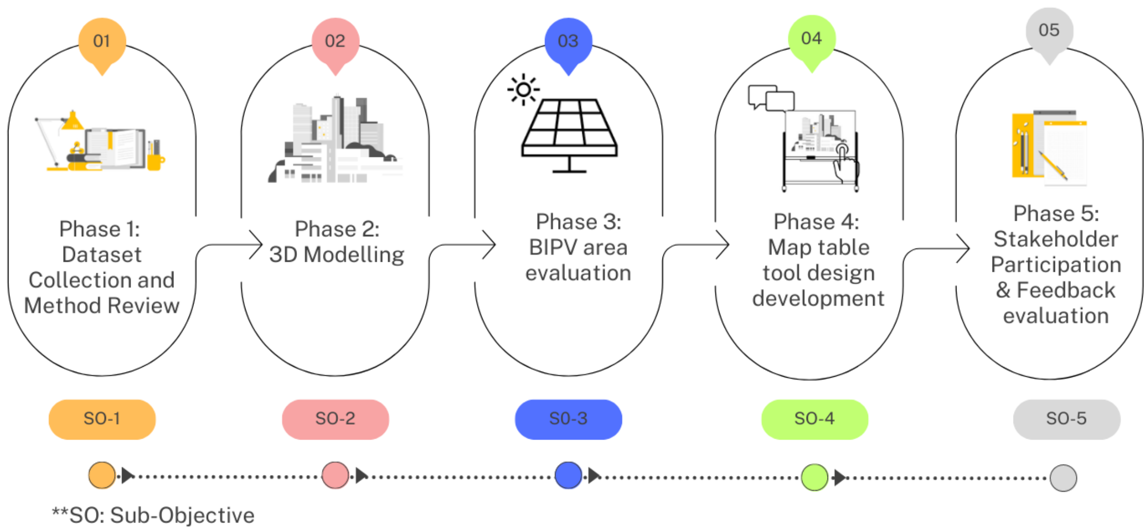

Figure 6 Methodology of the study: 5 Phases (Source: Author)

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3.1. Phase one: Dataset collection and method review

Phase one of this study primarily focused on data collection and literature review. The literature review was discussed to find out the existing potential methods and tools potentially utilized for this study which is presented in Chapter 2.2. Meanwhile, the dataset collection subsequently elaborates in the sub-section below.

3.1.1. Dataset Preparation

The dataset collection flows shown in Figure 7 contain three different types of data: textual document, vector data, and raster image. Geospatial and textual datasets were combined to develop the three-dimensional models.

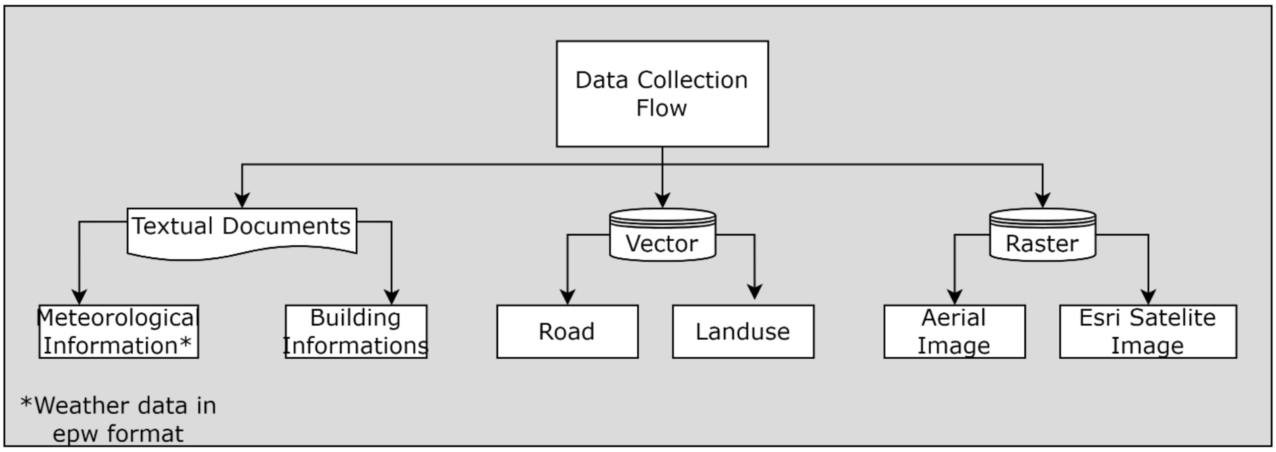


Figure 7 Data collection flow

The majority of datasets applied in this research are publicly open-source data accessible through online platforms, except the aerial image dataset provided by the Ministry of Spatial Planning and land affairs of Indonesia. Table 1 presents a comprehensive overview of the datasets collected for this study. Subsequently, each dataset is elaborated in the following sections.

Table 1 Overview of datasets collected.

Dataset	Type of data	Source	Use in study
Road	Vector	Provincial government website[2]	Counter-check location while delineating building footprints
Aerial image	Raster	Ministry of Spatial Planning and land affairs of Indonesia	Base map to create the 2D map and 3D model
Esri satellite image	Raster	ESRI world imagery	Building identification and building footprint delineation
Building information	Textual	CTBUH[3] and the companies website	Building identification and data tabulation
Weather data information	Textual	Open source website of weather datasets[4]	Irradiation analysis and BIPV evaluation

3.1.1.1. Weather dataset

The weather data information was obtained from the open-free source: *ClimateOneBuilding*[5] repository in Typical Meteorological Years (TMY) format. The dataset provides hourly information and follows the TMY/ISO 15927-4: 2005 methodology (Bre et al., 2021). The TMY file contains various datasets and information, including the Energy Plus Weather (*Epw*) format, which serves as the input for the study. The weather station that captured the information is located approximately 8 km from the study area.

[2] https://jakartasatu.jakarta.go.id/
[3] https://www.ctbuh.org/
[4] https://climate.onebuilding.org/
[5] https://climate.onebuilding.org/

3.1.1.2. Building information

Information about the buildings in the study area was gathered from multiple sources, including the Council on Tall Buildings and Urban Habitat (CTBUH) and the buildings' personal websites. The data compilation consists of building height, estimated number of floors, year of construction, and function. In total, 35 buildings were successfully identified, which can be found in ANNEX A: Buildings Identification.

3.1.1.3. Vector datasets

The vector data was acquired through the official website of DKI Jakarta's province[6]. All the data provided on the website are free and open source. The road vector data serve as an additional reference to locate the buildings' footprint, also used as a base layer on the map table.

3.1.1.4. Raster datasets

Two raster datasets are used as the base map for delineating the building footprint: an aerial image with a 10 cm resolution and a 1m resolution of ESRI world imagery. Though aerial image provides a high-resolution product, but it was captured in 2012. Concerning the landscape change over time, the ESRI world imagery was applied for the base map of the digitation process.

The combination of two raster datasets used as the base for delineating the building footprint: an aerial image with a 10 cm resolution and a one-meter resolution image from ESRI world imagery. While the aerial image provides a high-resolution product, it was captured in 2012. Considering the changes in the landscape over time, the ESRI world imagery was used to support identifying the newer buildings in the digitization process.

3.2. Phase two: Three-dimensional modeling

The three-dimensional modeling defined the real-world scene, infrastructure, and environment setting in the digital setting (Biljecki et al., 2015b; Billen et al., 2014; Ohori et al., 2022; Zhu et al., 2009) that prompt to be fundamental features to replicate the buildings and the environment condition, e.g., sun radiation for BIPV assessment.

Developing the 3D model requires specific datasets, which the least is the building's footprint vector data and height information to extrude the buildings into simple box form. However, contemplating the inexistence of any single information and building footprint dataset in the study area, the manual vectorization of the 2D map was also performed in this phase.

The overall workflow in phase two is displayed in Figure 8 and is divided into two main parts: (i) 2D map creation and (ii) 3D model development. In the 2D map creation part, the process starts with formatting and transforming all the datasets collected, followed by building footprint delineation and data tabulation. Data tabulation functioned to store the attribute information inside the building footprints. Subsequently, the 2D vector map becomes an input for developing the 3D model.

[6] https://jakartasatu.jakarta.go.id/

The 3D model this study developed using a procedural or rule-based approach. This procedural approach employs a unique shape grammar known as computer-generated architecture (CGA), which is saved in a rule package (*rpk*) format (Esri, 2022). Further details on the methods applied in 2D map creation and 3D model development are explained in the following sub-section below:

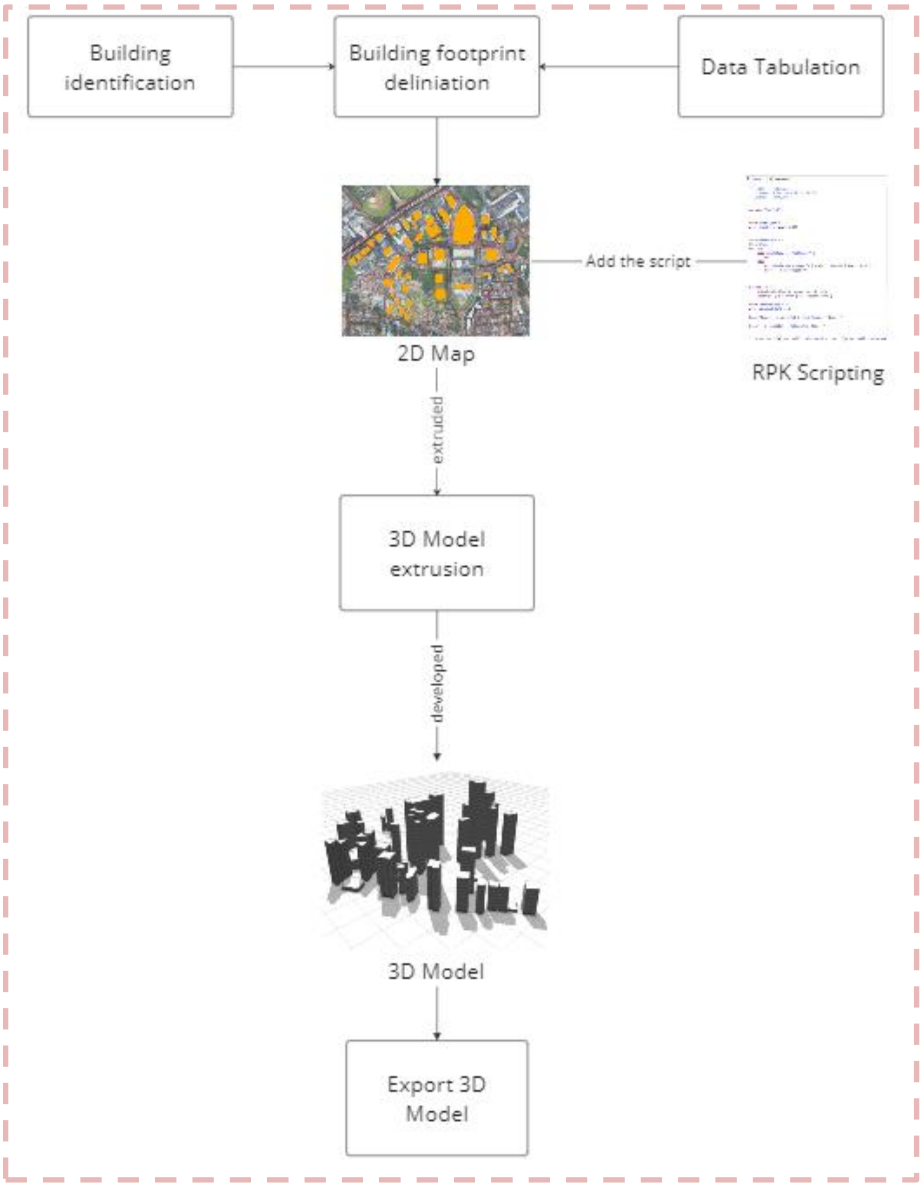


Figure 8 Phase two proposed workflow

3.2.1. 2D Map Vectorization

A combination of various datasets was utilized to create the two-dimensional map as the foundation for building the 3D model, including vector data such as roads and raster data such as aerial and satellite images. The delineation process involved manual digitizing using an on-screen technique, which is notably more suitable for digitizing aerial or satellite images (Knippers & Tempfli, 2013).

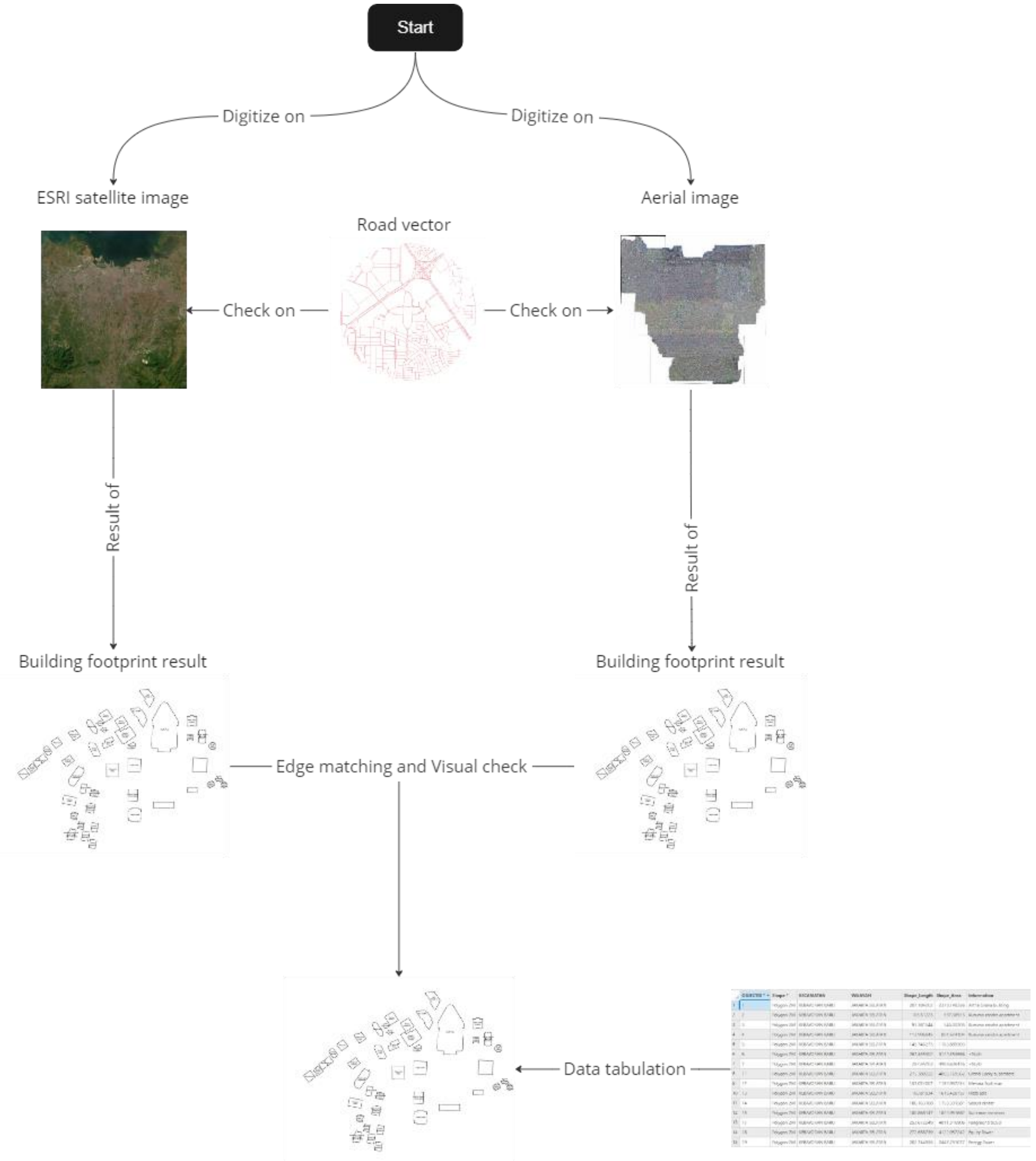


Figure 9 2D map vectorization workflow

The edge matching and visual check were performed to ensure the accuracy of utilizing two different base map resolutions when delineating the building footprints (Knippers & Tempfli, 2013). The decision to use two raster images was based on the fact that the aerial image was captured in 2012. However, due to landscape changes over the years, a satellite image was employed to assist in delineating newer buildings that emerged after 2012. Overall two-dimensional map vectorization workflow is depicted in Figure 9.

3.2.2. 3D Modelling: Geometry method

The three-dimensional modeling defined the real-world scene, infrastructure, and environment setting in the digital setting (Biljecki et al., 2015b; Billen et al., 2014; Ohori et al., 2022; Zhu et al., 2009) that prompt to be fundamental features to replicate the buildings and the environment condition, e.g., sun radiation for BIPV assessment.

(Ying et al., 2020) explain the current methods to create three-dimensional modeling: Topological and Geometric modeling. Topological methods emphasize the strong bond of structural design from three-dimensional objects without concerning the location. Even though the coordinate is shifted, the topological method manages the design consistency (Li et al., 2017). On the other hand, geometric methods are connected directly to the position of the objects. The model utilizes the primitive, e.g., point, line, surface, solid, and components, to depict the 3D model.

This study applies explicitly the geometric method where the model has a strong bond with object coordinates, and the 3D model developed here is made with a GIS-based application. The representation for the model, also known as the level of detail (*LoD*) (Kolbe, 2009), reaches LoD1: a simple box representation extruded from 2D building footprints with textual height information (Gröger & Plümer, 2012; Ying et al., 2020).

The *LoD* (Level of Detail) class plays a pivotal role in determining the visual structure of a 3D model. As the *LoD* increases, the output of the 3D model becomes more pronounced, closely mirroring real-world features. Thus, the role of data input is crucial in achieving this level of detail. By providing more data, the 3D model result will be more detailed and closely resemble the actual object. Each LoD level represents a different completeness achieved in the 3D model. However, due to the scarcity of available datasets, this study can only reach LoD level 1 (refer to Figure 10).

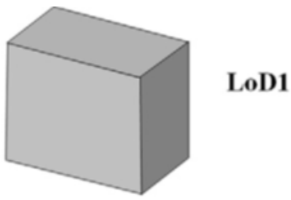


Figure 10 Example of LoD level one (Gröger et al., 2008)

3.3. Phase three: BIPV evaluation

Phase three primarily focuses on evaluating the BIPV (Building Integrated Photovoltaics) area using CAD environment software as the main processing tool. The workflow for this phase is illustrated in Figure 11. The first step involves analyzing the sun path projection, plotted on a polar chart, also known as a stereographic diagram (refer to Figure 12). This analysis uses the *sun path* function and requires an input of an Energy Plus Weather file (*epw*) dataset (Sadeghipour Roudsari & Pak, 2013).

The next step is to conduct a facade analysis using the radiation rose function to determine the amount of radiation on the area with a fixed tilt from different orientations (Sadeghipour Roudsari & Pak, 2013). In this study, the analysis focuses on a single fixed angle at 90 degrees, representing a flat vertical facade. The purpose is not to find the optimal tilt but to analyze the radiation in a specific configuration. All the analysis results are presented in grid cells with a value of 1 meter.

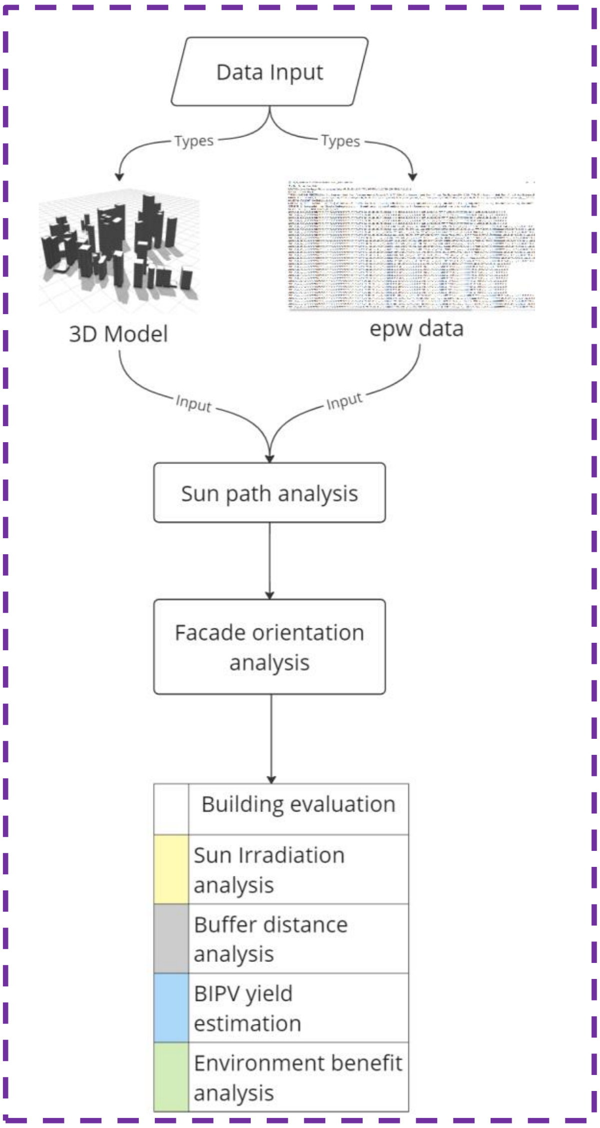


Figure 11 Phase 3: BIPV evaluation proposed workflow

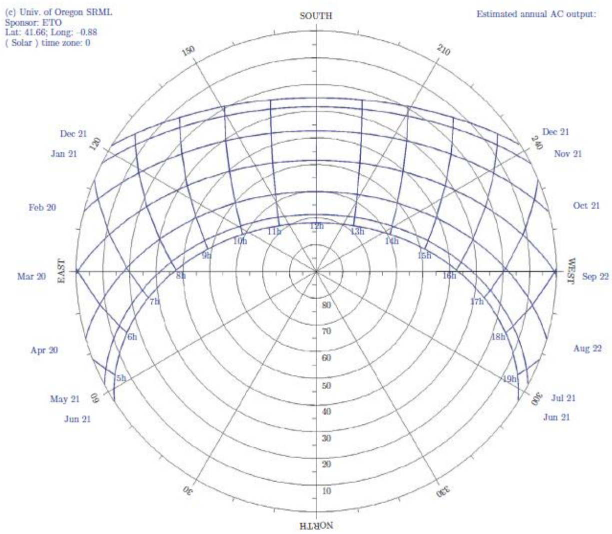


Figure 12 Example of the polar chart (Figure source:(P J, 2019))

Subsequently, the final part of phase three involves evaluating the building facade through several analyses, namely: (i) sun irradiation analysis, (ii) buffer area analysis, (iii) energy yield estimation, and (iv) environmental benefits: potential CO_2 reduction. In the following sub-section, the author explains the buildings being evaluated and the methods employed for these analyses.

3.3.1. Evaluated Buildings

Considering this study aims to inform stakeholders about the potential of Building Integrated Photovoltaics (BIPV) to support climate mitigation plans in dense urban settings. To achieve this, a proof-of-concept (*poc*) for BIPV evaluation started with six buildings: Prosperity Tower, FWD Tower, Mandiri I Tower, Mandiri II Tower, Residential the 8th Tower A, and Residential the 8th Tower B (refer to Figure 13). The author chose the buildings based on specific criteria: they are above 100 meters tall, surrounded by at least two obstructions from different orientations, and not the tallest in their respective blocks. These criteria were initially set to depict the potential of receiving sun irradiation for buildings located in complex landscapes where buildings with varied heights stand close to each other. Furthermore, these criteria were created to encourage open discussion with stakeholders about the sun's position concept in the sky and surrounding obstructions that can influence the radiation reaching the building's façade. Rather than choosing the tallest building that inarguably would naturally receive direct solar radiation without obstacles surrounding the environment (Sarbu & Sebarchievici, 2017).

Additionally, to avoid the stakeholder focusing more on tools and being distracted by many options (Pelzer et al., 2014), the proof-of-concept using six buildings is applied in the study. For detailed building information, refer to Annex A: building identification result and the map location of the buildings can be found in Figure 24.

Figure 13 The buildings evaluated: Menara mandiri I & 2, Prosperty tower, FWD tower, Residential Tower A&B (from left to right). (Figure source: (CTBUH, 2023))

The evaluation of the façade area focuses on the orientation of the façade, which is divided into four directions: north, east, west, and south. The panel's location on the façade is portrayed in Figure 14. Start with number 0 from the below left of the building and finish with window number 15 on the top right of the façade. Take into account the *Rhino-grasshopper* nature, and the numbering always starts with 0. Each panel in the area evaluation represents a window (referred to as "win" or "w") for simplicity in explaining the results. To avoid the system freeze during stakeholder participation, the author has pre-made the building paneling to facilitate and streamline the BIPV simulation for end-users. After the initial test, the building's façade is divided into 16 panels per façade with window panels embedded onto the surface at a fixed tilt of 90º. These occurred to provide a balance between computing time and realistic panel options for the users, which prevents the tool simulation from becoming the prime focus and negatively impacting the discussion during the participatory session (Goodspeed, 2013).

Figure 14
Windows panel

The panel sizes vary for each building, as the process is automatically divided into 16 by the software, and it is important to note that this research aims to inform that BIPV is the potential climate technology, not focused on designing the BIPV system itself. Nevertheless, the façade evaluation addressed the façade for each building with the corresponding of the building's location towards the surrounding obstruction, and not for the comparison across the building.

Even though the result of the facades evaluation is constant, but through the user experience (UX) from direct human-computer interfaces (Moizer et al., 2019; Nowakowski, 2020) is expected to bring a valuable aspect before-during-after the interaction (Vermeeren et al., 2010) that meets the goal of the stakeholder participation. Additionally, Biasutti (2011) addressed the flow theory concept that participants are motivated when they are engaged in the activity and create an optimal experience for the user experience. These emphasized the importance of the users experiencing the simulation alone despite the evaluation outcome being consistently unaltered.

Hence, after conducting several experiments to determine the most effective tool for running the BIPV simulation, as explained in the Logbook, the author selected the open-source software HIVE to drive the backend of the BIPV simulation. According to (Waibel et al., 2022), HIVE has been developed to provide almost instantaneous feedback, making it suitable for early-stage pre-design and an effective tool for communication with stakeholders.

3.3.2. Sun Irradiation analysis

The performance of solar gain evaluation on the windows panel utilized with HIVE was estimated by applying *Perez sky luminance* (Perez et al., 1993). The *Perez sky luminance* formula illustrates in equation 1 given the calculation at time step *t* for the individual sum of each component: beam ($I_{beam,t}$), diffuse ($I_{diffuse,t}$), reflected irradiance L_t indicates for snow-covers. For this research the snow-covers is not applicable because the study area located in equator line, and reflected irradiance is not considered for the input in the process.

$$I_{G,t} = (I_{beam,t} + I_{diff,t} + L_t)(1 - s(\beta)_t), t = \{1, \ldots, T\} \quad \text{Eq (1)}$$

Where beam irradiance ($I_{beam,t}$) formulated in equation 2, through the *direct normal* radiance (I_{DNI}), the angle between surface incidence angle and incoming solar ray ($\theta_{AOI,t}$) and obstruction level r_t ε [0,1].

$$I_{beam,t} = (I_{DNI,t} \cos\theta_{AOI,t})(1 - r_t) \quad \text{Eq (2)}$$

Equation 3 defined θ_Z and $\theta_{Az\,t}$ as solar zenith and azimuth angle; β stands for surface tilt angle, and $\theta_{Ap\,t}$ is surface azimuth angle (Waibel et al., 2022).

$$\theta_{AOI,\,t} = \cos - [\cos\theta_{Z\,t}\cos\beta + \sin\theta_{Z\,t}\sin\beta\cos(\theta_{Az\,t} - \theta_{Ap\,t})]$$

Eq (3)

In the formula of beam radiation, Waibel et al. (2022) differentiate the geometry obstructions into: solid, permeable, and no obstruction by values within the range of 1 to 0 (refer to equation 4). Solid obstruction refers to structures, such as buildings, where no radiation can pass through the obstruction. On the other hand, permeable obstruction refers to obstacles like trees, where some radiation can still pass through. However, in this study, we only consider solid obstructions because no information is available regarding the presence of trees in the study area.

$$r = \begin{cases} 1, \\ min\,[1, \sum_{p=1}^{P} \Delta l_{p,t}\, K_{p,t}\,] \\ 0, \end{cases}$$

Eq (4)

Continuing with the calculation of diffuse beam using the Perez sky radiance model, estimated in equation 5. Where $(I_{how,\,t})$, $(I_{beam,\,t})$, and $(I_{beam,\,t})$ are horizon brightening, isotropic sky hemisphere, and circumsolar brightening.

$$I_{diff,t} = I_{hor,t} + I_{dome,t} + I_{circ,t}$$

Eq (5)

The detailed explanation of solar irradiation calculation refers to (Waibel et al., 2022) paper.

3.3.2.1. The Solid obstruction concept

When describing the potential sun radiation reaching the façade, it depends on the objects that block the incoming sunlight, also known as obstructions (Wang et al., 2021). These obstructions can come from the surroundings and the self-shadowing of the buildings. In this study, the obstruction is not separately calculated but is instead included directly in the process of sun irradiation calculation. However, to understand the concept that obstructions can decrease the chances of receiving sunlight, this aspect is explained as part of the analysis.

Figure 15 illustrates the incoming sunlight falling on the building façade, providing a visual context of obstructions and the shadowing cast. The extent of obstruction and shadowing is determined by factors such as the sun's location (elevation and azimuth), the height of the buildings that block sunlight, and the distance between each pair of buildings (Schüler et al., 2018).

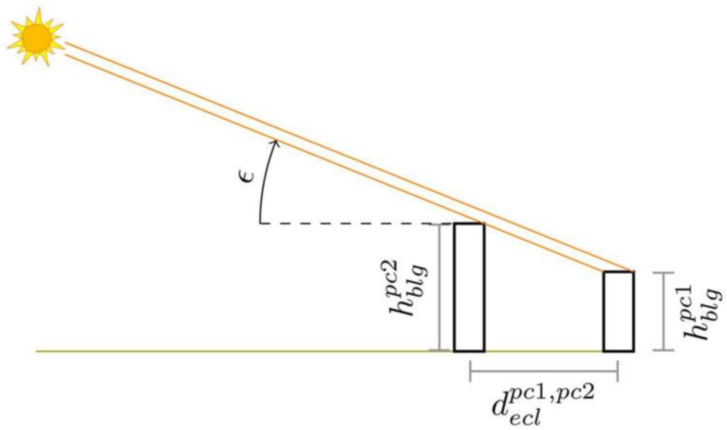


Figure 15 Obstruction to the incoming sun (Figure source: (Schüler et al., 2018))

To illustrate the concept of obstructions in the results, the explanation includes a spatial buffer analysis to measure the planar distance (d) between pairs of buildings (Schüler et al., 2018). The radius distance was set within the range of 25 meters as a minimum and 100 meters as a maximum (see Figure 16).

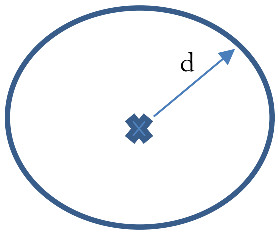


Figure 16 The example of buffer distance (Figure adapted from: (Zhou et al., 2018))

Once again, it is important to note that in this study, cast shadowing is not a separate calculation; instead, it is already included in the estimation of solar irradiation.

3.3.3. BIPV yield estimation

To calculate the annual PV potential *E* (kWh/m^2) on the windows panel was used the formula adapted from (Panagiotidou et al., 2021) (see equation 6). Where (ηr) stands for the module efficiency in percentage, (*PR*) is the performance ratio, and (*G*) is the total annual radiation on the tilted surface in kWh/m^2.

$$E = \eta r \times PR \times G$$

Eq (6)

Considering the actual condition of the building's exterior architecture is mainly covered by glasses (see Figure 13), the BIPV cell selected is the transparent/translucent cell (TPV) to provide a visually pleasing option to the stakeholders (Lai & Hokoi, 2015). It's important to note that each cell type has different efficiency, which known the modification of the cell will reduce the efficiency performance (Manoj Kumar et al., 2018). According to Lee et al. (2020), the power efficiency of TVP is over 12% at an average transmittance, which is rounded to 0.12 for the PV yield calculation purpose. The performance ratio (PR) value integrated for this research uses the average worldwide value of 0.70 (Khalid et al., 2016). Take into account the formula adapted from (Panagiotidou et al., 2021) does not consider the performance losses.

3.3.4. Environmental benefit analysis

One of the significant advantages of a photovoltaic installation is the proportional environmental benefit of CO_2 emission reduction (Thebault et al., 2022). To estimate the number of CO_2 emissions reduced by the installed BIPV, the formula from (Thebault et al., 2022) was applied (refer to equation 7).

$$RedCO2 = E(y) \times \frac{eCO2, grid - eCO2, PV}{Apv}$$

Eq (7)

Defined the $E(y)/A_{pv}$ as the annual pv energy produced per square meter, and e_{CO2}; $_{grid}$ as the average emission affiliated with the electricity production, the value given is $e_{CO2}; grid = 0.275$ kgCO2/kWh, this value referred from the consideration European energy mix in 2019. Meanwhile, the e_{CO2}; $_{PV}$ identifies as the life-cycle GHG emission for PV systems given a value of 0.050 kg CO_2/kWh (Samarasinghalage et al., 2022). Consider that the values specified for the estimation refer to European standards because there is not yet a fixed guideline in the study area.

3.4. Phase four: Maptable tool development

The expected outcome of the map table development in this research is to effectively facilitate stakeholder participation in Indonesia by informing them about the potential energy transition option - BIPV in dense urban areas. To achieve this goal, a BIPV simulation with the 3D model's representation and the user interface has been designed and tested on the map table. During the development of the map table interface/tool for running the simulation, the author considered three main requirements to envisage stakeholder interaction with the tool (see Figure 17) as the foundational indicators for designing the tool: (i) ease of use (Dias et al., 2013) (ii) software compatibility and (iii) information provided (Ryall et al., 2006). The model and simulation created were tailored to work well on the touchscreen interface and provide a user-friendly experience for stakeholders.

The first component: ease of use, ensures that all users, without any exceptions, can easily operate and understand the developed tool. The second component focuses on software compatibility for the map table, ensuring the simulation process runs smoothly, including testing hand gesture sensitivity. Lastly, it is crucial to emphasize the importance of providing users with valuable and insightful information. Therefore, the users are expected to grasp the research aim through the developed tool, which emphasizes direct user interaction.

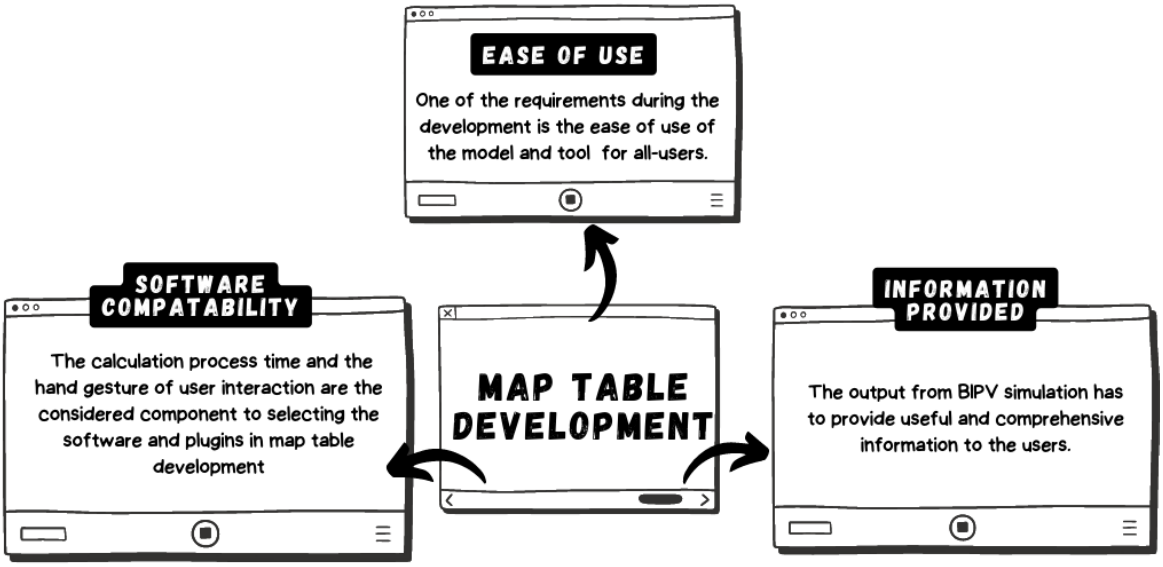


Figure 17 The requirements for PSS tool development to envisage stakeholder interaction with the tool (source: author)

The design of the tool compiles with three main parts: (i) a three-dimensional model scene, where the users can interact with the 3D building models, (ii) a user interface that allows the users to carry out simulation tests and present the information result, and (iii) the annual of solar gain information or also known as sun irradiation.

The development of the map table tool requires several stages to be accomplished, which depicts the overall workflows in Figure 18. In regards to the expected outcome enable to provide direct interaction between the users on the map table, the first step is to test the hand gesture on the map table with the input of the developed 3D model to find out the sensitivity and hand operation of the software application. Considering the sensitivity and compatibility for hand gestures of each software application is different from one to another. Even though the map table can be integrated with various software options (Shrestha et al., 2018), the compatibility of the software application to be operated is crucial to test. Hence, the second step is to conduct the test of the BIPV simulation to find out whether the software application is stable and computing time is feasible for a stakeholder participation session.

Afterward, the activity followed by designing the user interface that supports the users to operate the simulation and shows the information result. The user-interface design contains the '*pull-down menu*' for building geometry and orientation selection, '*tick menus*' for choosing the pre-defined panels, and '*toggle switch*' to start the simulation. Alongside the menu selection, the information on the panel area, the total area selected, the total annual energy generated, the estimation of annual emissions that can be reduced, the PV price, and the estimation of the total amount of PV price is provided on the user interface. Consider that the selection of geometry and the panels were limited and pre-defined to avoid the computational failure explained in section 3.3.1. The only setting users can modify freely is PV price because there is not yet a reference for Indonesia's BIPV price. The PV price input is designed to be typed down by the users.

Nevertheless, the information on the sun irradiation of the façade is also displayed next to the user interface. The graph was the embedded design of the BIPV simulation, which is the default design and unalterable. The graph information presented annual and monthly sun irradiation, displayed in the bar chart presented as “Win,” which refers to the window (explained in section 3.3.1.).

The designed tool is refined and evaluated weekly by the experts until it reaches the final design to facilitate stakeholder participation in Indonesia. The tool development processes were mainly built in *CAD* environment applications.

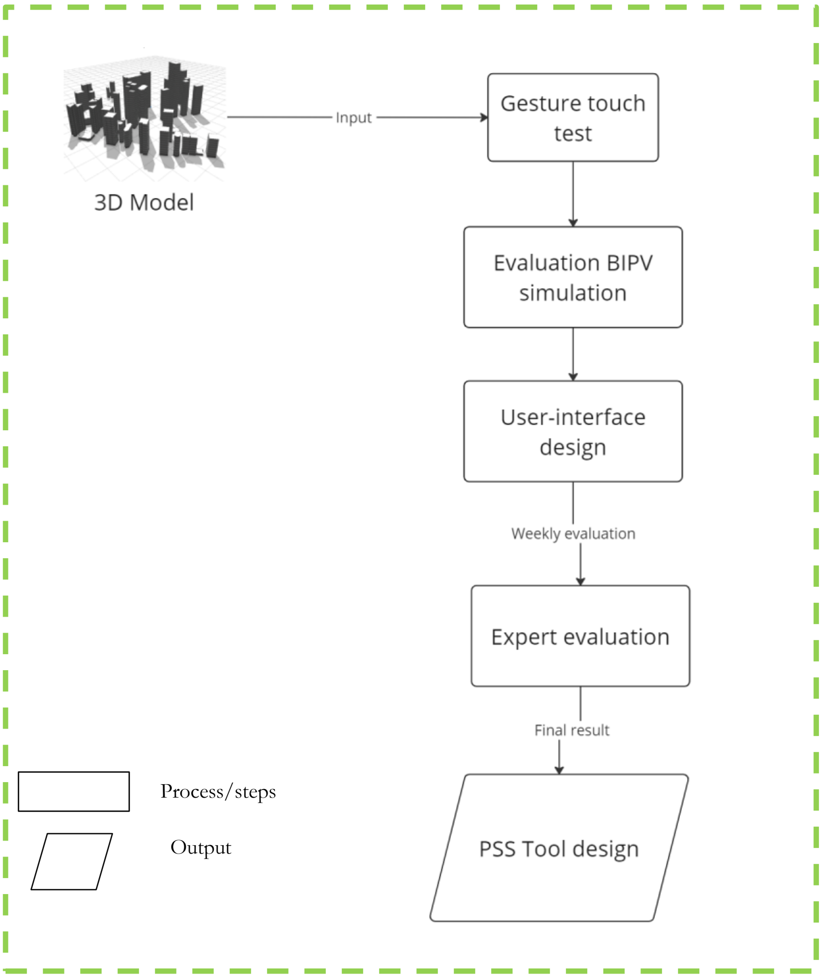


Figure 18 Phase 4: Map table tool development proposed workflow.

3.4.1. Simulation process on the map table

The final output of the map table tool is designed to be operated by the users and displayed in Figure 19: the instructions for the simulation process on the map table. The activity starts with the users testing the touch gesture and be familiarize themselves with manipulating the 3D model, then instructed to select the building geometry, façade orientation, whether East-West-North-South, and panels on the building's façade. Given the adjustable PV price input, the users can type the value directly on the map table. The users run the simulation at the end of the process by selecting the toggle button.

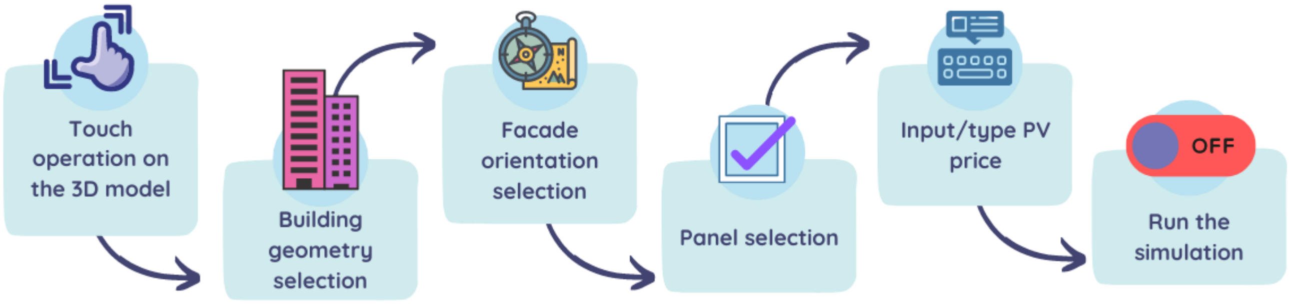


Figure 19 The steps of simulation on map table (Source: Author)

3.4.2. Personalize map table evaluations

Myers (1993) stated that redesigning the interface based on actual end-user recommendations is a challenging process. Moreover, it also requires the designer's intuition to determine when to stop the iteration process. The tool was evaluated both in a controlled experiment and a real-world stakeholder workshop (Aguilar, 2022; Flacke et al., 2020). For research purposes, experts evaluated the developed model and tool in controlled conditions. The evaluation took place iteratively weekly, from February 8th, 2023, until March 16th, 2023. The tests were conducted directly on the map table in the DISC room at the Faculty of ITC, with a real participation setting.

3.5. Phase five: Stakeholder participation and feedback evaluation

The last phase of this research is to hold the stakeholder participation workshop in Jakarta, Indonesia. The feedback received during the workshop is evaluated using the usability and added value framework. Considering the complexity of involving multiple stakeholders in the workshop, using a map table to support the activity.

In this research, the primary focus of the PSS approach was on the informing task (Vonk, 2006), which aimed '*To inform the stakeholders the potential energy transition option: BIPV in the dense urban area.*'. One expected outcome is that the stakeholders will increase their awareness and knowledge of the issue to perform energy transition in dense urban areas and the potential of BIPV to lessen the wicked situation. The increasing stakeholder awareness for this study was defined when the participants '*agreed*' after the workshop that they learned about the renewable energy issue in urban dense areas and their knowledge regarding BIPV as one of the climate technologies is increasing.

To achieve the goal, stakeholder engagement in the informing task was facilitated through a demo workshop conducted in a distributed synchronous setting at different locations and times (Isenberg et al., 2011). The feedback from stakeholders was recorded in the questionnaire and then evaluated through usability (Aguilar et al., 2021; Brömmelstroet, 2013; Pelzer, 2017) and added value (Pelzer, Geertman, & Van Der Heijden, 2015; te Brömmelstroet, 2017) indicators.

The workflow for phase five is displayed in Figure 20. The activities start with stakeholder identification, selecting the framework, preparing the questionnaire, holding the stakeholder participation workshop, and evaluating the feedback. All the detail for each step is subsequently described in the following sub-sections.

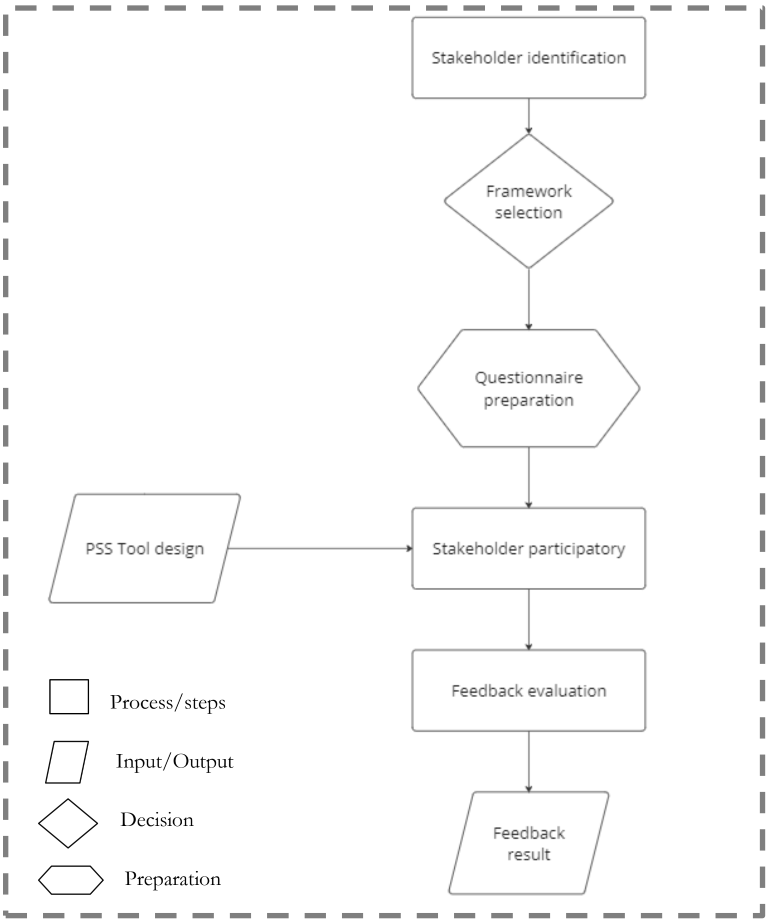


Figure 20 Phase 5: stakeholder participation proposed workflow

3.5.1. Stakeholder identification

Several stakeholders are involved in this research process, and about nine organizations are participating in the workshop. Table 2 provides the stakeholder identification according to their task in renewable energy activities; each stakeholder's position in this research will be put from an equal standpoint. All the incoming feedback will be considered important, regardless of the stakeholder's position in the energy transition activity in Indonesia.

Table 2 List of workshop participants

Stakeholders	Types of Organization detail information
Ministry of national development planning agency	[Government/Research]: Responsible for executing the plan and project for renewable energy
IESR (Institute for Essential Services Reform)	[NGO]: collaborate with the government to support renewable energy activity by providing analysis and studies and capacity buildings.
Greenpeace Indonesia	[NGO]: Worldwide NGO that actively voices environmental support.
Ministry of Economic and Finance of Indonesia	[Government]: allocate financial support for renewable energy projects
Audit Board of the Republic of Indonesia	[Government]: In charge of inspecting and auditing all the national project financial flow.
State Electricity Company (PLN)	[State-owned/Government]: Responsible for managing the nation's electricity support.
National Research And Innovation Agency (BRIN)	[Research Institute]: The national research agency which carries out national scientific activities, including renewable energy.
IPB University	[Academia]: The representative from an academic perspective, who is on the neutral side to support the renewable activity in Indonesia.
Ministry of State-Owned Enterprises (BUMN)	[Government]: The institution is in charge of re-arrange all the activities and policies regarding energy transitions.

3.5.2. Stakeholder participation workshop session

The workshop session was initially to be conducted in a group discussion setting. However, the session possibly changed into a semi-structured interview if only one stakeholder was present. The activity begins with an introduction to the research and an explanation of the problem analysis, followed by a demonstration of how to operate the tool and model. The stakeholders are slowly guided to interact with the model and tool. Throughout the workshop activity, the author will act as the facilitator and chauffeur, observing the participants to ensure they are confident enough to operate the tool independently. Once the participants were familiar with the tool, they were persuaded to test the model and tool by themselves. At that moment, the author observes the activity and monitors whether the participant can use the tool independently. The author always stands by the participants' side and is alert if the stakeholders need help. During this part, the author also fosters interactive communication among the stakeholders and induces the participants' critical thinking by opening up the discussion. In the end, the questionnaire is distributed to the participants for feedback on the activity, the usability of the tool assessment, and the added value of criteria development (See Figure 21).

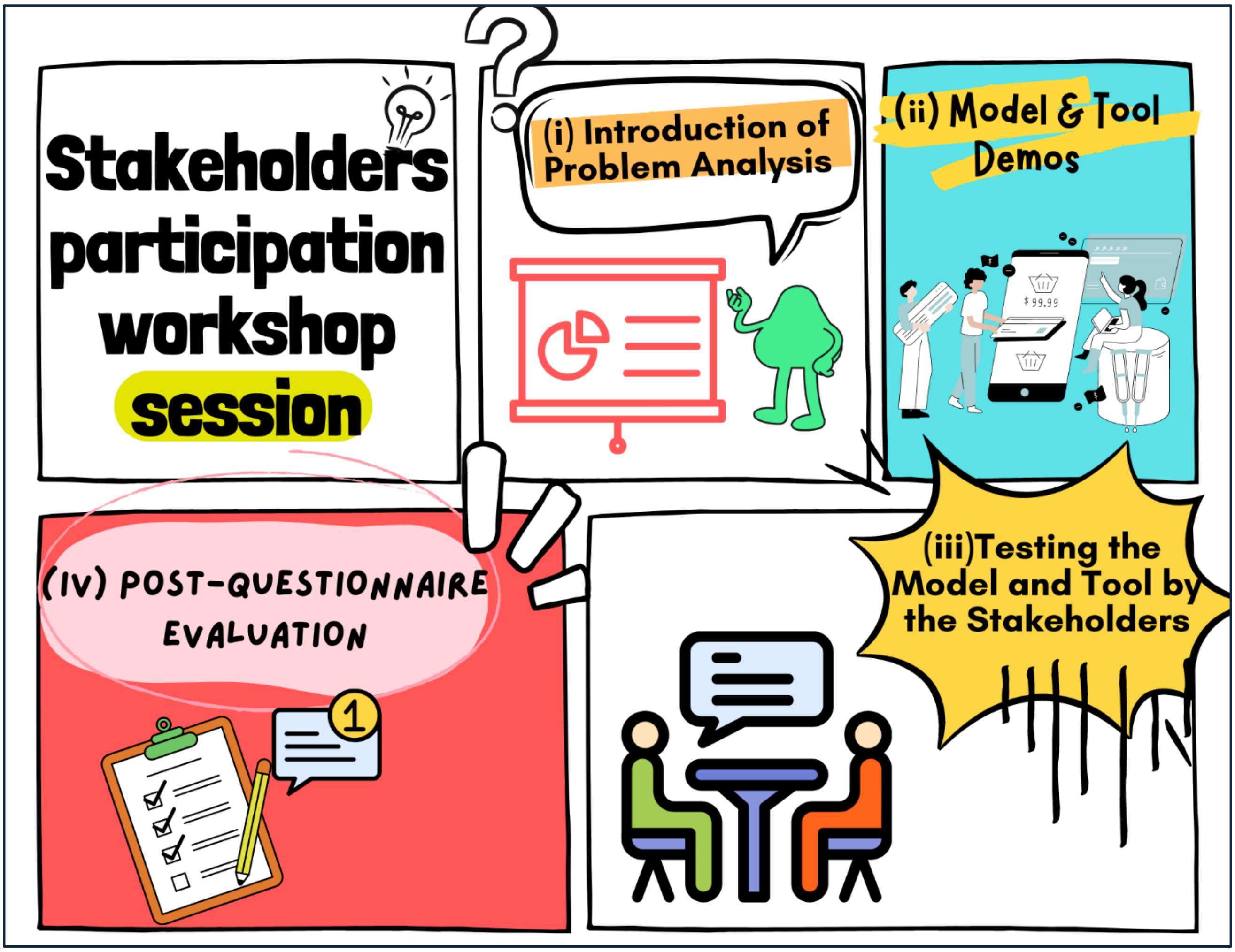


Figure 21 Participation session flow (Source: Author)

Considering that the model and tool testing process involves multiple steps, Figure 22 illustrates the use-case diagram to demonstrate the sequential interaction between stakeholders and the tool. The detailed interaction between stakeholders and the tool can be found in section 3.4.1.

The use case diagram also provides an overview of the author's role, which has an extended role as a facilitator. In this context, "extended" implies the author's role is only activated when the participants seek help or encounter issues while testing the model and tool. The stakeholder placed on the left side of the diagram indicates they are the primary actor who initiates the use of the system. Meanwhile, the author is on the right side of the diagram, which indicates the secondary actor who was given the reactionary role, which is only invoked upon request from the primary actor.

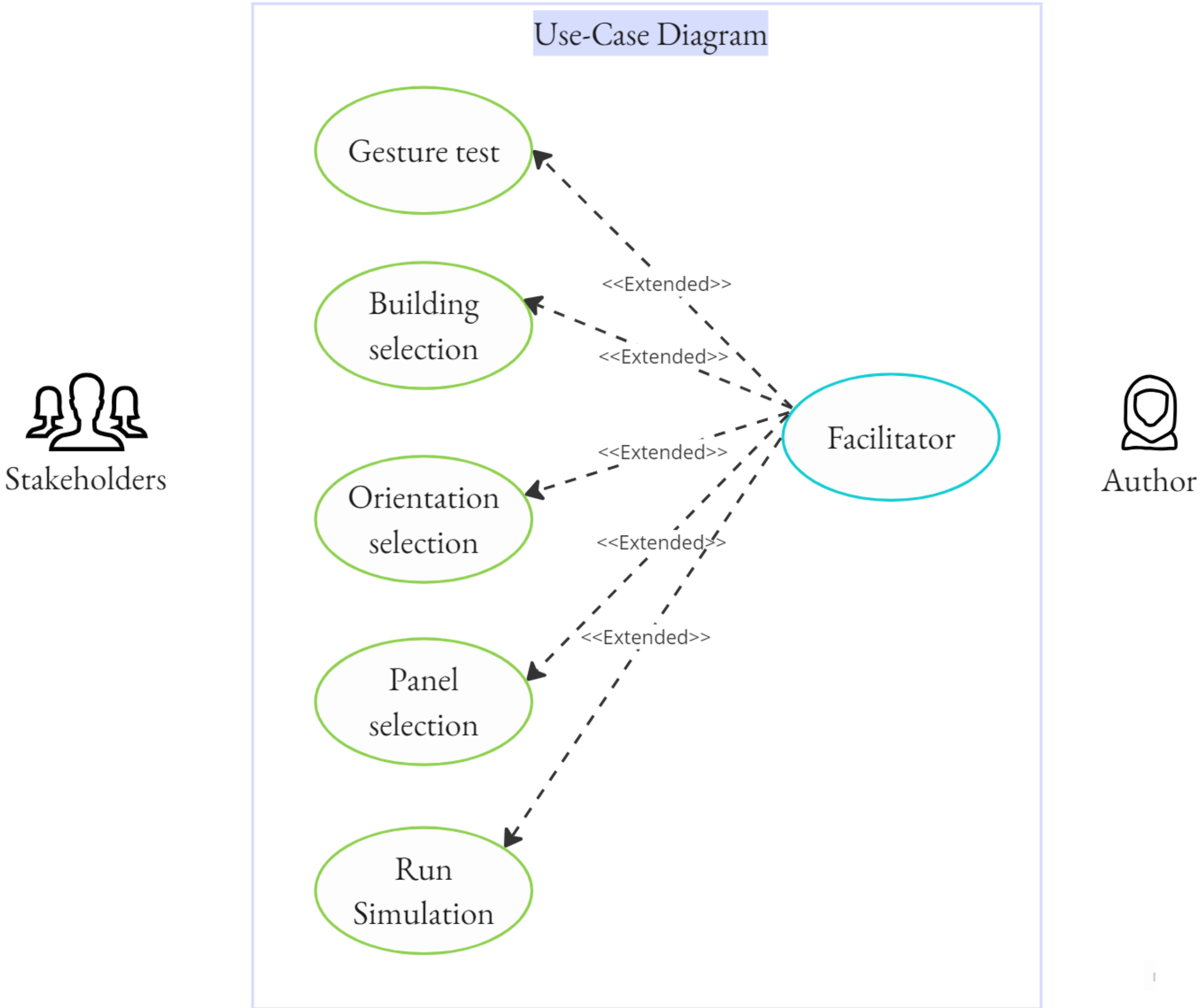


Figure 22 Use-case diagram (Source: Author)

3.5.3. Stakeholder feedback evaluation

The evaluation of the workshop session aligns with the study's goal to inform the stakeholders about the potential climate technology, increase their awareness, and transfer tacit knowledge. To assess whether the stakeholder's participation achieved the research's aim, such methods as questionnaires, observation, and post-workshop interviews are excellent for feedback evaluation (Goodspeed, 2013).

This study evaluated the stakeholder participation workshop with questionnaire feedback from the participants and post-workshop interviews. The questionnaire contains open-end and close-end types of questions in ANNEX D: Stakeholder participation workshop in Jakarta. The open-end question referring to the answer will be more descriptive; meanwhile, the close-end question will be answered with yes or no, or with the defined scale. The closed-end question type in this research is examined with a scale of one to five, which one representing: "*strongly agree* or *very easy*" and five meaning: "*strongly disagree* or very difficult." The full scale can be seen in Table 3. However, during the session, the author observed the whole process and interactively asked questions at the end of the workshop. Additionally, if the number of participants is only one person, the session will be flipped into a semi-structured interview with questions similar to the questionnaire. Meanwhile, the post-workshop interview focuses on receiving feedback regarding the developed framework, whether there should be an improvement and the "*if*" scenario of BIPV installation preference from the stakeholders.

Table 3 Evaluation scale

Scale		Representable
Very easy	Very Satisfied	1
Easy	Satisfied	2
Neutral	Neutral	3
Difficult	Dissatisfied	4
Very difficult	Very dissatisfied	5

The evaluation of the feedback was concentrated on usability and added value indicators. The usability for PSS is defined as measuring how effectively users can operate the tools and how it influences their perception of the added value of planning support tools. As displayed in Figure 23, the indicators applied in this research focus on the tool's usability and the added value from participants. The participatory process with a map table will be evaluated based on the usability of the tool's performance, whether it is ease to use (user-friendliness), the waiting duration of the tool performance (calculation time) and measure the satisfaction of the participants for the whole session (Aguilar, 2022; Brömmelstroet, 2013; Pelzer, 2017; Pelzer et al., 2014, 2016; te Brömmelstroet, 2017).

Meanwhile, the added value indicators of the participatory evaluated in the object learning from the participatory session and the efficiency of the map table compared to the contemporary paper-based participatory are evaluated. Object learning pertains to users' understanding of problem analysis and the intervention's effects (Pelzer et al., 2016), while efficiency is described by improved performance and productivity compared to the workload before implementing PSS (Brömmelstroet, 2013; Pelzer et al., 2014). According to Pelzer et al. (2015), added value refers to improving planning practice after applying PSS.

The questionnaire distributed to the participants covers all the indicators mentioned before (i) Usability (User friendliness, satisfaction, and calculation time) and Added value (object learning and efficiency). Both indicators represent open and closed questions. The questionnaire overview can be seen in ANNEX D: Stakeholder participation workshop in Jakarta.

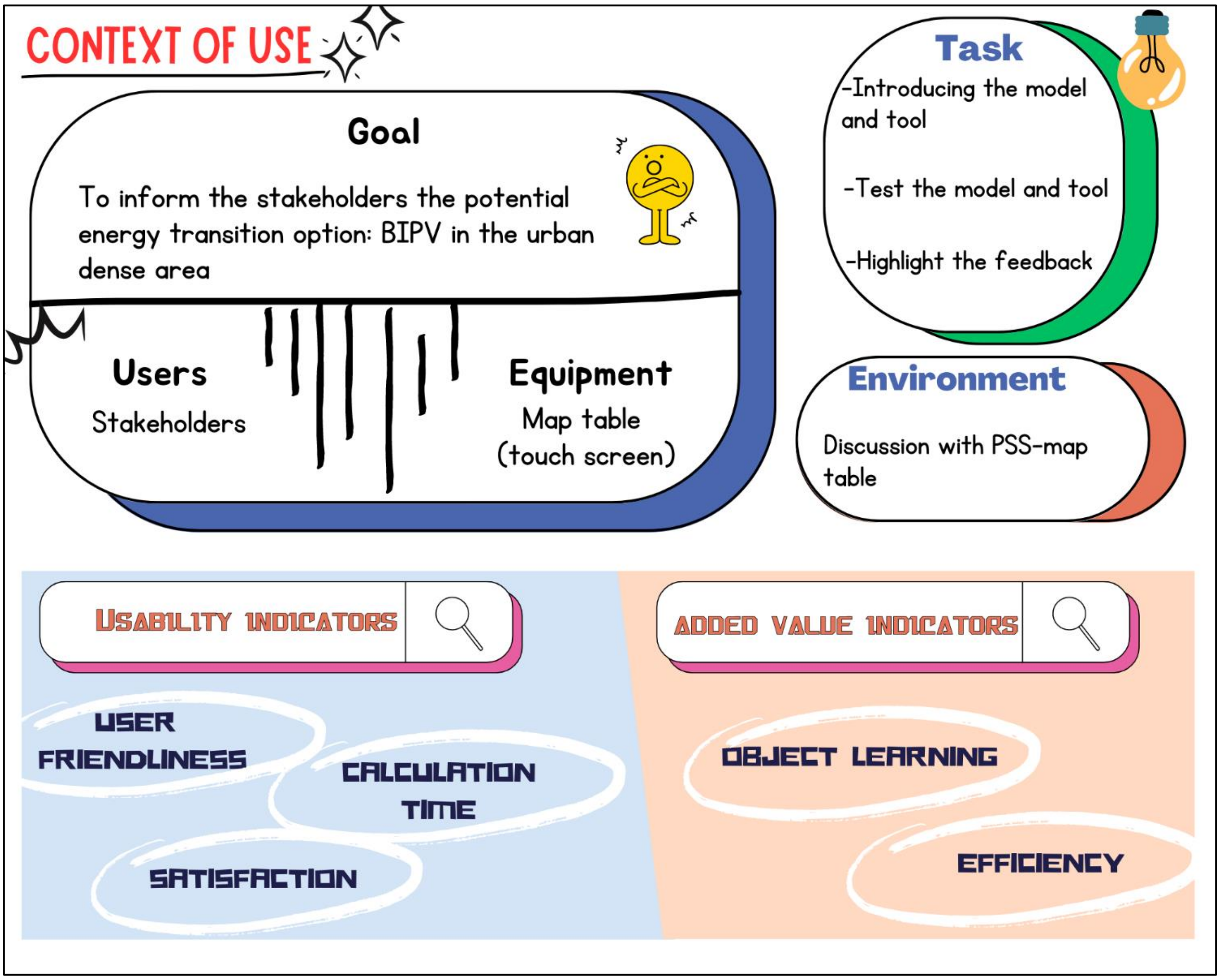


Figure 23 Usability and Added value framework applied in the research (Source adapted from: (Aguilar, 2022; Brömmelstroet, 2013; Pelzer, 2017; Pelzer et al., 2014, 2016; te Brömmelstroet, 2017))

3.6. Summary

Chapter three describes all the background methods applied in the developed framework, which contains five different phases applied in this study. Apart from the methods, this chapter also explains the research workflow. The expected result from all the methods mentioned will be discussed in the subsequent chapter.

4. RESULT

This chapter displayed all the expected results of the study. Several subsequent chapters explain the result, corresponding with the developed framework's research phase, except phase one, explained in the literature review and the methods. The section ended with an explanation of the final developed Solar Paulia framework.

4.1. Phase two: 3D Model development

Considering the '*no data*' situation, the author successfully identified 35 buildings in the study area. The findings from the building identification show that most of the building's functionality is mainly offices and apartments within the building's height range, which varied from 8 to 279 meters. All the detected buildings were delineated and tabulated. The result of data vectorization of the two-dimensional building's footprint is depicted in Figure 24, which shows identified buildings within the six height ranges, namely: (i) less than 50m, (ii) 50 to 10 m, (iii) 100 – 150m, (iv) 150 – 200m, (v) 200 – 25 m, (vi) more than 250m. The detailed building information is provided in Annex A's: building identification part.

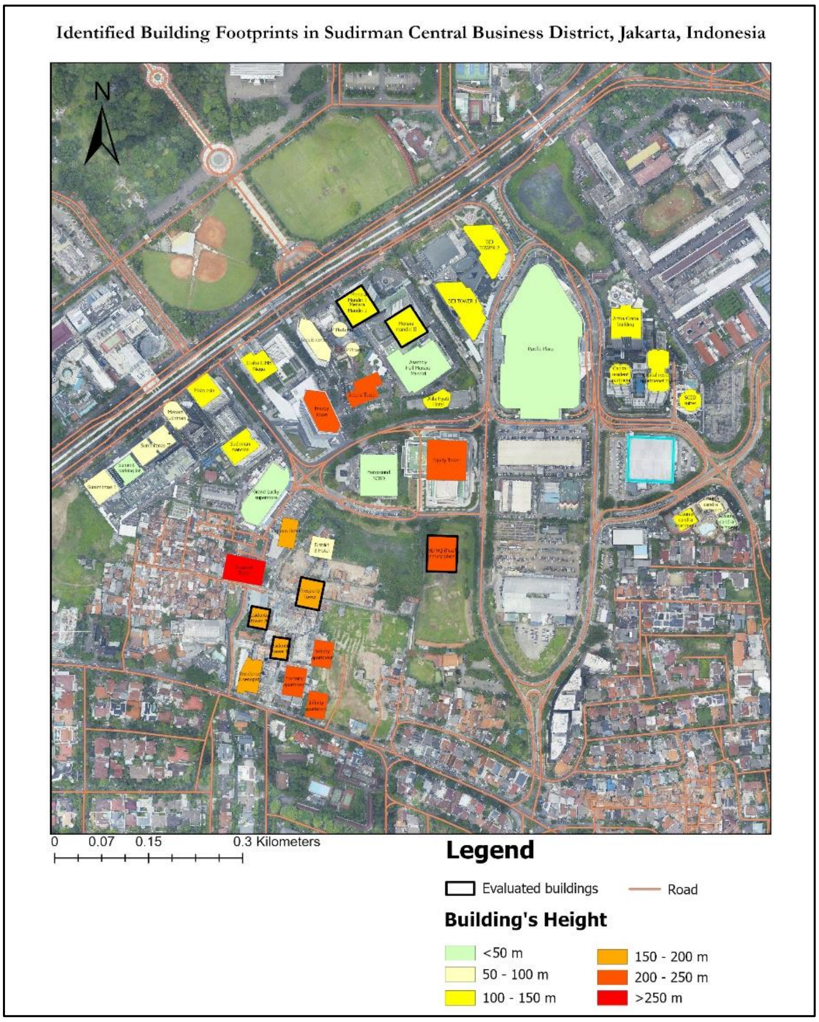


Figure 24 Building Footprints study area.

The 3D model in this research functionally extrudes the 2D shapefile with the height (textual) input through a rule-based modeling process. The result of the 3D model in the study area is represented in a simple box of LoD 1, shown in Figure 25.

Figure 25 Three-Dimensional model developed

4.2. Phase Three: BIPV evaluation

Figure 26 illustrates the result of the sun path analysis in the stereograph diagram. The sun projection consistently demonstrates a relatively constant irradiation time since the study area is located in the equator line. To determine the potential façade orientation within the study area, the author set one point on the ground and arranged the input 3D buildings as the obstruction. The analysis revealed the highest probability of receiving sun radiation falls between the range of angle orientation 140º - 30º. It should be noted that the façade orientation, determined based on a single point in the middle of the study area, may give varied results during building evaluation.

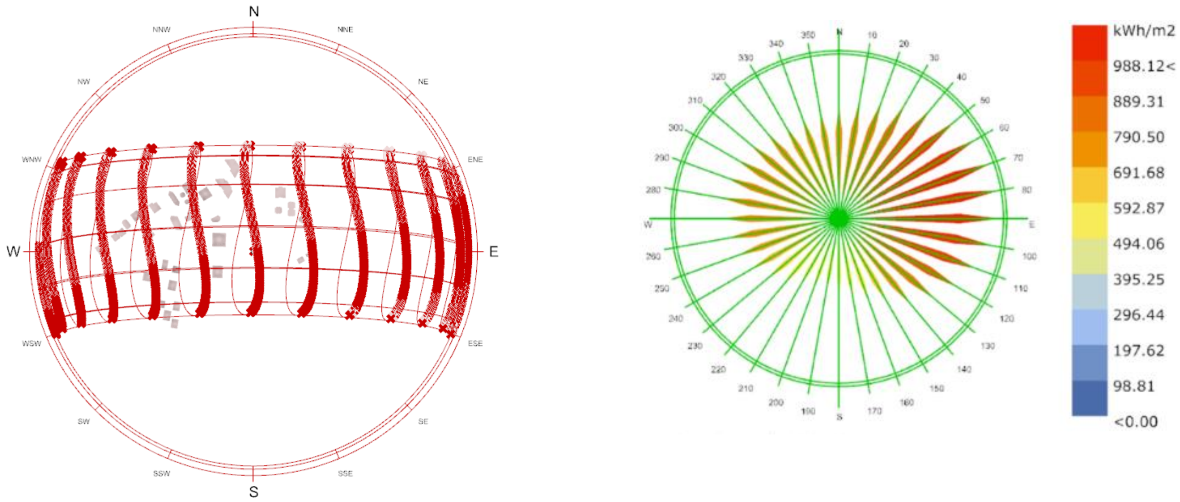


Figure 26 Stereograph diagram and facade orientation analysis result

4.2.1. Building façade evaluation

The façade evaluation has performed a proof-of-concept (*poc*) on six buildings: Prosperity Tower, FWD Tower, Mandiri I Tower, Mandiri II Tower, Residential the 8th Tower A, and Residential the 8th Tower B. The total yearly irradiation in kilowatt hour (kWh) per square meter for each building from different orientations is presented in Table 4. The overall findings indicate that three buildings exhibit the highest solar potential on the East façade, two on the North façade, and one on the West façade. While the least façade produces, the energy is in the South orientation for almost all the buildings, except Residential Tower A and Prosperity Tower. Both buildings show the same pattern with the least energy yield on the North façade.

Table 4 Buildings' yearly irradiation result (kWh/m2)

	Yearly irradiation/square meter	**Façade area**	**Yearly irradiation**
Prosperity Tower	kWh/m²	m²	MWh/year
East facade	234,1	8656	2026,3
South facade	192,2	7090	1362,6
North facade	172	7207	1239,6
West facade	198,4	8655	1717,1
FWD	kWh/m²	m²	MWh/year
East facade	202,8	11933	2420
South facade	112,9	9921	1120,
North facade	192,6	9983	1922,7
West facade	227,6	12049	2742,3
Mandiri I	kWh/m²	m²	MWh/year
East facade	188,8	6443	1216,4
South facade	132,2	6162	814,6
North facade	164,5	6041	993,7

West facade	183,4	6230	1142,5
Mandiri II	kWh/m^2	m^2	MWh/year
East facade	169	6442	1088,6
South facade	147	6162	905,8
North facade	183	6041	1105,5
West facade	171,3	6230	1067,1
Residential tower A	kWh/m^2	m^2	MWh/year
East facade	222,9	6155	1371,9
South facade	194,6	5670	1103,3
North facade	125,7	5670	712,7
West facade	194	6155	1194
Residential tower B	kWh/m^2	m^2	MWh/year
East facade	154,5	6449	996,3
South facade	84,6	5091	430,6
North facade	162,2	4876	790,8
West facade	139	6452	896,8

Solar irradiation has a proportional relation with the energy yield of BIPV and the reduction in CO_2 emissions. This relation implies that the more exposed façade to the sun radiation, the higher the BIPV energy generated and reducing more CO_2 emission. However, it should be noted that not all radiation can be converted into electricity, as it depends on the types of BIPV cells installed.

Considering the visual aspect and the current building's exterior, translucent BIPV types are selected references for yield calculation (Equation 6 in Section 3.3.3). Figure 27 depicts the energy yield estimation output shown in the y-axis and corresponds with the height of buildings in the x-axis, where the height is between ranges 126 m, 188 m, and 209 m. The findings portrayed that the highest buildings do not always produce more energy than the lower-height buildings. However, it is instead determined based on the orientation of the façade. For instance, Tower B on the South face produced the least energy even though the building's height is 188 m, compared to Mandiri towers which are 126 m tall. Additionally, the highest potential building that produces energy is not the tallest building evaluated, but a 188 m tall East facing Property tower.

Nevertheless, consider that the result of energy received on the building's facade is affected by the surrounding obstruction and the location of the buildings, which implies some buildings and facades generated more energy than others. Moreover, the energy yield produced from BIPV follows the efficiency and performance ratio from the BIPV modules (Panagiotidou et al., 2021). By applying different cell modules will affect the energy yield performances.

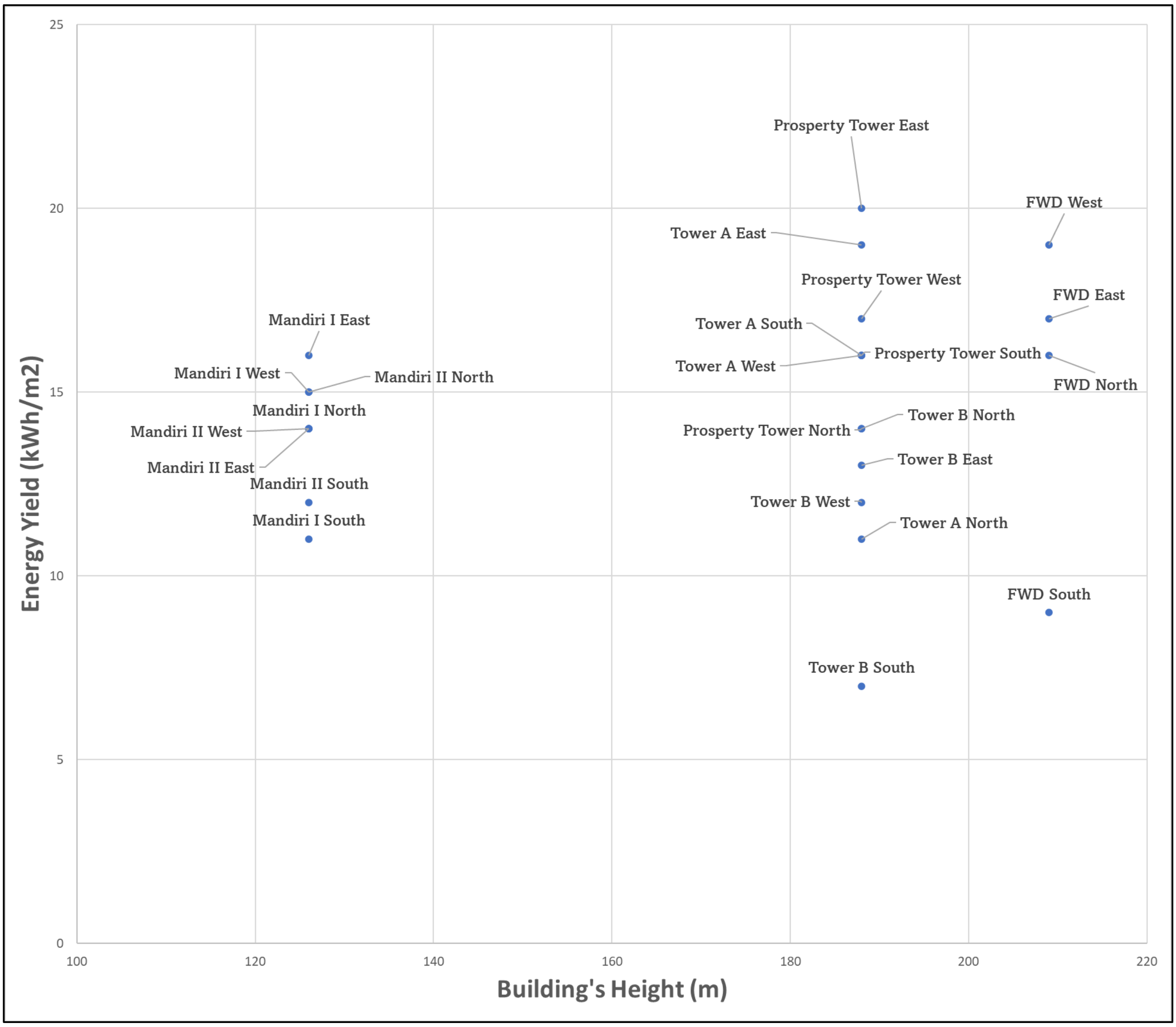


Figure 27 BIPV yield estimation result

The subsequent analysis provided in the BIPV area evaluation is an environmental benefit, estimated from Equation 7 that the CO_2 can be reduced if the BIPV is installed. Table 5 displays the total CO_2 that can be reduced per building from different façade orientations. Considering the proportional relation, the outcome expected has a similar rank of the highest and the least from solar radiation and BIPV yield.

Table 5 Potential CO_2 reduction from BIPV installation

CO2 reduction yearly (kg/m^2)	EAST	NORTH	SOUTH	WEST
Prosperity Tower	67	59	58	60
FWD	68	54	50	66
Mandiri I	57	50	40	55
Mandiri II	51	55	45	52
Residential Tower A	61	38	59	59
Residential Tower B	47	48	26	42

Thus, each building was again evaluated, with 16 pre-defined panels for each façade. The decision of 16 panels was decided after the early-stage test that required computational time when providing more panels. Also, presenting a realistic option for users to select the panels which avoid the tool simulation garnered more attention than the discussion (Goodspeed, 2013). Due to this, the disparities in panel size are inevitable, as it follows the area of the façade. However, as the height of the building is uniform (only one particular height per building), the panel height section was the same for all façade in one building. As a result, the outcome of panel evaluation has always remained constant. Nevertheless, referred to in section 3.3.1 that for user experience, the simulation by themselves is important to motivate the participants to grasp the valuable information during stakeholder participation sessions.

The findings from the panel evaluation of each façade show that the highest area is not always generating the most energy, which explains that it occasionally receives less sun irradiance compared to the lower area. As the building's evaluated height ranges are 126 m, 188 m, and 209 m tall, Figure 28 shows the example of three different building facades representing three different height ranges to showcase the findings.

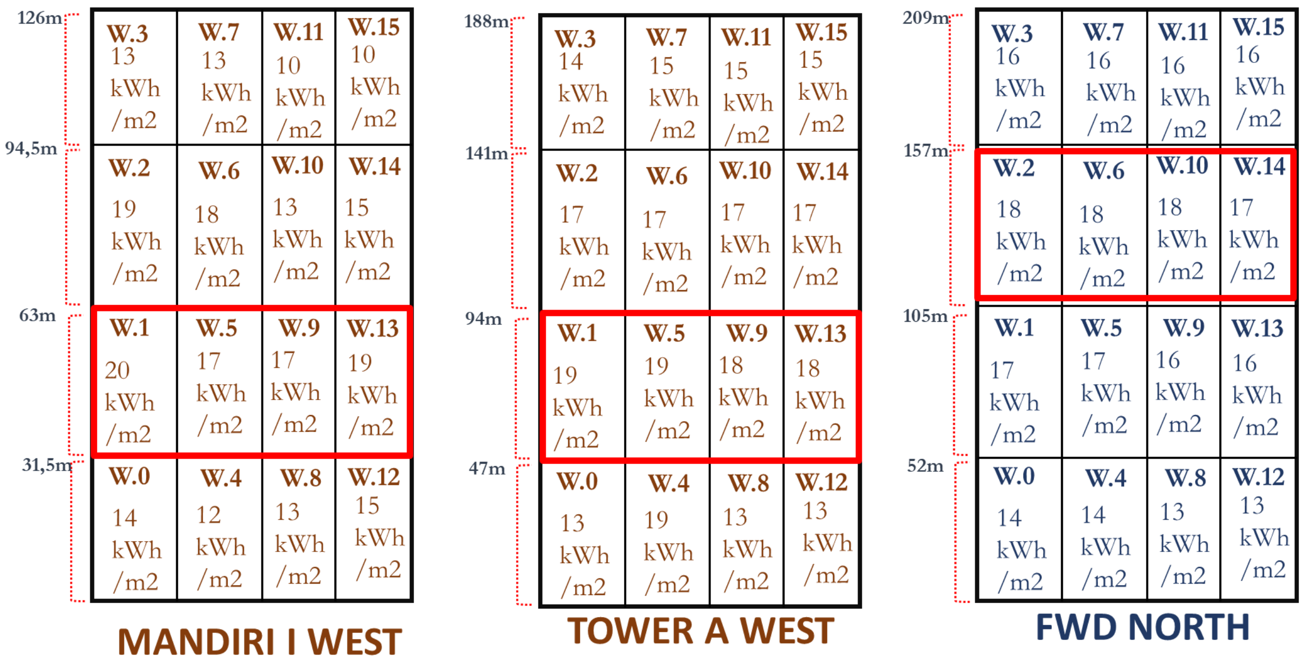


Figure 28 The example of energy yield estimation in three different ranges of building height and orientation. From left to Right: Manidiri I West façade, Tower A West façade, FWD Tower North façade.

On the left side in Figure 28, the Mandiri I tower, with a height of 126 m tall, depicts the west façade orientation, which shows that the second row, with a height between 31,5 to 63 m generated more energy than the highest row. Meanwhile, Tower A, which has a height of 188 m, illustrates that the highest generated energy for the west façade is on the second row, located 47 m to 94 m high from the ground. The right side of Figure 28 displays the FWD tower with about 209 m tall height, which shows the third-row panels that, in the range of 105 m to 157 m, produced the most energy for the north façade of the FWD tower.

Even though the findings can not be comparable across the buildings and focus per façade each building, the evaluation findings showcase the buildings' environment (Samarasinghalage et al., 2022; Schüler et al., 2018), and the sun's position in the sky (Kalogirou, 2014) determines certain power can be generated. The detailed evaluation for each building's façade is explained in ANNEX B: BIPV detail result per panels.

4.2.2. Compatibility with Map Table

Concerning the final output is presented on the map table for being evaluated by the stakeholders (see Figure 29). The BIPV simulation with the 3D model has to work well while being tested. A series of experiments have been conducted to ensure its reliability, and the end result is documented in ANNEX C: Map table tool development.

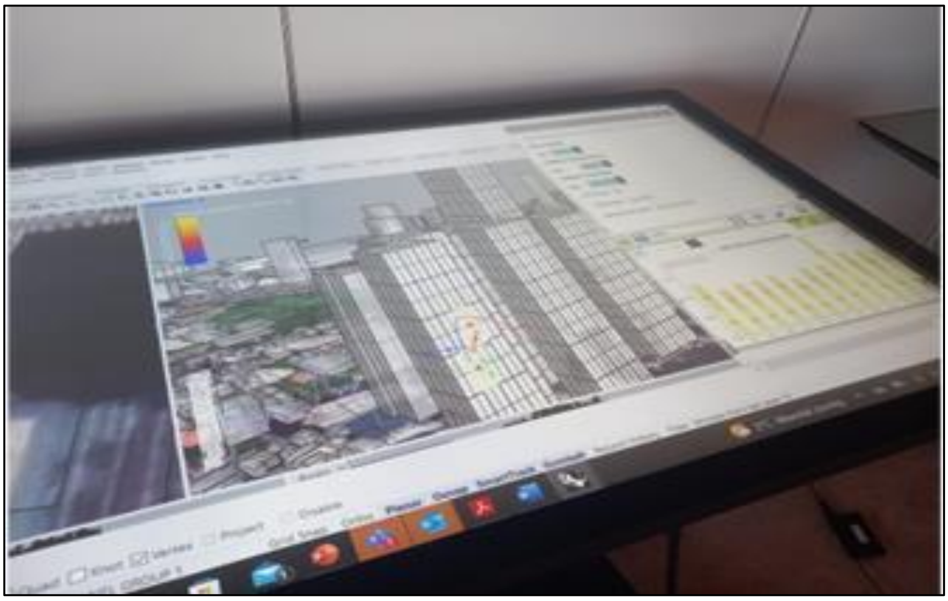


Figure 29 Output on map table (Figure source: Author)

4.3. Phase four: Map table tool development

Figure 30 illustrates the developed map table tool that encompasses three main components, namely: (1) The 3D model scene, (2) The user interface, and (3) Annual solar gain information. The subsequent section will discuss the results obtained from each component of the map table tool. The overview of the scripts to develop the tool components can be found in ANNEX C: Map table tool development section: the Script of developed map table tool .

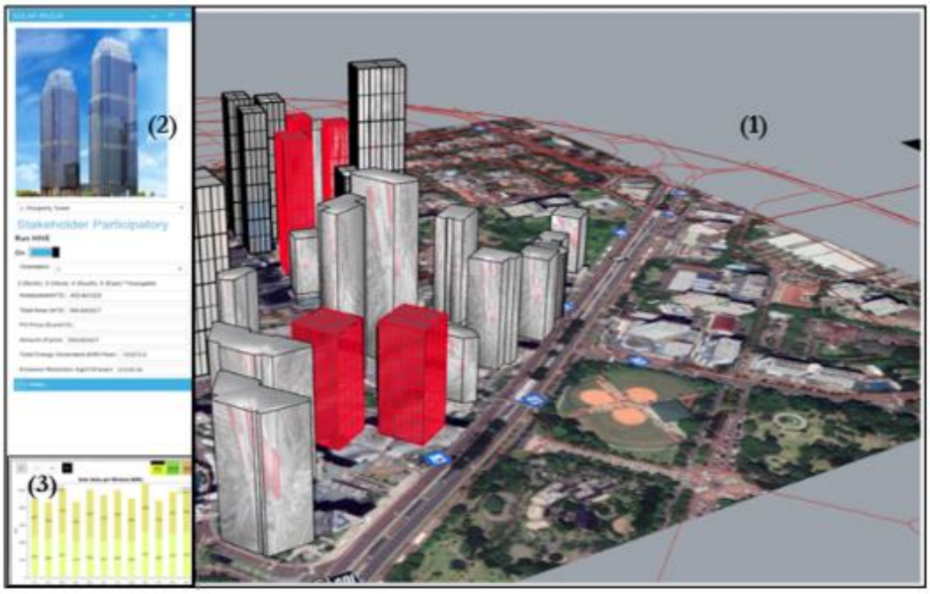


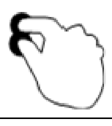
Figure 30 Overview of Map table tool and model developed.

4.3.1. First component: 3D model scene

The three-dimensional model scene accommodates the hand gesture manipulation on the 3D model, enabling users to perform direct hand gesture operations on the touch screen. These operations include rotating, zooming in, zooming out, and moving the scene.

Table 6 describes the hand gesture operation for the manipulation option on the 3D model scene in this research. It is important to note that these gesture operations adhere to the default settings of the computer operating system (OS).

Table 6 Touch gesture operation (Figure source: (Feng et al., 2012))

Hand-Gesture	The operation description
Rotate 	To rotate the 3D scene, it needs only one finger to operate.
Zoom-in 	Zoom-in option requires two fingers to flinch on the scene.
Zoom out 	The zoom-out option requires two fingers to spread on the scene.

Move 	The move option here is to swipe the scene without changing the rotation or zoom-in/out and drag the view simultaneously using two fingers to drag.

4.3.2. Second component: User-Interface

The user interface allows the participant to interact with the 3D model and run the BIPV simulation. After the number of iteration processes, the interface's final product illustrated the complete picture in Figure 31. The interface has several components of selection that will be explained below :

(1) The geometry selection

This part includes building selection with the pull-down menu. In response to any action taken in this part will directly connect with the change in the 3D model scene and the building's picture.

(2) Orientation and panel selection

The orientation selection used a pull-down menu that was represented in numbers. When selected, the number will automatically proceed into the façade chosen. Afterward, the panel can be selected. The buildings' panels are divided into 16 panels per façade for every building. The panel section is designed with tick options that represent with numbers. If the panel number is ticked on the interface, then the panel on the 3D model will immediately change the color on the selected panel.

(3) Run the model and information results

After the building and panel are chosen, the model simulation can be performed by selecting the "*run*" button. The output shows the annual BIPV energy yield generated (kWh/Year), annual CO_2 emission reduction (kgCO2/Year), the area in (m^2) per panel, the total area selected in (m^2), and PV price calculation box, where the users can input the price of BIPV, then directly give a total price per square meter. The simulation video was made and can be accessed through the youtube website[7].

[7] https://youtu.be/UrBjrEr-j3A

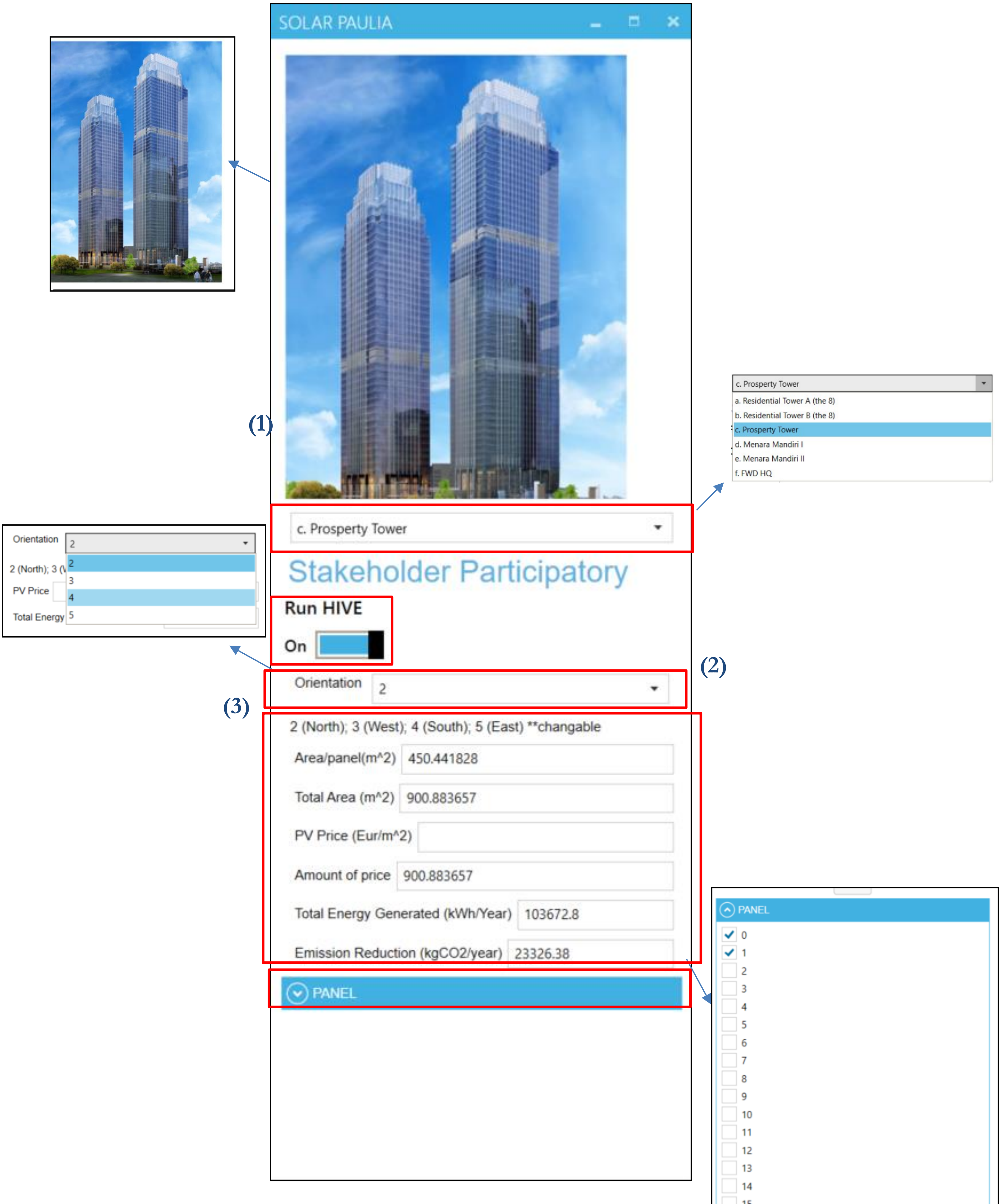


Figure 31 User-interface design

4.3.3. Third component: Annual solar gain Information

The last component displayed on the map table is the solar gain information, presented through a graph visualization (See Figure 32). The solar gain depicts the annual, monthly solar irradiation received on a selected panel. The graph applied in this research is already embedded in the HIVE plugin. The panel in the graph is called a window, which stands for the abbreviation Win, followed by the numbering, which always starts with the number 00 (see section 3.3.1). The x-axis denotes the months from January to December, while the y-axis illustrates the solar radiation received in kWh/year. The result's setting can also be presented in kWh/year/m2. The graph was developed with the *Grasshopper* plugin: *conduit*.

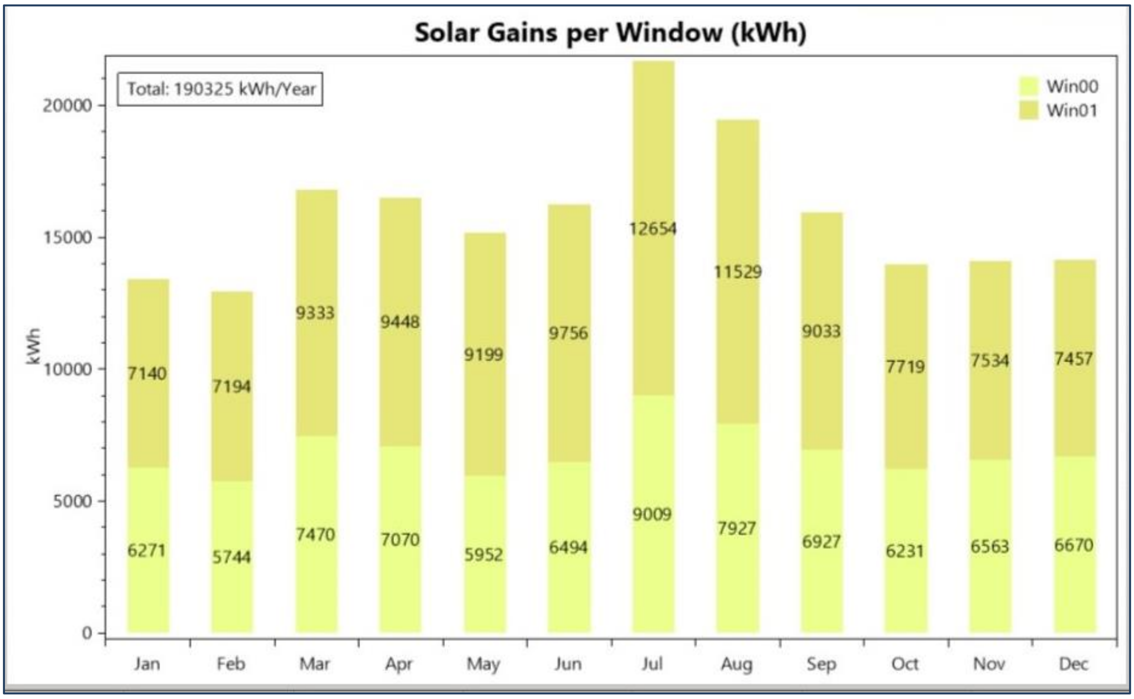


Figure 32 Overview of yearly solar gain graph result

4.4. Stakeholder participation in Indonesia

The stakeholder participation workshops were held in Jakarta from 24th March 2023 until 25th April 2023, which were directly moderated, facilitated, and chauffeured by the author. The workshop targets Indonesia's policymakers in the renewable energy field as participants. There are nine different organizations/institutions participating in the stakeholder participatory, which have diverse backgrounds and scopes of work, e.g., government, NGO, research institutes, and academia. The participatory sessions were scheduled separately for each stakeholder, except the representative from the Audit Board of Indonesia and the State electricity company of Indonesia (PLN) was pre-arranged to set the workshop together. Due to the touch screen size, the workshop participants were limited to a maximum of three people involved. Thus, except for the session with the representative of IPB university, all the workshops were held in person.

Table 7 List participants (n=16)

List of stakeholders	Number of participants (n)
Greenpeace Indonesia	3 (all Male)
Ministry of Finance	3 (M=2; F=1)
Audit Board of Indonesia	1 (Male)
State electricity company of Indonesia (PLN)	1 (Female)
IESR Indonesia	2 (M=1; F=1)
Ministry of State-owned (BUMN)	3 (M=1; F=2)
Ministry of National Development Planning Agency (Bapenas)	1 (Male)
BRIN Indonesia	1 (Male)
IPB University	1 (Male)

A total of 16 attendees from various organizations participated in the workshop process (refer to Table 7). The Government institution representatives included the Ministry of State-owned/BUMN, the Ministry of National Development Planning Agency /Bapenas), the State electricity company of Indonesia (PLN), and the Ministry of Finance and Audit Board of Indonesia. The workshop also involved non-governmental organizations (NGOs) engaged in renewable energy activity, namely Greenpeace Indonesia and Institute for Essential Service (IESR). Thus, the National Research and Innovation Agency (BRIN) Indonesia as a research institute representative and IPB University for the academic side were invited to ensure a balanced stakeholder field background. A detailed explanation of all stakeholder's tasks is described in Table 2. Upon the agreement from the stakeholders, all the activities could be documented, both in photo, video recording, and audio recording.

Figure 33 Stakeholder participation in Jakarta

The stakeholder participation session started with the research introduction and problem analysis, followed by demonstrating how the model and tool work. Subsequently, stakeholders had the opportunity to try the tool themselves. Initially, the author provided step-by-step instructions on operating the model and tool, then gradually stepped back and enabled participants to interact independently. Whenever participants hesitated to test the model and tool, the author actively encouraged and guided them. Moreover, the author ensured that all the stakeholders had the same opportunity to experiment with the model and tool. Throughout the session, all the participants actively asked questions and showed a high interest in the research. The average duration of the stakeholder participation workshop was between one to three hours, depending on the interactive communications that occurred.

4.4.1. Stakeholder feedback evaluation

The stakeholder feedback evaluation in this research is the last phase of the developed framework. Throughout the questionnaire at the end of the participatory activity, all the stages in the framework include the model tool developed and the stakeholder's evaluation workshop held. The question types are mixed between close and open-ended to elaborate more on the stakeholder's perspective towards the research. The results were evaluated using usability and added value indicators.

Furthermore, during the stakeholder participation, the author also asked questions regarding the developed framework and the "*if*" installation scenario. Aside from that, the author led the discussion to validate answers from one institution to another, whether the statements are subjective or actual conditions. Regarding participants' privacy, the questionnaire does not contain any personal information, so the results remain anonymous except for the organization's name and gender type. In total, nine organizations were involved in the participatory workshop, one institution semi-structured interview, and one through an online meeting.

Before continuing to the feedback result in the coming section, notes that the participant's answer could not represent their institutions but rather the individual perspective because of the small sample represented. The entire feedback output is available in Bahasa Indonesia, and the translation in English is accessible in ANNEX D: Stakeholder participation workshop in Jakarta and also provided in share point[8].

[8] LogBook_Stakeholder Participation Result.xlsx

4.4.2. Feedback evaluation on usability indicators

To perceive how the user's interaction with the developed model and tool from the usability indicators, namely: user-friendliness, satisfaction, and calculation, were applied to evaluate the feedback. The user-friendliness projected for the ease-of-use terms in the interaction between participants and model-tool. More than half of the participants, about 53,33%, rate the interface (e.g., button, slider, and tick option) as very easy to use, while the rest, divided into almost equal numbers, found it easy and neutral (see Table 8).

The model navigation on the 3D model scene got a higher evaluation result for the easiness of operation (see Table 8). Still, one participant stated the "*looks of the 3D model scene are too technical and CAD environment, which it scares the non-technical person*", whereas 6,67% found it difficult. Furthermore, some participants shared similar comments; for instance: P1, P7, and P9 mentioned, "*It will be nice if the building selection can be directly on the map.*" An additional unexpected concern from participants was thought the tool might be difficult for women to operate it. Due to this, in the middle of fieldwork, the author tried to balance the participant's genders.

All the participants showed great interest and curiosity while examining the model and tool. When the participatory session occurred in a group, the participants also had an active discussion among themselves. This development stimulates the participants to think more critically and triggers the transfer of knowledge from one to another.

The number of participants in the group was between two to three people due to the author's request regarding the touch screen size. While the testing took place, the author observed that the ideal group size consisted of three people because when the author guided one participant to try the model, the other two had an open discussion among themselves. If there were only two participants, while the author helped one participant, the other one silently only listened. There was not much concern when the participatory one-on-one session. The author encourages the participant, actively opens the discussion, and indirectly contemplates them to be more critical in response.

Table 8 User-friendliness indicators evaluation result

User-friendliness (Ease to use)	Interface (e.g., button, slider)	Model navigation (Zoom in-out, rotate, pan)
Very easy	53,33	53,33
Easy	26,67	40
Neutral	20	0
Difficult	0	6,67
Very difficult	0	0

Positive responses from the participants were portrayed with the findings on satisfaction level with the model, tool, and information provided during the participatory session underlines that 26,7% stated very satisfied, 60% participants felt satisfied, and the rest neutral (see Table 9). The excitement was expressed while testing the model and tool, all because it was the first time for all stakeholders to experience play with the 3D model and BIPV simulation through the touch screen.

Table 9 Satisfaction evaluation

Satisfaction	(%)
Very Satisfied	26,7
Satisfied	60
Neutral	13,3
Dissatisfied	0
Very dissatisfied	0

Concerning the running time of the model and the tool, which was one obstacle while developing the model and tool, was reflected in the participatory session. About 26,67% strongly agree, and 33,33% agree that the processing time of the simulation took time to show the result (see Table 10). Contemplating the model simulation run on the laptop with low processing power led to the processing time issue.

Table 10 Feedback on information provided and model calculation time

The model & Information provided	Information understanding	The simulation running time
Strongly agree	40	26,67
Agree	46,67	33,33
Neutral	13,33	26,67
Disagree	0	13,33
Strongly disagree	0	0

The questionnaire (See ANNEX D: Stakeholder participation workshop in Jakarta) also discovered the strength and limitations of the model and tool developed (See Table 26). The majority expressed the strong interactive visual aspects as the strongest features of the model and the detailed information provided. Some participants mentioned it is a helpful tool for supporting decision-makers more efficiently than the paper-based participatory. Though the participatory map table has never been applied before, several participants agreed it is *easy to use* and *easy to learn*.

Compared with the limitation, most responses concentrate on the model running time and the 3D model realisticness. The author already expects the drawback of the developed tool and model will come from the 3D model level of detail, considering the 3D model is only displayed in box representation (LoD 1). Meanwhile, in terms of processing time, due to an unexpected situation, the workshop was using the author's device, which has not a high processor of capacity. At the beginning of the session, all the participants were informed regarding this issue to clarify the process time situation explicitly. This explanation probably influences the participant's feedback reflecting on the computational power needs in the limitation.

In response to the evaluation of the limitation, the question of improving the model and tool was included. (See Table 27) previewed the insight from the participants on which part of the model and tool has to be changed, added, and/or removed. The response varied for each participant and deliberately showcased indirectly the participant's interest, which relates to their background. For instance, the stakeholder from economy and finance institutions preferred to add more detailed information on the cost-benefit of BIPV.

On the other hand, the participants from the research and academia side gave insight for providing more geo-information information: compass and the direction of light (sun path).

4.4.3. Feedback evaluation on added value indicators

Concerning the learning time to operate the model and tool for all the participants will be different. More than half of the users responded that the time to learn was very short and short (see Table 11). Respectively about 26,7% indicated to be very short and 52,3% short, while 13,3% stated neutral. However, about 6,7%, or equal to 1 person, declared a need for a long time to learn, which the participant mentioned while testing the model. Though required time, the participant actively asked about the function of each button and tried out the model for more than 30 minutes to grasp the entire procedure for operating the model and tool.

Table 11 Learning time feedback

Learning Time	(%)
Very Short	26,7
Short	52,3
Neutral	13,3
Long	6,7
Very Long	0

Regarding finding out, the users perceived the renewable energy (RE) problem in dense urban areas and the impact of BIPV installation. The feedback revealed a positive response: about 66,67% strongly agree, and 33,33% agree they learned about RE issues in dense urban areas (see Figure 34).

In conclusion, from all participant's reactions when introducing the research, it was inferred they had never heard of BIPV as one of the climate technologies. Insight from the feedback confirmed that 46,67% strongly agree, and 53,33% agree that their knowledge about BIPV increased after the workshop participatory session (see Figure 34).

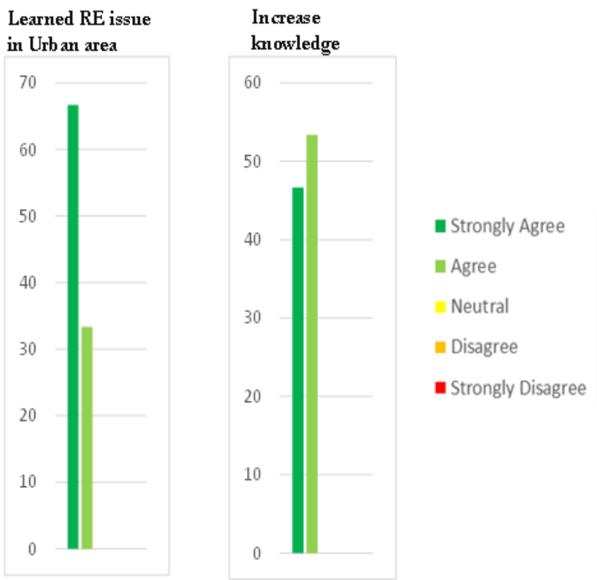


Figure 34 Feedback on added value: Object learning

To get a more detailed measurement of the stakeholder point of view in object learning, open-ended questions were included in the questionnaire, asking the users to describe the most important knowledge received through the participatory session. From the responses acquired, it is analyzed whether the participant understands the issue of RE activity in the dense urban area and gets to know the impact of BIPV as the solution for the problem matters. Table 28 shows all the feedback from the stakeholders, which most mentioned getting to know the BIPV as a potential intervention to handle the RE issue in dense urban areas. While several people focus more on the new concept of participatory using digital tools, some concentrate more on the visual aspect.

The second indicator of added value is to analyze the efficiency of the tool developed by comparing contemporary paper-based participatory and PSS tool provided, whether the participants think as decision-makers, it helps the process of planning and discussion. The findings showed (see Figure 35) that 73,33% of participants strongly agree, and 26,67% agree that the PSS tool can support the planning and discussion process. Accordingly, the result of preference on the PSS tool indicates the majority positively, 66,67% strongly agree, and 26,67% agree to choose a map table over a paper-based one. However, about 6,67%, or one person, disagree to favor the PSS tool. The user stated:

"*It is a good tool to perform the discussion, but no matter how extensive the digital tool is, we still need documented paper. Additionally, our people are not entirely digital-literate*".

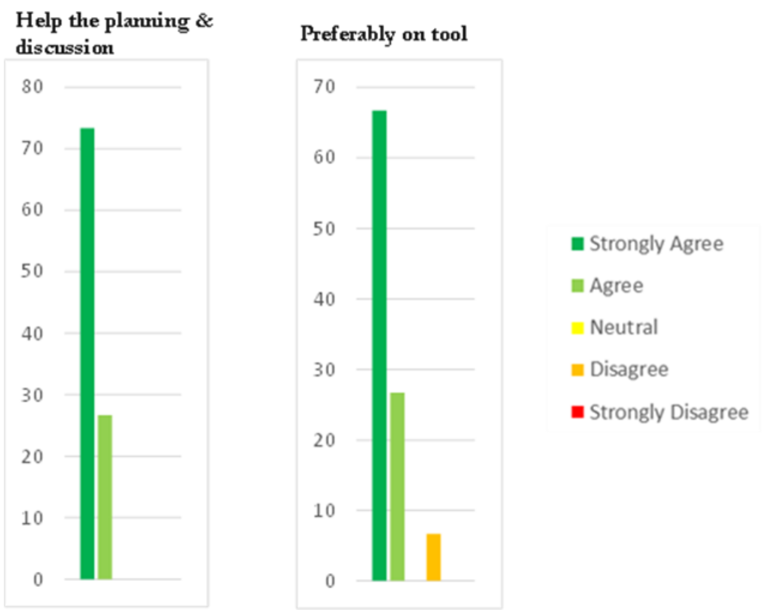


Figure 35 Adde value: Efficiency indicators feedback

Considering all the participants are decision-makers in Indonesia's renewable energy activity, the current tool's applicability is also assessed through the open question (see Table 29). From the result, it can be concluded that all stakeholders involved proclaimed model and tool developed is applicable to support the decision-makers.

4.4.4. Barriers and limitation

BIPV practices in Indonesia are relatively unknown and seemingly a new technology. Acknowledge this status; the author includes a feedback question of possible limitations of BIPV installation if applied in Indonesia. All participants already mentioned several limitations before the questionnaire was handed out during the interactive participation. For instance, P4 asked.

"*Is there any industry producing this technology in Indonesia*?",

While P14 clearly explained

"*With Indonesia's current renewable energy activity status, it might be difficult to implement because of the unstable regulation and political issue*."

On the other hand, P7 and P11 were raising concerns about the building ownership status for maintenance purposes and if there is an impact on the neighbours. Hence, P11 stated.

"*It can be a hassle and disturbance for us to see our building under construction for installing BIPV. Thus, I think it will not be an aesthetic pleasure for people when they see a building under construction.*"

Some participants from the finance sector pointed out and doubted that installing BIPV integrated on the façade could benefit price trades and electricity support. One comment stated.

"*Why do we have to install it if we already have excessive electricity support from the solar farm and coal support? We have lots of coal power plants, and we cannot just stop the operation*".

In the evaluation result (see Table 30), most participants were concerned about financial matters, renewable energy policy, and aesthetic issues. Some participants mentioned there might be a high chance of a conflict of interest, considering multi-stakeholders are involved in the process. Another possible hindrance to the implementation was the government's consumer incentive and the existence of the BIPV industries and distributors.

4.4.5. Developed scenario

At the end of the participatory session, the final evaluation and analysis of one building were disclosed to develop a stakeholder scenario of BIPV installation preference. The session started with an explanation of the output. Afterward, the participants were requested to select which orientation and windows to install the BIPV. The author also reminds the stakeholder to choose wisely, considering the installation cost, the total energy generated, and CO_2 reduction.

During the selection, the participants showed critical thinking, with most of the considerable weight on the cost and finance matters concerning the placement to install BIPV. The majority chose the highest façade orientation with two segments with the highest energy yield. Only one person did not want to choose the panel but preferred to select the façade and stated:

"*I cannot choose the panel because the PV system is integrated into one system, representing this case's façade orientation*."

4.4.6. Stakeholder's feedback for the developed framework

The feedback on the developed framework was through the post-workshop interview with the stakeholders. Regarding having five main phases, the question directly pointed out the participant preferences if there should be a change, add, or remove to the developed framework. According to the feedback, all the participants agreed it should not be taken out of any phase from the framework, but they provided input to revise the step on the stakeholder participatory phase. For instance, include the monitoring system for control checks for each phase and involve stakeholders in every stage, or incorporate the stakeholder's feedback at the beginning and end of the framework phases. The feedback from the participants is generated per organization. All the feedbacks were available in video and/or audio recording.

4.5. Solar Paulia Framework

Figure 36 provides the overall picture of the developed framework in this study, called the Solar Paulia framework. The framework has five stages that consist of both technical and social approaches. The five phases included in the framework are explained above throughout the research on this study. Each stage requires several steps and analyses to be performed.

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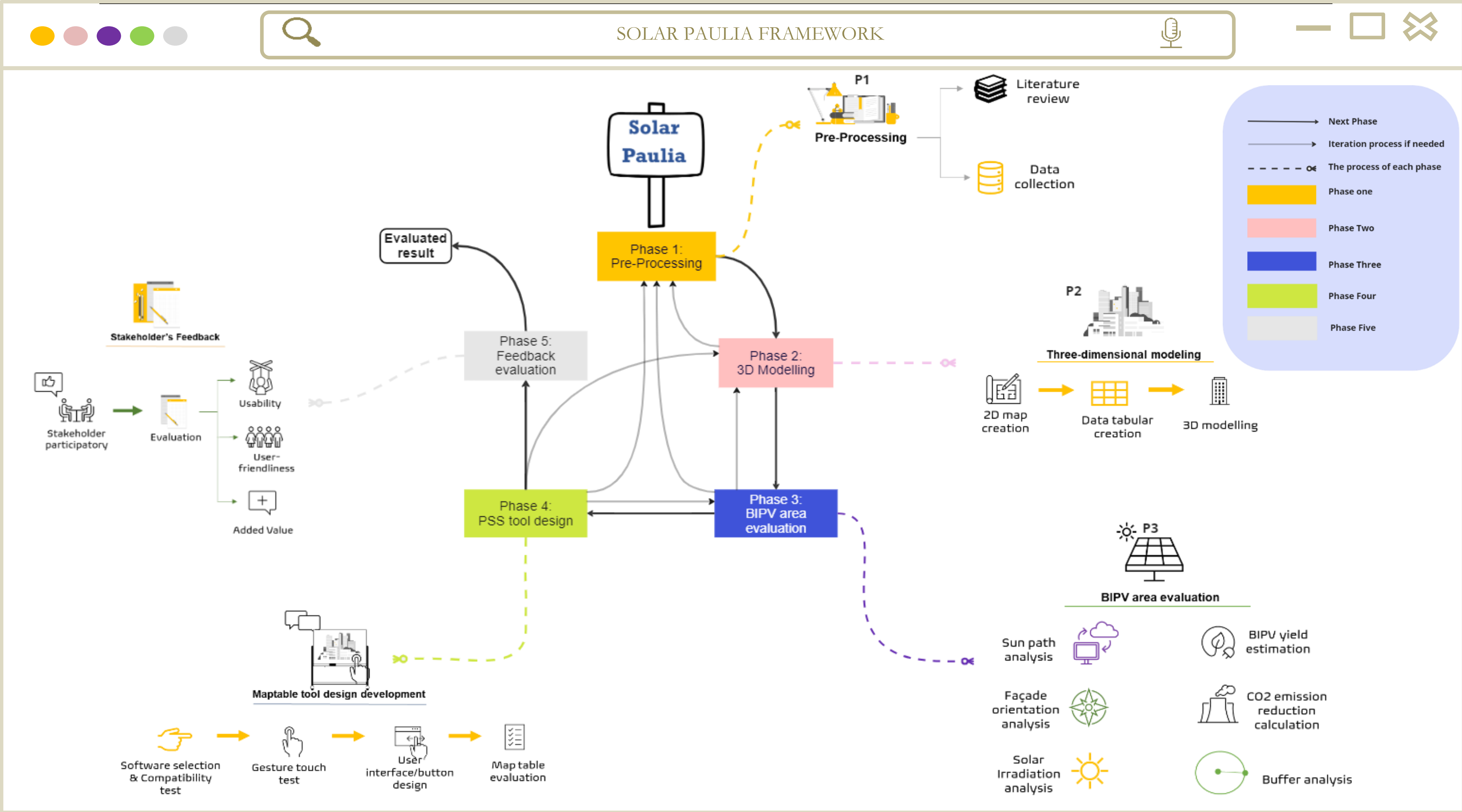

Figure 36 Solar Paulia Framework (Source: Author)

4.6. Tools overviews

After the iteration of experiments with several software and plugins, the selected one that fulfills the research aim requirement is depicted in Figure 37. The tools architecture applies the combination of Geographic Information System (GIS) and Computer-Aided Design (CAD), which the result expected will represent on the map table. The GIS software mainly builds the three-dimensional model, including creating a two-dimensional map. Meanwhile, the *CAD* software focuses more on developing the BIPV simulation tool and user interface. The process was centralized with *CAD*-based software as the umbrella for all the plugins applied to create the interface.

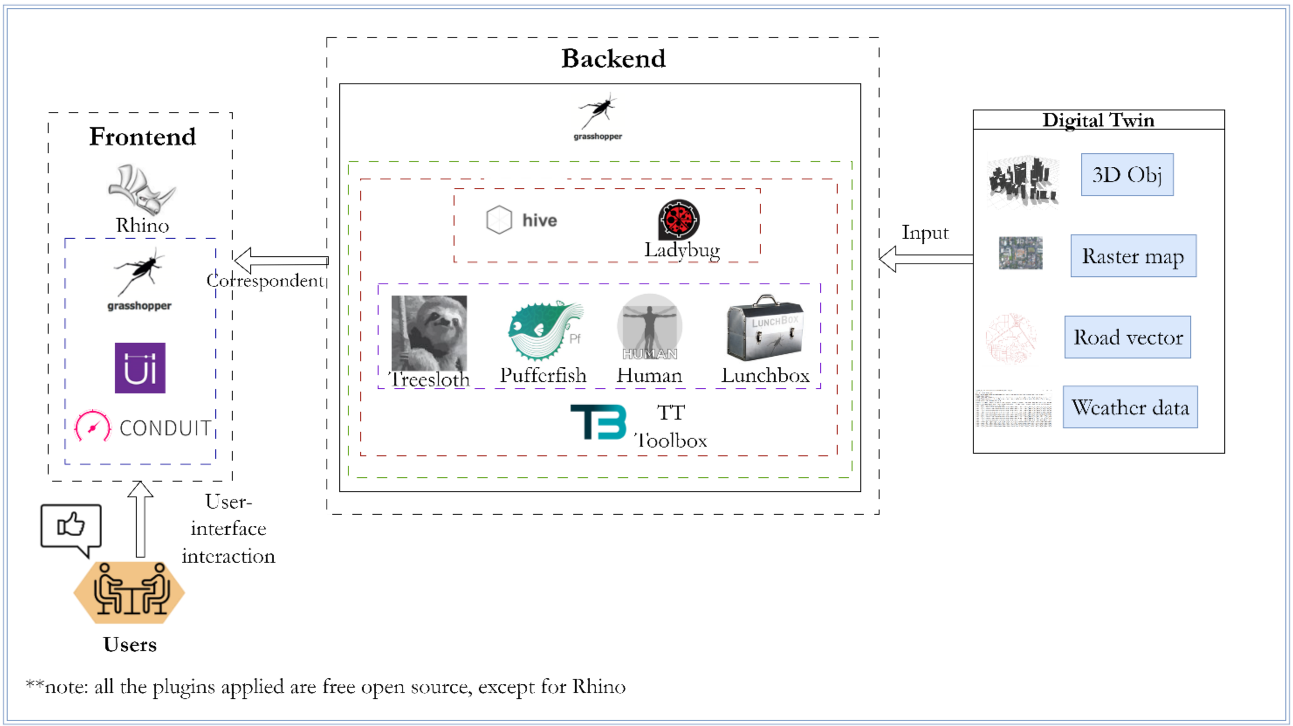

Figure 37 Tools overviews function in the research.

The front end concentrated on *the* 3D model scene's using the CAD environment and *Human-UI* and *conduit* plugins. The *Human-UI* plugin has a function to be the user interface that allows the user interaction to run the BIPV simulation. Meanwhile, the conduit purposely provides visual information on the annual radiation result.

The backend part runs all the processes to ensure the simulation works on the front end, supported by several plugins: HIVE, *ladybug*, *tree sloth*, pufferfish, *human*, *lunchbox*, and *TT toolbox*. The component to launch the BIPV simulation uses HIVE. As for *ladybug* support to input *epw* data, the *tree sloth*, *pufferfish*, *human*, and *lunchbox* are to construct the buttons on the interface. While *TT toolbox* is responsible for directly transferring the output result in Excel format. The overall summary of the plugins is described in Table 12.

Table 12 Summary explanation of the selected plugins(Source: (Grasshopper, 2022))

Frontend		
Plugins	Summary	Steps/function
Human-UI	A free customized plugin that is purposedly to develop a user interface. It offers many options to explore and do experiments. However, the limitation comes to people who cannot code because some parts to re-arrange the function require code in phyton and c#. Furthermore, the plugin is no longer updated, as the developer teams have already disbanded, but the plugin still can work perfectly.	Phase four: developing the user interface on the map table
Conduit	Released by proving ground apps, the plugin is practically perfect for custom data visualizations.	
Backend		
Plugins	Summary	Steps/function
Ladybug	The plugin provides climate data analysis, which can support environment study and interactive weather data visualization.	Phase three: BIPV simulation
HIVE	Developed by ETH-Zurich University, the plugin mainly focuses on energy performance in buildings.	
Human	Used for the input of building's figure component and saved the works to the Rhino layer	Phase four: to develop the button for the interface to support running the BIPV simulation
Lunch Box	The plugin has a component for managing the geometry and is used for paneling options to divide the surface of the building façade. The lunch box plugin is designated for geometry manipulation.	
Pufferfish	Pufferfish is perfect for shape control operation and, in this research, is applied for numbering the panel.	
Tree Sloth	The plugin is explicitly for managing the data tree and is applied for constructing the data tree process. The tree sloth is used as a complement support combined with other plugins.	
TT Toolbox	The plugin supports the extraction outputs of the Excel workbook.	

4.7. Summary

Chapter four mainly explains the results of the research. The section starts with 3D Model development, followed by the BIPV area evaluation result, then continues with map table tool design, then the stakeholder participatory feedback evaluation. At the end of the section, the developed Solar Paulia framework was depicted as the accumulated processes performed beforehand: phase one until phase five. The next chapter discusses the study's findings, limitations, and recommendations.

5. DISCUSSION

5.1. Findings in the study

The research activity demanded a coherence between technical models and social involvement to address the current real-world challenge of climate change. The study concentrated on bringing up the issue of performing renewable energy activity in dense urban settings by introducing BIPV as a climate technology to the decision-makers in Indonesia. Some findings in this study were discovered through all the activities and experiments, which are driven by the technical and social part.

The proof of concept on building evaluation started with six buildings which provided the evaluation of several methods, which stands a possibility to larger the scope of the area and the number of buildings in the future. Through the spatial buffer analysis, findings were that the six buildings were located in close range with surrounding buildings within around or even less than 25 meters. Substantially, it has to be noted that the evaluated building's height is above 100 meters. While interpreting the result, it showed the concept of solid obstruction was significantly affecting and lowering the outcome of energy generated (Schüler et al., 2018). These findings potentially describe the perfect setting of dense urban areas, with skyscraper buildings and close distance per pair of buildings. Thus, this might explain the probability of a less dense area possibly generating a higher energy yield compared to a dense urban area is greater. However, these cases need a proper further evaluation, considering that the height of the building itself will impact the energy yield (Schüler et al., 2018).

In interpreting the sun irradiation result of each facade for six evaluated buildings, given the range of value between 84,6 – 234,1 kWh/m^2/year. Referring to (Compagnon, 2004) findings about the threshold of the annual solar irradiation value for the BIPV façade, the result from this study are relatively low. However, (S. Freitas & Brito, 2019) stated that the potential of vertical BIPV occupied more surface area, resulting in a higher total power produced, which depicts the solar radiation for the total façade area in the study are between 430 – 2742 MWh/year. Thus, S. Freitas & Brito (2019) study and Lewis (2007) study strongly suggest applying the BIPV system in warm and sunny countries to reach energy efficiency goals. Considering the aesthetic issue of PV panels (Lai & Hokoi, 2015), the translucent types of PV modules were utilized to estimate vertical PV yield and emissions that can be reduced from BIPV installation. The result of these calculations is lower in comparison with other types of PV modules, as explained in Martín-Chivelet et al. (2022) research, where the degree of transparency and the module's color are the main parameters that determine the efficiency of the BIPV module, which implies significant losses.

Discovered during the BIPV area evaluation that the highest façade area is not always generating the most energy; this was revealed on the West façade of the FWD tower evaluation. This finding illustrated the complex environment of dense urban areas where many factors influenced the performance of BIPV, such as the surrounding environment and solar radiation angle (Vahdatikhaki et al., 2022). The surrounding environment refers to the obstructions that potentially block the incoming sun, leading to the shadowing effect falling on the buildings (Samarasinghalage et al., 2022). Another major role play affecting the solar energy received is the sun's position in the sky, identified by the sun's elevation and sun azimuth, which always have a fixed position annually (Kalogirou, 2014). Regarding the study area located on the equator line, the solar time between noon and night was constantly stable throughout the year.

The findings from the evaluation per panel interpret in various results, which depict the position of the sun on the sky and the surrounding environment playing a significant role (Kalogirou, 2014; Martinez-Gracia et al., 2019; Munari Probst et al., 2013; Sengupta et al., 2017). Where the highest position panel was not always the most exposed to the sun, the example of this case illustrated in the result of the west façade Prosperity Tower (See Figure 39), the West façade of Mandiri I (see Figure 46), and west façade of Tower A (see Figure 54). Furthermore, the result of the lowest panel for all the buildings showed the least exposure to the sun.

To further highlight, the final simulation process of BIPV using the HIVE plugin provided fast feedback, which is suitable to support stakeholder engagement in the case of response. Additionally, in terms of input 3D model, the plugin recognizes the geometry model within the level of detail one that is applied in this study. However, it is mentioned by the developers that the plugin has less documentation and is not adequate for the detailed design (Waibel et al., 2022).

The developed framework, model, and tool were presented in a stakeholder participation workshop, providing more qualitative feedback. The input from stakeholders for the developed Solar Paulia framework mentioned quite similar feedback for each participant, with the majority of seven participants mentioning that the stakeholder involvement was better at the beginning and the end. In comparison, two participants stated the stakeholder should be involved in every stage, and the rest agreed that the Solar Paulia framework is already perfect (See Table 31).

The evaluation of the model and tool was concentrated on usability (Aguilar et al., 2021; Brömmelstroet, 2013; Pelzer, 2017), and added value indicators (Pelzer, Geertman, & Van Der Heijden, 2015; te Brömmelstroet, 2017). Most participants find the user interface design and model navigation to be user-friendly or user-friendly (see Table 8). Thus, the stakeholders also expressed satisfaction with the workshop session (see Table 9) and agreed that the information provided was easy to understand (see Table 10). However, the critical feedback on the processing time referred to the simulation time taking a long time to process; about 26,67% strongly agreed, and 33,33% agreed with the statement. These conditions were induced by the incapability of the computer processor used for stakeholder participation.

The findings after the workshop session showed that all the participants agreed (see Figure 34) that they learned about the renewable energy issue in the urban area, and their knowledge regarding BIPV as one of the climate technologies is increasing, which depicts one of the expected outcomes of the stakeholder participation explained in the section, to increase their awareness is achieved. In addition, all participants agreed that the tool presented could help the planning and discussion process. Hence, the majority of participants, more than 90%, prefer choosing the map table rather than conventional paper-based ones. However, one person disagrees that a map table is better than a paper-based participatory and raised a concern that not all Indonesians are digital-literate.

As the stakeholders perceived the information, they did not acknowledge such a climate technology called BIPV existed. The concern raised the most was concentrating on financial matters because the installation price was much higher than the rooftop PV. The second concern raised was about the aesthetic issue, which had been explained during the session that the translucent could answer this problem. The positive response to the developed model and tool will be a helpful aid for stakeholder engagement and planning support, as the tool has an extensive visualization. The significant finding of input preferences from the stakeholders was that one statement mentioned that women have less sense of direction than men. However, in some workshops with a woman participant, the feedback was diverse on whether it is difficult or easy for women to operate. Due to the lower of participants women, some feedback might be biased and subjective. This situation requires further evaluation with a more balanced sample of gender participants.

In response to the awareness of the current climate change situation and renewable energy activity goal, the participants seemed to not fully aware, as some comments stated Indonesia already oversupplied the electricity from coal power plants. This situation requires full attention to whether decision-makers in Indonesia understand the reason behind energy transition activities or only fulfill the target of numbers. During the entire stakeholder participation workshop, not a single participant asked or was concerned about how beneficial the technology is to reducing CO_2 emissions. However, it was understandable as the concern was more about financial and visual pleasing, which is always a crucial issue of vertical PV installation on a building's façade (Hamzah & Go, 2022; Heinstein et al., 2013; Osseweijer et al., 2018).

5.2. Answer of Sub-objectives

Sub-Objective 1: *To review the software applications applied for solar potential analysis on the building's façade.*

The literature review of the potential existing software and tool applicable in section 2.1 shows several applications to perform solar potential analysis on building façade in a variation of paid software such as PVSITES, BIMSol, Revit-dynamo, and publicly open-source tools inter alia, ladybug, HIVE, and CEA.

There are two main inputs to carry out the solar potential analysis: the three-dimensional model and the weather dataset. The 3D model has a function to showcase the façade area and provides an overview of obstructing surroundings. Certain datasets are to be used for developing the 3D model: Lidar data, Digital elevation model (DSM), and buildings footprints. While the weather dataset, which is usually depicted in TMY or EPW format, is an important input for the solar potential analysis.

Sub-Objective 2: *To develop a 3D city model for vertical PV installation.*

The findings from the literature review described in section 3.2.2 show two main methods for developing the 3D model: the Topology model with strong object structural relation and the Geometry model with a strong relation to the coordinate of the object.

Hence, in consideration of the dataset scarcity, the 3D model developed was created from the primitive component such in this research could not reach a higher level of detail, and the findings from the literature review incorporating the available datasets, the Geometry model representing in the level of detail 1.

Sub-Objective 3: *To evaluate the façade area for BIPV installations.*

The area evaluation consists of several analyses, namely: (i) sun irradiation analysis, (ii) BIPV yield estimation, (iii) CO_2 emission reduction estimation, and (iv) buffer distance concept analysis. All these methods mentioned were explained in Section 3.3, and the results were interpreted in Chapter 4.2.

Sub-Objective 4: *To develop the PSS map table tool design for vertical PV simulation.*

The final design of the tool presented three main components: (i) the 3D model scene to manipulate the touch gesture on the 3D model, (ii) the user interface for direct interaction to simulate the BIPV, and (iii) the sun irradiation graph result. The further detailed concept can be seen in Chapter 3.4, and the results can be perceived in Chapter 4.3.

Sub-Objective 5: *To evaluate the stakeholder's feedback on the developed framework.*

The stakeholder feedback was evaluated through a stakeholder participation workshop held in Jakarta. The questionnaire was distributed at the end of the session. The evaluation was concentrated on providing input for the developed tool and framework and also to inform and increase the awareness of the stakeholder regarding the BIPV as a potential climate technology for dense urban areas. The result of the stakeholder evaluation is explained in Section 4.4.

5.3. Limitations of the study

After the research has been done, certain limitations and uncertainty will be discussed one by one in this sub-section.

The data scarcity does not allow to reach a high level of detail for the three-dimensional model developed. Concerning the *'no data'* situation, the representation of the 3D model could not portray the real condition and detail of the building's façade, such as window to wall ratio (Panagiotidou et al., 2021). Regarding this case, the author identified all the buildings and gathered the building's height information through the website search engine, leading to the uncertainty of the building's detail. Thus, because this study is not designing the BIPV, the division of paneling on the façade is based on the author's interpretation with consideration of not overwhelming the stakeholders when selecting the panel in the stakeholder participation session.

Considering the weather dataset used in this research is an open and free source, it is only provided until 2021, which leads to the not displaying the current weather condition and affecting the calculation of sun irradiation. Emphasizing the BIPV evaluation phase, there are some drawbacks have to be mentioned which potentially affect the calculation result: (i) the obstruction, such as a tree, is not included for the obstruction input because there is no data for this information, (ii) the HIVE plugin still considered as a novel tool, the only publications discussed this were coming from the developers, (iii) the algorithm to calculate energy yield was applying the simple formula, which does not consider the performance loss such as dust (Kiani Ghalehsard et al., 2021), the electricity wire (Polo et al., 2021), high temperature (Skandalos et al., 2022) or gradual time performance decrease (Skandalos et al., 2022), (iv) as the result of the simple formula of energy yield causing the uncertainty while estimating the emission reduction.

Another limitation has to be mentioned regarding HIVE as the selected plugin to evaluate the BIPV area was suitable for addressing the early stage of conceptual design and decision-making because of the fast computation, but does not accurate enough for real design (Waibel et al., 2022). The developer of HIVE also suggests using advanced tools such as EnergyPlus or TRNSYS for the final design evaluation (Waibel et al., 2022). Thus, the numbering system in HIVE did not correspond with the panel selection, in which all the numbering results on the graph always start with the number zero. This inconsistency could not be changed, as the plugin system was ready-made that way.

Due to the unpredictable circumstances, the workshop used a touch screen laptop with insufficient system support during the participatory time to run the simulation, which led to the waiting time taking longer than usual. Even though this condition was mentioned at the beginning of the participatory session, it affects the feedback from stakeholders regarding the usability assessment of the tool. Additionally, another point that has to be mentioned for the participatory session is the imbalance of gender distribution among participants might be creating biased results among the male participants.

5.4. Recommendation for future study

There is always room for improvement; in this study, some parts should be mentioned to improve for future development and study. First to mention is the completeness of 3D model representation. Acquiring the dataset through field surveys is possible in response to the data scarcity issue. However, consider that this might require some legal permit documentation process. Improving the 3D model with detailed information, such as surface material (Osseweijer et al., 2018), and the shape of geometry buildings (Biljecki et al., 2015a), will allow more comprehensive results in solar potential estimation suitable for the final architecture design.

Another recommendation is that this study's phase of BIPV evaluation can be optimized in the tilt and azimuth angle (Vahdatikhaki et al., 2022). To showcase the best optimal installation design, which can be deprived in horizontal and vertical tracking (Robledo et al., 2019). Regarding the scope and location of the study area to have a further comparison and analysis with less dense areas is recommended to try out. To find out whether the energy generated is higher if the setting of the landscape is less dense (Panagiotidou et al., 2021). Since this stud already provided a proof of concept for evaluating the BIPV façade area on six particular buildings, it is recommended to test this approach for a larger scope of the area, which could lead to the city scale zonation of where the location potentially received more sun irradiation (Saretta et al., 2020).

Considering the number of feedback from stakeholders that request to add analysis to economic performance, further analysis such as payback period (Thoy & Go, 2022), internal rate of return (Chen & Yu, 2021), life cycle energy and cost (Samarasinghalage et al., 2022), and net present value (NPV) (Scognamiglio, 2017). Regarding the stakeholder engagement was presented in asynchronous distribution, while ideally, the PSS workshop is held in a setting (Aguilar et al., 2020). This type of workshop setting can be tried using the Solar Paulia framework in the future. Furthermore, involving different groups of stakeholders, e.g., citizens and private companies, can likely add more value to the sense of information and perspective.

To further research, the effect of BIPV implementation on society should take seriously matter; this situation is called the Rebound effect, where the improvement of technologies potentially decreases energy saving as a consequence of human consumption behavior (Aydin et al., 2017; Khazzoom, 1980; Wirl, 1997).

6. CONCLUSION

This study mainly aimed to develop a Solar Paulia framework to accomplish the gap of informing the decision makers in Indonesia about vertical solar panel technology through the PSS tool called map table. This research shows that Building integrated photovoltaic (BIPV) is potentially a promising climate technology option for densely populated urban areas. Therefore, this thesis contributes to raising the awareness of decision-makers in Indonesia about renewable energy technology options by conducting a participatory session in Jakarta. The sessions demonstrated the BIPV simulation on the 3D models with the map table tool. The stakeholders had the opportunity to interact with the 3D model and run simulations through the user interface on the touch screen. To the best of the author's knowledge, no prior study was done to inform the stakeholders about potential BIPV technology, which enables the stakeholders to simulate the BIPV in the 3D model environment on a map table touch screen. This study's novelty lies in this explanation.

The author employed a combination of methods for this study, included: created the 3D geometry models (Ying et al., 2020), sun irradiation analysis (Waibel et al., 2022), energy yield estimation (Panagiotidou et al., 2021), estimation of CO_2 emission reduction (Thebault et al., 2022), designing a map table tool (Dias et al., 2013; Ryall et al., 2006), facilitating stakeholder workshops (Goodspeed, 2013), and evaluating stakeholder feedback using usability indicators such as user-friendliness, satisfaction, and calculation time(Aguilar, 2022; Brömmelstroet, 2013; Pelzer, 2017; Pelzer et al., 2014, 2016; te Brömmelstroet, 2017), as well as added value indicators like object learning and efficiency (Brömmelstroet, 2013; Pelzer et al., 2014).

By applying these methods above, this study successfully demonstrated that harnessing BIPV technology on building facades can support generating clean energy. At the same time, resolve the challenges associated with land scarcity in densely populated urban areas. Furthermore, from this study, we also learned the perspective and insight from the decision makers in Indonesia regarding the BIPV acceptance, as reflected in the feedback questionnaire's result. It is important to inform the stakeholders of BIPV as a potential climate technology to be utilized in city-setting areas.

In this study, the BIPV area evaluation revealed that the highest façade area did not always generate the highest energy yield. This finding can be attributed to the sun's position in the sky (Kalogirou, 2014; Martinez-Gracia et al., 2019; Martínez-Rubio et al., 2016). Acknowledge this research opened the investigation to what extent the decision-makers are aware of such a climate technology. Overall the building evaluation served as a proof-of-concept that quantifies with existing data and methods. This opens up opportunities for further research on BIPV in Indonesia.

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ANNEXES

ANNEX A: Buildings Identification

All the buildings that were successfully identified are listed in Table 13. The information regarding the buildings, such as height, number of floors, the building function, and year of construction, was collected from web search findings.

Table 13 Building identification result

FID	Buildings	Height (m)	Floor	Function	Year of construction
Building 0	Summitmas II	76	19	Office	1992
Building 1	Summitmas I	80	20	Office	1985
Building 2	Menara Sudirman	87	20	Office	1995
Building 3	Plaza asia	104	26	Office	2005
Building 4	Graha CIMB Niaga	131	28	Office	1993
Building 5	Residence 8 senopaty equity tower / Office 8 Building	161	32	Resident	2015
Building 6	Treasury Tower	279,5	57	Resident	2018
Building 7	Residential tower A (the 8)	188	43	Resident	2012
Building 8	Residential tower B (the 8)	188	43	Hotel	2012
Building 9	Langham Hotel	161	43	Resident	2021
Building 10	Etertnity apartment	205	51	Resident	2017
Building 11	Infinity apartment	205	51	Resident	2017
Building 12	Prosperty Tower / District 8 Office tower 2	188	43	Office	2018
Building 13	Sequis center	77		Office	1980
Building 14	Infinity apartment	205	51	Resident	2017
Building 15	District 8 Hotel/Residential Tower		26	Resident	2017
Building 16	Energy Tower	217	40	Office	2008
Building 17	KPP Pratama	87	20	Office	N/A
Building 18	Menara Mandiri I	126	28	Office	1995
Building 19	KPP Pratama	87	20	Office	N/A
Building 20	Sequis Tower	210	40	Office	2019
Building 21	Menara Mandiri II	126	28	Office	1996
Building 22	Alila Hyatt Hotel	144	23	Hotel	2019
Building 23	FWD HQ (Pacific century place)	209	40	Office	2017
Building 24	BEJ Tower 2	132	29	Office	1998
Building 25	Equity Tower	220	44	Office	2010
Building 26	BEJ Tower 1	140	32	Resident	1994
Building 27	Artha Graha building	125		Resident	1995
Building 28	Capital resident apartment	112	33	Resident	2007
Building 29	Capital resident apartmenet tower 1 n 2	144	38	Resident	2007
Building 30	Kusuma candra apartment	110		Resident	1995

Building 31	SCBD suites	102	30	Resident	2010
Building 32	Kusuma candra apartment	68		Resident	1997
Building 33	Kusuma candra apartment	26		Resident	1997
Building 34	Sudirman mansion	136	34	Resident	2007

ANNEX B: BIPV detail result per panels

In detail, the proof-of-concept of six buildings evaluated for BIPV area evaluation is discussed in the subsequent section. The evaluation follows the methods in Chapter 3.3.

- **<u>Prosperity Tower</u>**

The prosperity tower is approximately 188 meters, within the range area per panel on facades between 443 m^2 - 541 m^2 (see Table 14). The location of the building is shown in Figure 38.

Table 14 Area per panel for Prosperity tower

	Area per panel
Prosperity Tower	m^2
East facade	541
South facade	443
North facade	450
West facade	541

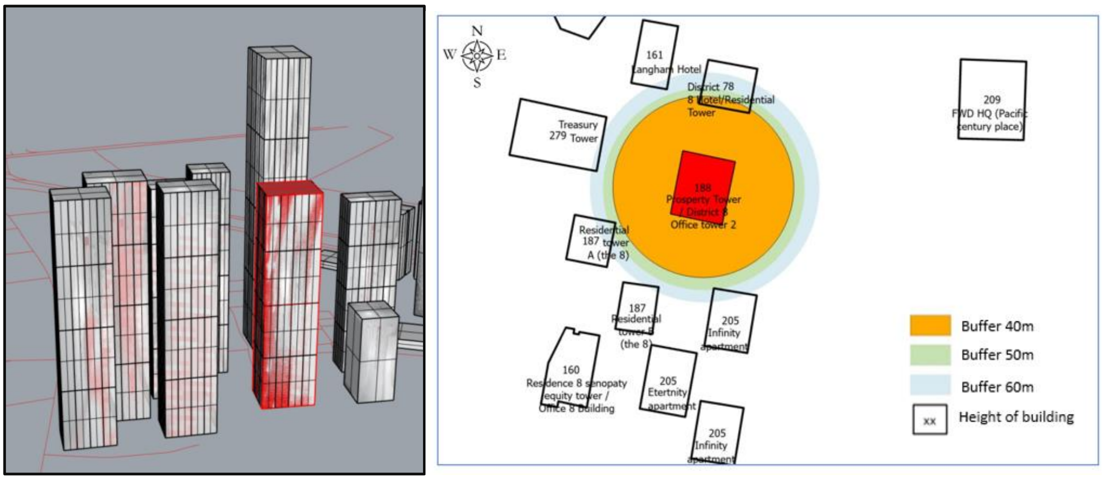

Figure 38 Left: Overview location of prosperity tower; and Right: Buffer distance for Prosperity Tower

It shows other buildings for the North, West, and South façade surrounding the position of the building. However, the distances between the buildings are not close range, which is in the range of 40 to 60 meters. The height of the window panels of Prosperity Tower which shows the height difference for each panel every 47 meters.

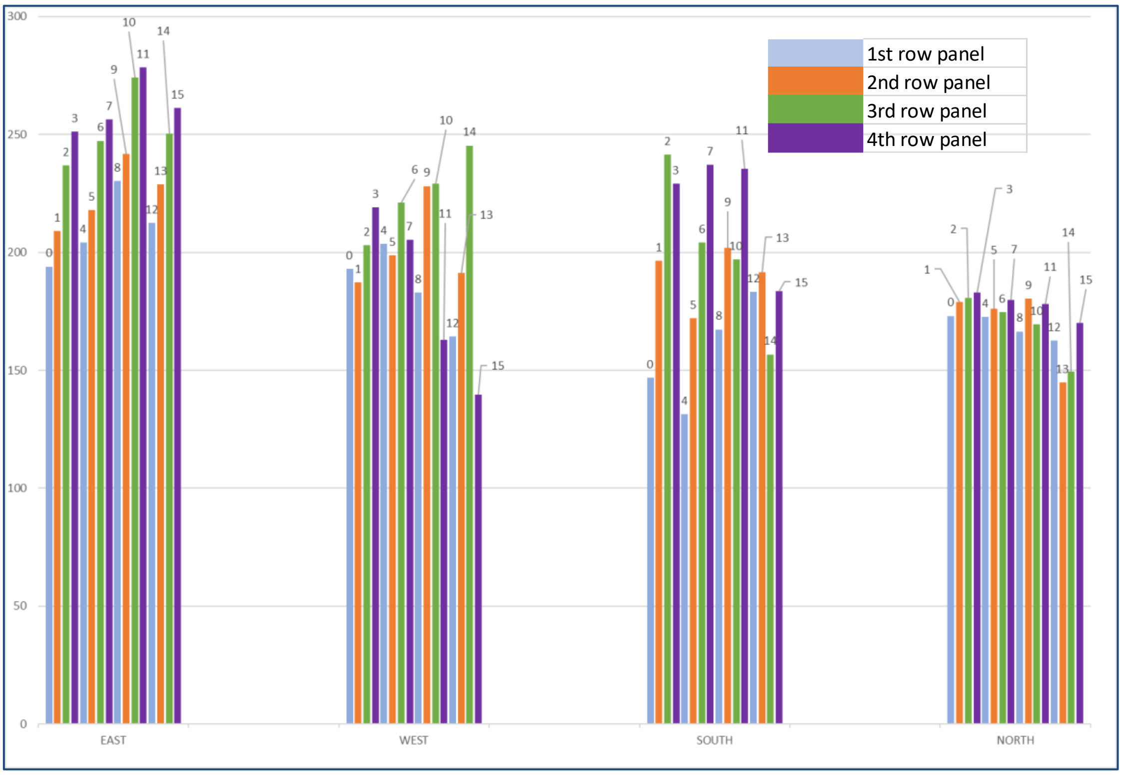

Figure 39 Sun Irradiation per window on Prosperity Tower

Figure 39 displays sun irradiation per window on different façade orientations, showing that w.11 on the East façade received the most sunlight. In contrast, w.4 on the South façade got the least sun radiation. Thus, from Figure 39 result illustrates the phenomenon of the highest façade is not always receiving more sun irradiation (Salimzadeh et al., 2018), which depicted in w.15 of the West façade, which is located at the height of 188 m, but results in the least exposed to the sun on West façade.

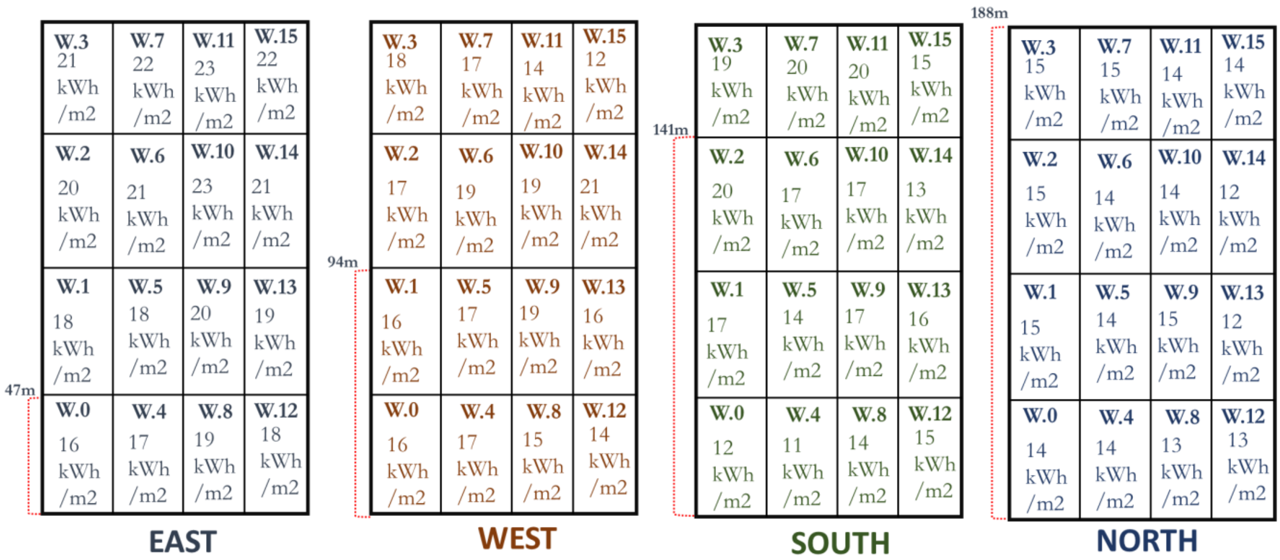

Figure 40 Energy yield per window on Prosperity Tower

Error! Reference source not found. Figure 40 displays the yearly energy yield estimation result in kilowatt hours per square meter (kWh/m^2) if BIPV is installed on the particular window. Thus, Table 15 shows the estimation of CO_2 emission that can be reduced for each window when BIPV is installed on the façade. It provides the overview for every façade orientation. The rank of highest to lowest energy yield windows and reduced CO2 emission are the same as the sun irradiation result. Respectively, the highest potential façade is on the East side, while the lowest is depicted on the North façade.

Table 15 CO_2 reduction per window for Prosperity tower

Prosperity Tower				
CO2 reduction yearly (kg/ m^2)	**EAST**	**WEST**	**SOUTH**	**NORTH**
window 0	3,7	3,6	2,8	3,3
window 1	4,0	3,5	3,7	3,4
window 2	4,5	3,8	4,6	3,4
window 3	4,7	4,1	4,3	3,5
window 4	3,9	3,8	2,5	3,3
window 5	4,1	3,8	3,3	3,3
window 6	4,7	4,2	3,9	3,3
window 7	4,8	3,9	4,5	3,4
window 8	4,4	3,5	3,2	3,1
window 9	4,6	4,3	3,8	3,4
window 10	5,2	4,3	3,7	3,2
window 11	5,3	3,1	4,4	3,4
window 12	4,0	3,1	3,5	3,1
window 13	4,3	3,6	3,6	2,7
window 14	4,7	4,6	3,0	2,8
window 15	4,9	2,6	3,5	3,2

- **<u>FWD Tower</u>**

FWD is the tallest and biggest building evaluated for this study, about 209 meters high. As a result, the panel size of FWD is also the largest within the range of 620 m^2 to 746 m^2 (see Table 16).

Table 16 Area per panel for FWD Tower

	Area per panel
FWD	m^2
East facade	746
South facade	620
North facade	624
West facade	753

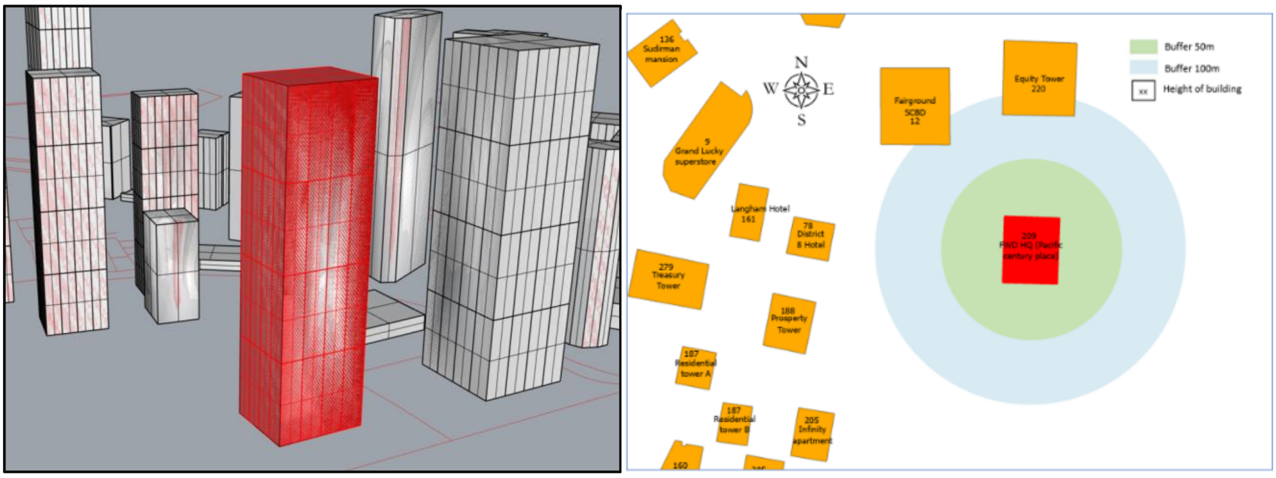

Figure 41 Left: FWD tower location in the 3D model; and Right: Spatial distance buffer result of FWD

The position of the FWD tower is displayed in Figure 41, which shows no close buildings near the East and West façade. At the same time, there is one building right in front South façade, which is also taller than FWD. For the Northern orientation façade, there are two buildings right in front of the Northern façade, which is also higher than FWD. According to the result of buffer distance, the buildings mentioned in the previous sentence are within the range radius of 50 meters for building facing the South façade and within the range of 100 meters for buildings facing the Northern façade.

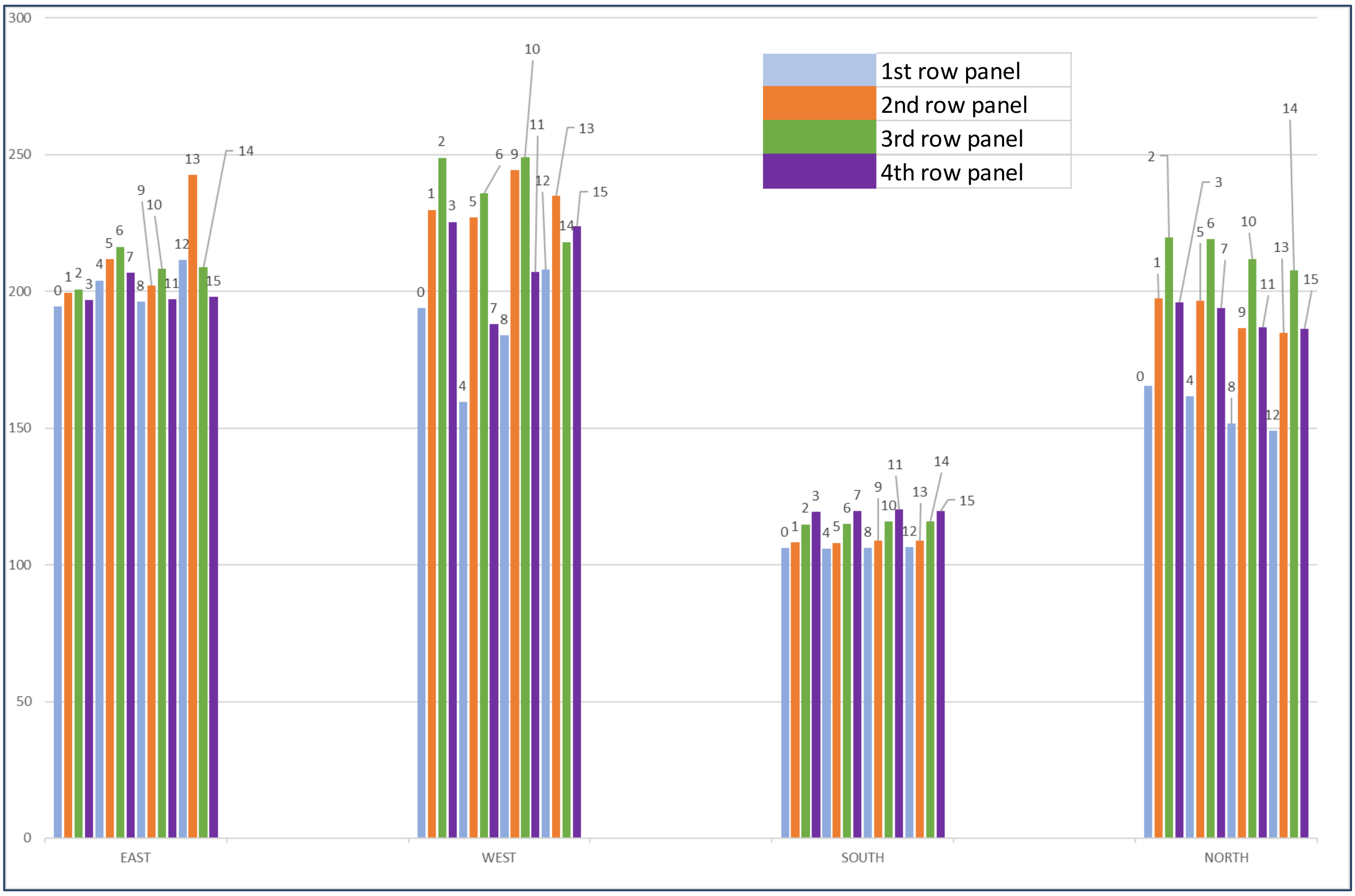

Figure 42 Sun Irradiation results on FWD windows.

The sun irradiation results for FWD are depicted in Figure 42, which explicitly has a big gap between the East-West-North and South façade—depicted that the overall South façade was less exposed to the sun. Nevertheless, this situation depicts the influence of the peer building's distance and height explained above.

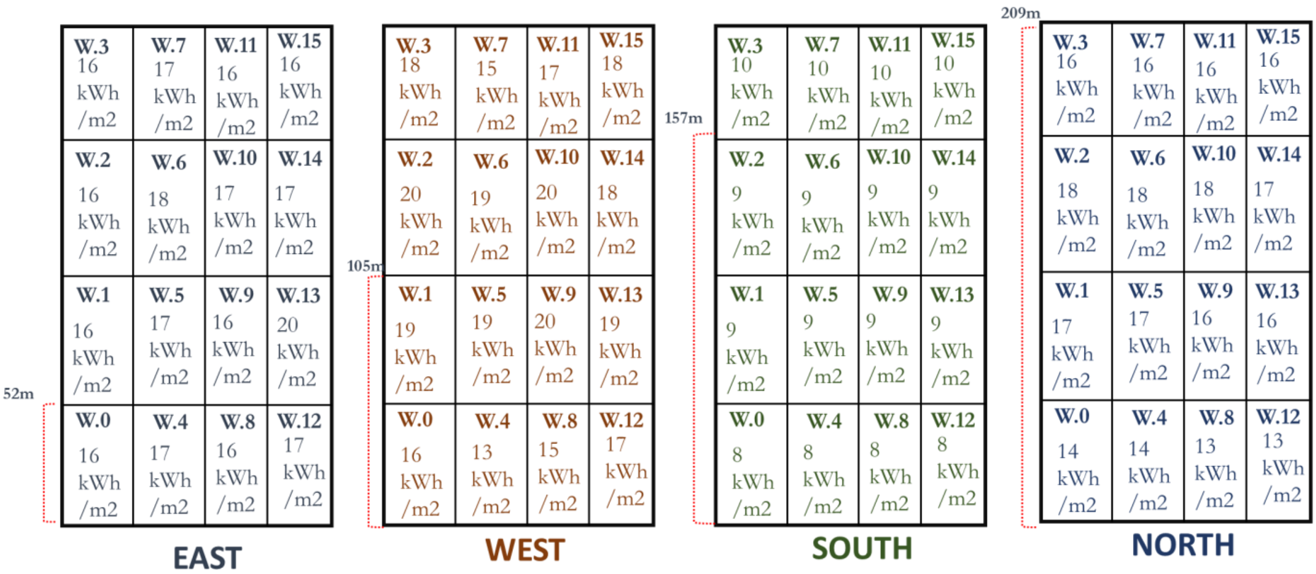

Figure 43 BIPV yield estimation on FWD windows.

The result of the energy yield calculation for FWD illustrates per windows in Figure 43. The lowest yield is on w.4 South orientation with 8 kWh/m^2/year, while the highest is w.13 on the East façade with 20 kWh/m^2/year. Meanwhile, the emission estimation reduced if the BIPV installed per window on FWD is shown in Table 17. The East and West façade possibly deduct ± 4 kg/m^2/year of CO_2 per window, and about ± 3,6/ m^2 /year of CO_2 per window for the North façade. Though the South façade has the lowest result, it still can reduce more than 2 kg/ m^2 /year of CO_2 per window.

Table 17 The result of CO_2 emission reduction of FWD

FWD				
CO2 reduction yearly (kg/m^2)	**EAST**	**WEST**	**SOUTH**	**NORTH**
window 0	3,7	3,7	2,0	3,1
window 1	3,8	4,3	2,0	3,7
window 2	3,8	4,7	2,2	4,2
window 3	3,7	4,3	2,3	3,7
window 4	3,9	3,0	2,0	3,1
window 5	4,0	4,3	2,0	3,7
window 6	4,1	4,5	2,2	4,1
window 7	3,9	3,6	2,3	3,7
window 8	3,7	3,5	2,0	2,9
window 9	3,8	4,6	2,1	3,5
window 10	3,9	4,7	2,2	4,0
window 11	3,7	3,9	2,3	3,5
window 12	4,0	3,9	2,0	2,8
window 13	4,6	4,4	2,1	3,5
window 14	3,9	4,1	2,2	3,9
window 15	3,7	4,2	2,3	3,5

- **<u>Mandiri I</u>**

The third building evaluated was Mandiri I, which has a height of about 126 meters. After the division of the panels, the range of the panel area on the Mandiri I façade are between 377 m^2 to 403 m^2 (see Table 18).

Table 18 Area per panel for Mandiri I

	Area per panel
Mandiri I	m^2
East facade	403
South facade	385
North facade	377
West facade	389

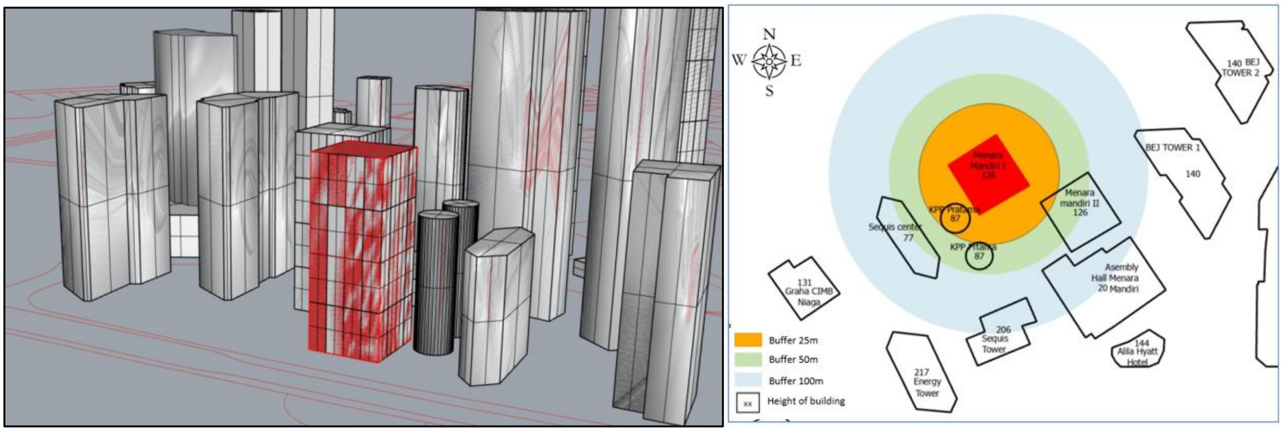

Figure 44 Left: The location of Mandiri I Tower in the 3D model; and Right: Buffer distance of Mandiri I

The position of Mandiri I is not straight, facing the compass direction. Aside from that, Mandiri I is surrounded by several tall buildings on the West and South façade (see Figure 44). While the North façade faces the road, and the East does not have any buildings in front of the façade. At the same time, the closest building is located within a radius of 25 meters.

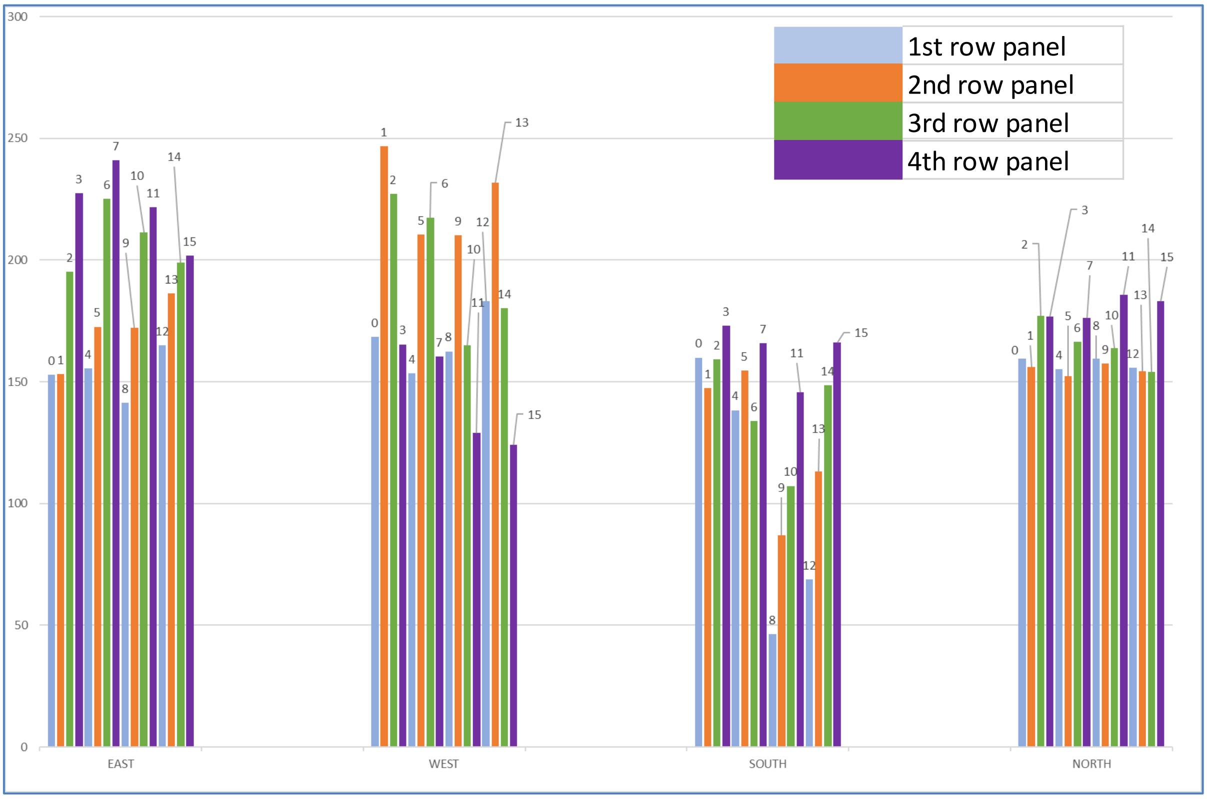

Figure 45 Sun irradiation result on Mandiri I facades.

The result of sun irradiation analysis is provided in Figure 45, which shows the highest radiation is on w.1 on the West façade and the lowest on w.8 on the South façade. Compared to each façade, the South façade has huge fluctuated differences between each panel. Thus, overall, the panels on the first and second rows always received less sun for all façades.

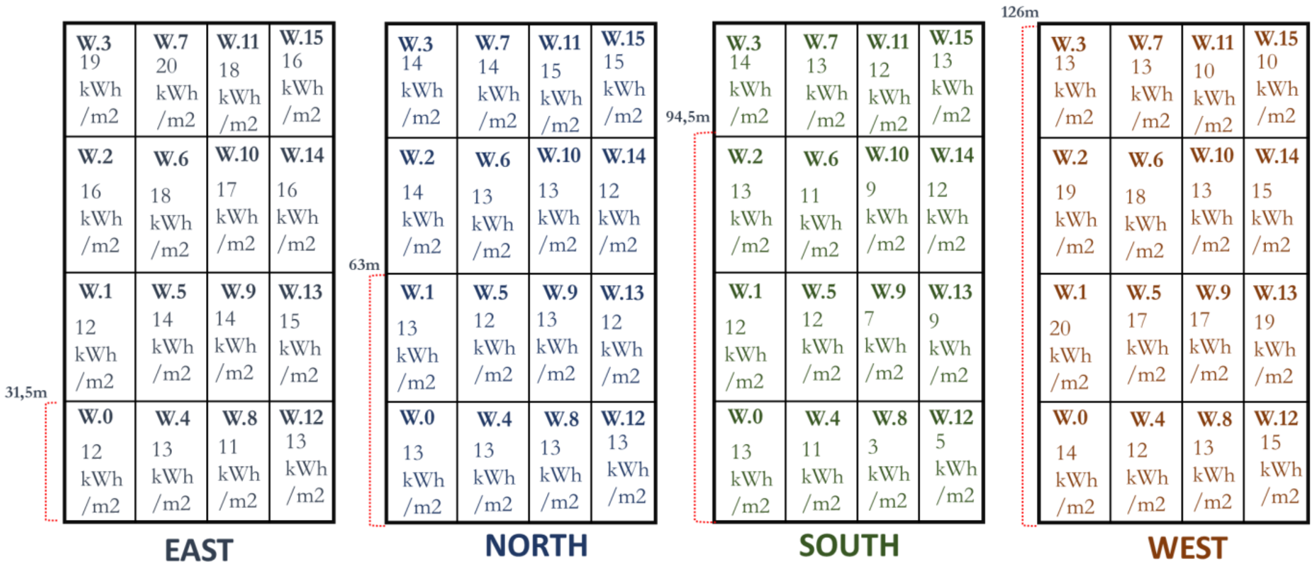

Figure 46 BIPV yield estimation for Mandiri I

The result of the BIPV yearly yield estimation per window is shown in Figure 46. The yield estimated for the East façade is 11 kWh/m^2/year to 20 kWh/m^2/year, while on the West façade between 10 kWh/m^2/year and 20 kWh/m^2/year. Regarding the South and North façade, all the windows yield less than 15 kWh/m^2/year. Table 19 displays the estimation CO_2 can be reduced when BIPV is installed on the windows.

Table 19 The estimation of CO_2 reduced for Mandiri I

Mandiri I				
CO_2 reduction yearly (kg)	**EAST**	**WEST**	**SOUTH**	**NORTH**
window 0	2,9	3,2	3,0	3,0
window 1	2,9	4,7	2,8	2,9
window 2	3,7	4,3	3,0	3,3
window 3	4,3	3,1	3,3	3,3
window 4	2,9	2,9	2,6	2,9
window 5	3,3	4,0	2,9	2,9
window 6	4,3	4,1	2,5	3,1
window 7	4,6	3,0	3,1	3,3
window 8	2,7	3,1	0,9	3,0
window 9	3,3	4,0	1,6	3,0
window 10	4,0	3,1	2,0	3,1
window 11	4,2	2,4	2,8	3,5
window 12	3,1	3,5	1,3	2,9
window 13	3,5	4,4	2,1	2,9
window 14	3,8	3,4	2,8	2,9
window 15	3,8	2,3	3,1	3,5

- Mandiri II

Mandiri II is located precisely next to Mandiri I and has the same height, exterior structure, and panel size area (see Table 20).

Table 20 Area per panel for Mandiri II

	Area per panel
Mandiri II	m^2
East facade	403
South facade	385
North facade	377
West facade	389

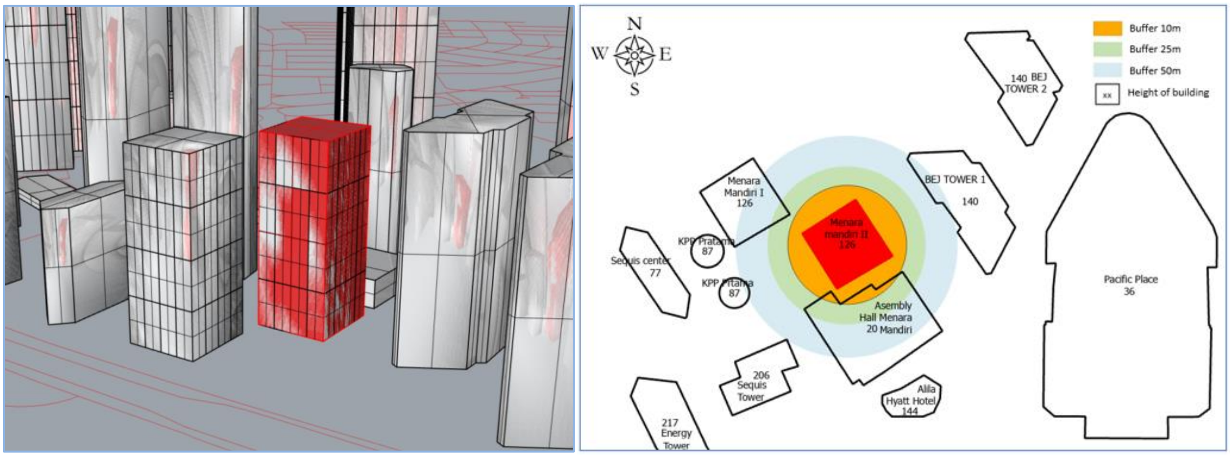

Figure 47 Left: Mandiri II building Location in the 3D model; and Right: Mandiri II buffer distance with pairs buildings

Regarding the building position, Mandiri II is located on the southern side and surrounded by other buildings. However, in height comparison, the building surrounds on the south, and west façades are shorter, and within a range of 50 meters on the East side, there is one building about 20 meters higher than Mandiri II. The overview illustration can be seen in Figure 47.

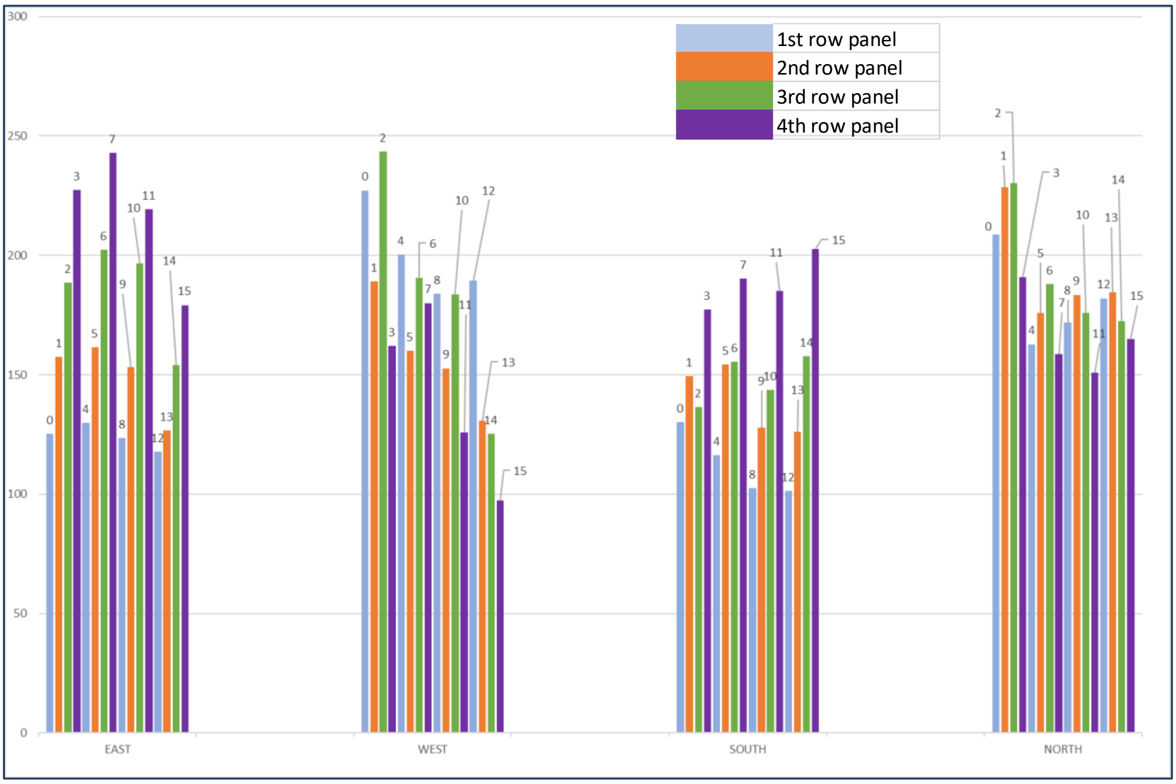

Figure 48 Sun irradiation analysis for Mandiri II

The result of sun irradiation analysis for Mandiri II is depicted in Figure 48, which shows the most window received sun irradiation are w.7 on the East façade and w.2 on the West façade. Meanwhile, the least sun exposure is w.15 on the West façade.

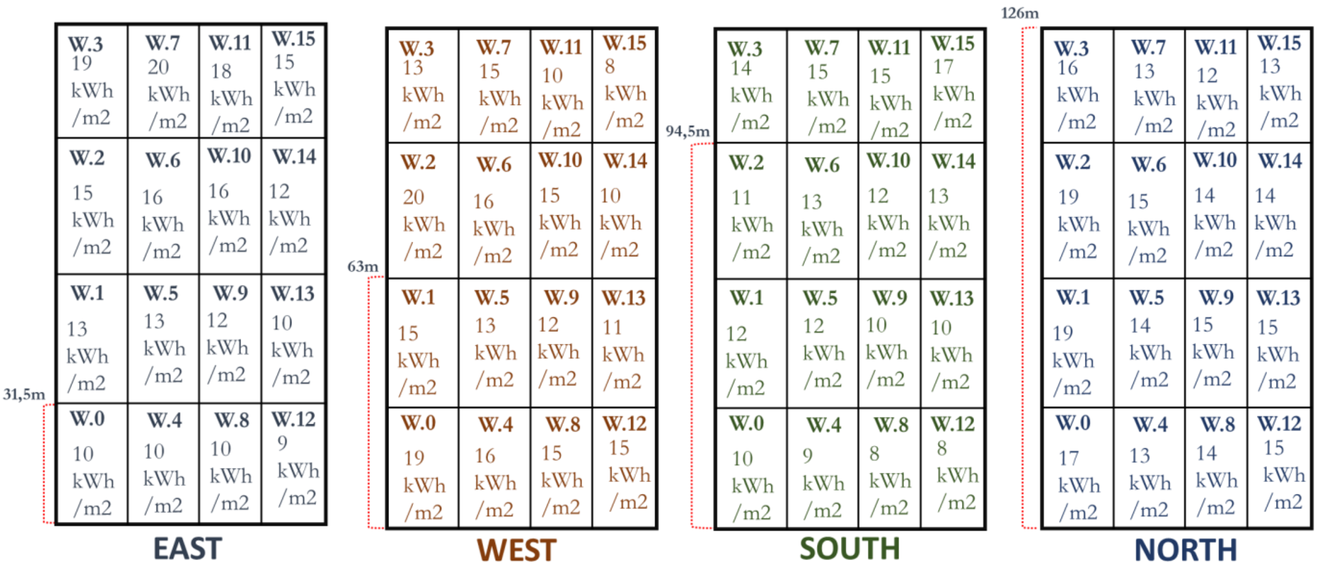

Figure 49 BIPV estimation results for Mandiri II

Figure 49 displays the result of the BIPV yield estimation for Mandiri II and the emission reduction estimation in **Error! Not a valid bookmark self-reference.**. The output shows another phenomenon: the highest-located panels do not always receive the highest radiation depicted on the North façade.

Table 21 Emission reduction for Mandiri II

Mandiri II				
CO_2 reduction yearly (kg)	**EAST**	**WEST**	**SOUTH**	**NORTH**
window 0	2,4	4,3	2,5	3,9
window 1	3,0	3,6	2,8	4,3
window 2	3,6	4,6	2,6	4,4
window 3	4,3	3,1	3,3	3,6
window 4	2,5	3,8	2,2	3,1
window 5	3,1	3,0	2,9	3,3
window 6	3,8	3,6	2,9	3,6
window 7	4,6	3,4	3,6	3,0
window 8	2,3	3,5	1,9	3,2
window 9	2,9	2,9	2,4	3,5
window 10	3,7	3,5	2,7	3,3
window 11	4,1	2,4	3,5	2,9
window 12	2,2	3,6	1,9	3,4
window 13	2,4	2,5	2,4	3,5
window 14	2,9	2,4	3,0	3,3
window 15	3,4	1,8	3,8	3,1

- Resident Tower A and B

Resident Tower A and B are 188 m tall and bound next to each other. However, the total panel area per façades has different sizes (see Table 22).

Table 22 Area per panel Tower A and B

	Area per panel
Tower A	m^2
East facade	385
South facade	354
North facade	354
West facade	385

	Area per panel
Tower B	m^2
East facade	403
South facade	318
North facade	305
West facade	403

Both towers, A and B, are surrounded by tall buildings with a minimum height of 160 m, illustrated in Figure 50. In comparison, tower A has a closer range with the North pair buildings, while tower B has a closer range with South pair buildings (See Figure 51).

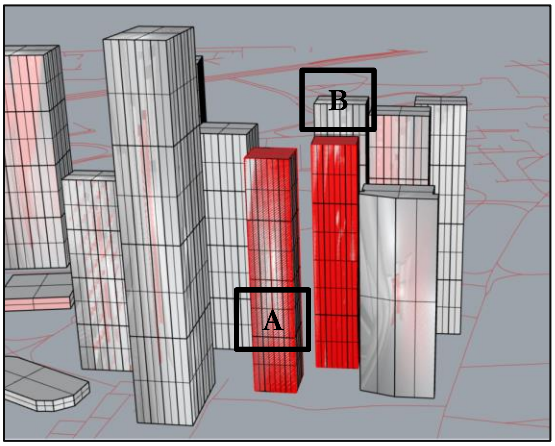

Figure 50 The 3D model scene of Tower A and B

Figure 51 depicts the buffer distance for towers A and B as within 25 m, 50 m, and 100 m. Tower A has less obstruction on the East and West sides. In contrast, the South has several buildings, including Tower B. Meanwhile, Tower B is surrounded by other buildings from all orientations, located closer to the obstruction.

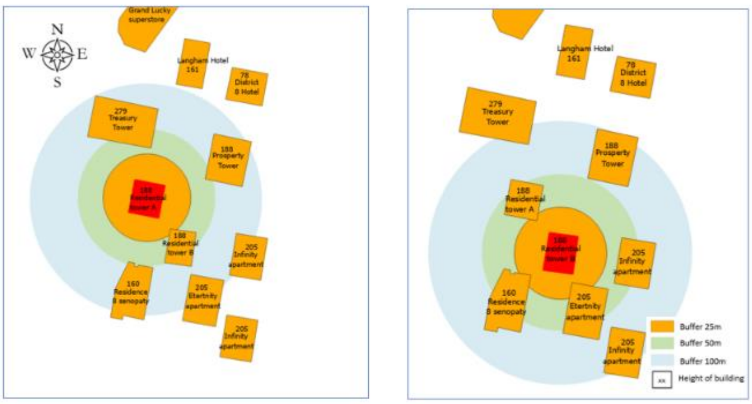

Figure 51 The buffer distance for towers A and B

Being surrounded by tall buildings impacted the amount of radiation incoming for both. As shown in Figure 52 for tower A, the most sun exposure is w.7 on the East façade, and the least is w.1 on the South façade. While for tower B the most exposed is w.15 on the East façade, and the least exposed is w.0 on the South façade (see Figure 53).

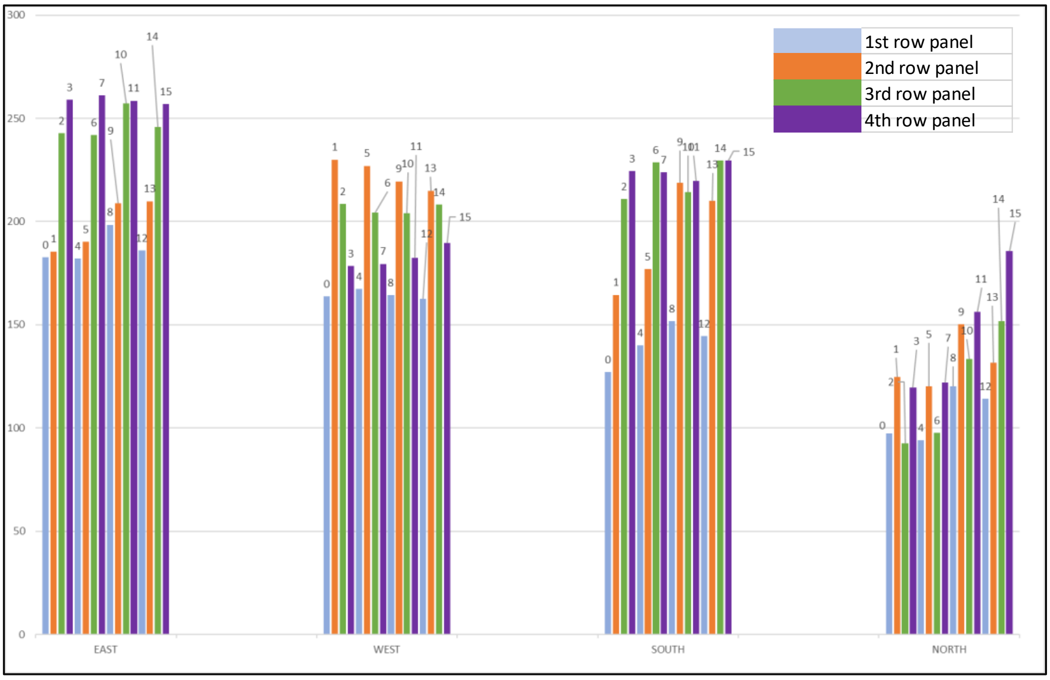

Figure 52 Tower A Sun Irradiation result

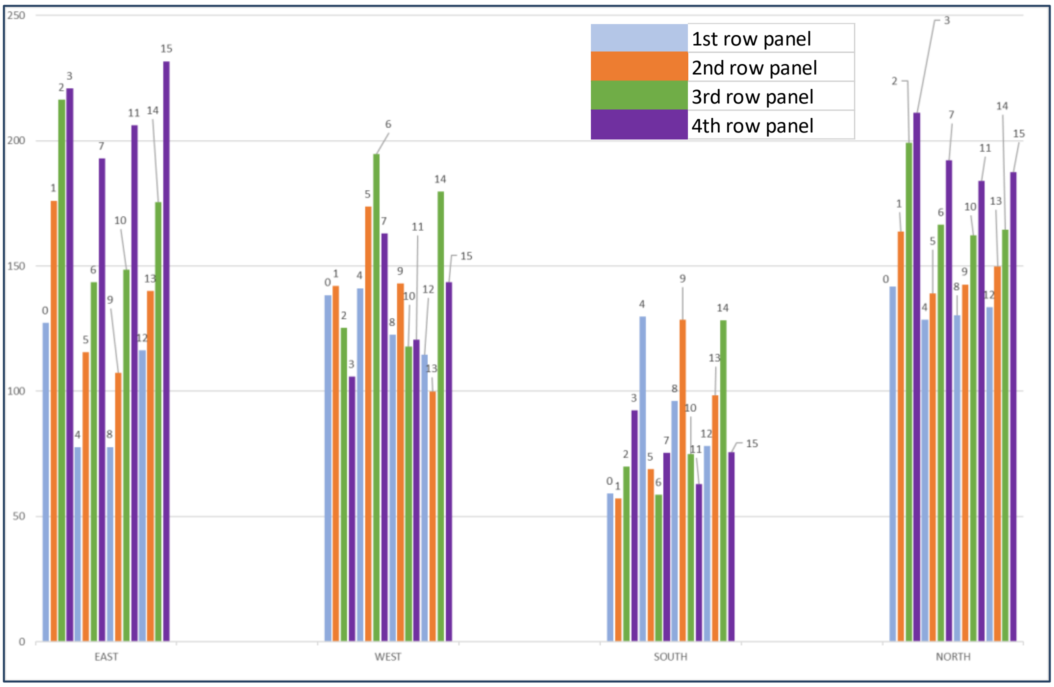

Figure 53 Tower B Sun Irradiation results

The result of the BIPV and emission reduction estimation are also impacted by the condition of both Tower A and B, surrounded by tall buildings. The output of yield estimation on Tower A can be seen in

Figure 54, while the result for Tower B is depicted in Figure 55. The estimation calculation for the environmental benefits: the total CO_2 emission can be reduced per window for both towers A and B, as shown in Table 23.

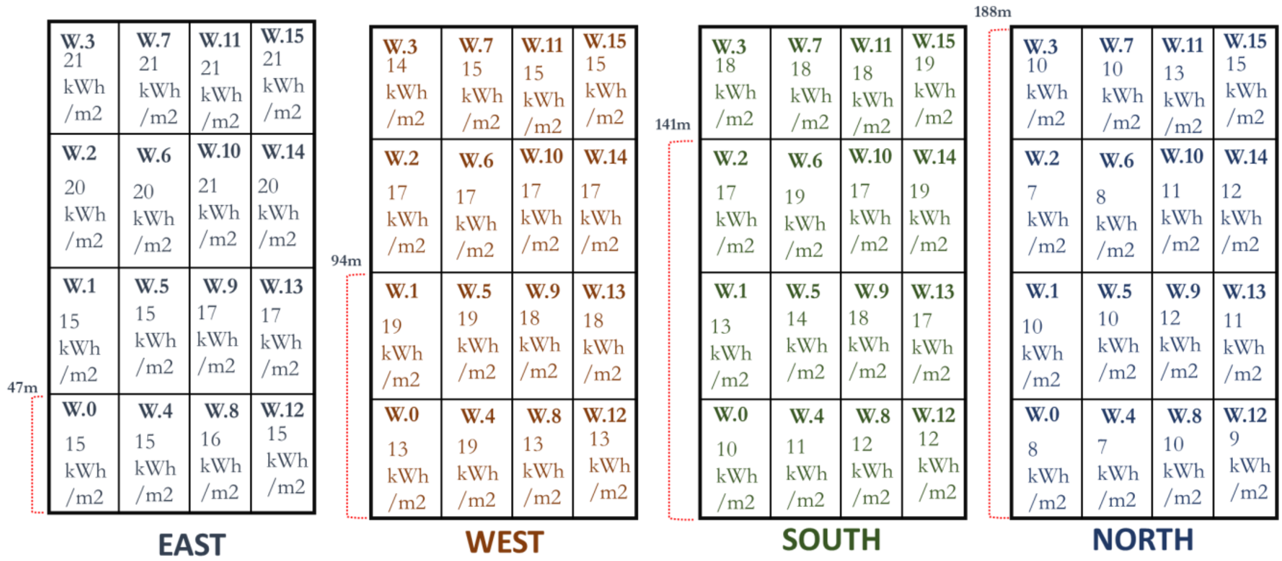

Figure 54 BIPV estimation on Tower A

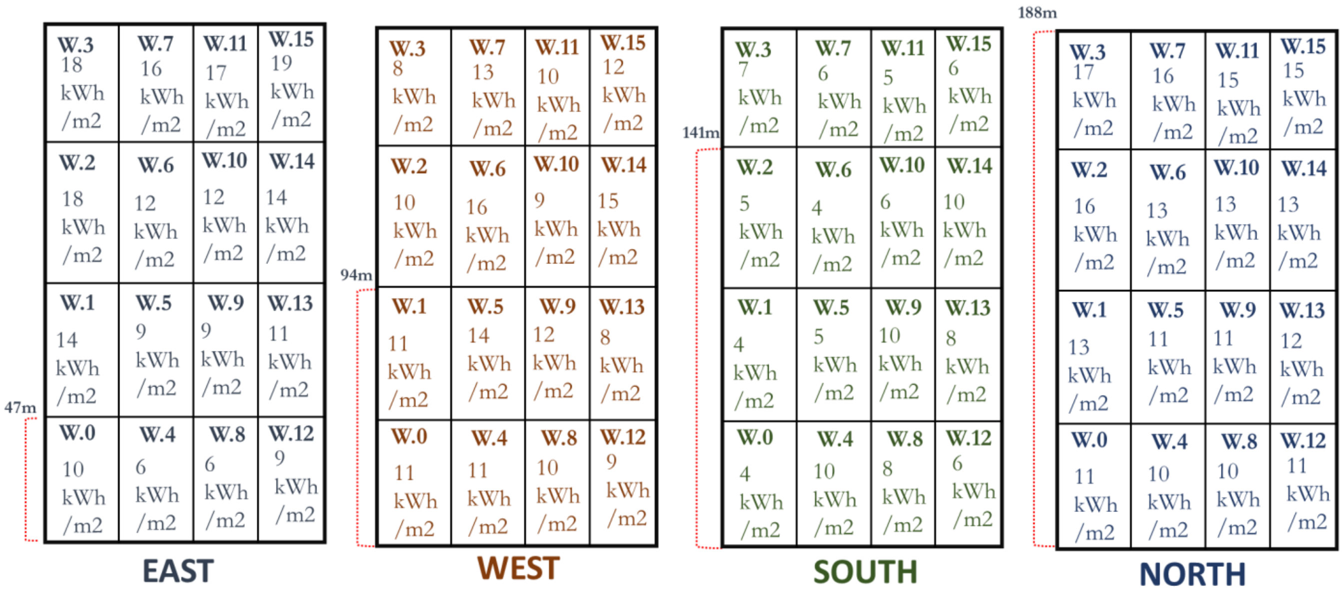

Figure 55 BIPV estimation on Tower B

Table 23 Numbers of CO_2 emissions can be reduced from Tower A and B.

Tower A				
CO2 reduction yearly (kg)	**EAST**	**WEST**	**SOUTH**	**NORTH**
window 0	3,5	3,1	2,4	1,8
window 1	3,5	4,3	3,1	2,4
window 2	4,6	3,9	4,0	1,7
window 3	4,9	3,4	4,2	2,3
window 4	3,4	3,2	2,6	1,8
window 5	3,6	4,3	3,3	2,3
window 6	4,6	3,9	4,3	1,8
window 7	4,9	3,4	4,2	2,3
window 8	3,8	3,1	2,9	2,3
window 9	3,9	4,1	4,1	2,8
window 10	4,9	3,9	4,0	2,5
window 11	4,9	3,4	4,2	3,0
window 12	3,5	3,1	2,7	2,2
window 13	4,0	4,1	4,0	2,5
window 14	4,6	3,9	4,3	2,9
window 15	4,9	3,6	4,3	3,5

Tower B				
CO2 reduction yearly (kg)	**EAST**	**WEST**	**SOUTH**	**NORTH**
window 0	2,4	2,6	2,7	1,1
window 1	3,3	2,7	3,1	1,1
window 2	4,1	2,4	3,8	1,3
window 3	4,2	2,0	4,0	1,7
window 4	1,5	2,7	2,4	2,5
window 5	2,2	3,3	2,6	1,3
window 6	2,7	3,7	3,1	1,1
window 7	3,6	3,1	3,6	1,4
window 8	1,5	2,3	2,5	1,8
window 9	2,0	2,7	2,7	2,4
window 10	2,8	2,2	3,1	1,4
window 11	3,9	2,3	3,5	1,2
window 12	2,2	2,2	2,5	1,5
window 13	2,6	1,9	2,8	1,9
window 14	3,3	3,4	3,1	2,4
window 15	4,4	2,7	3,5	1,4

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ANNEX C: Map table tool development

In this section, the information regarding the plugin used for the user interface of map table tool development and the *grasshopper* algorithm during the iteration process is displayed and explained below.

- **Plugins source of map table tool developed**

The list of plugins applied for the map table tool development, including the source of the plugins, is shown in Table 24. All the plugins mentioned are free open source that can be accessed and downloaded publicly.

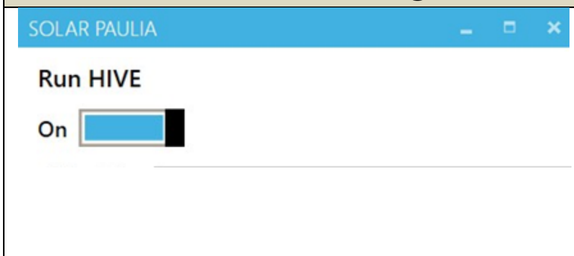
Table 24 The sources of the plugin used in the map table tool development

Frontend	
Plugins	Source
Human-UI	https://grasshopperdocs.com/addons/human-ui.html
Conduit	https://provingground.io/tools/conduit-for-grasshopper/
Backend	
Plugins	Source
Ladybug	https://www.ladybug.tools/
HIVE	https://www.food4rhino.com/en/app/hive
Human	https://www.food4rhino.com/en/app/human
Lunch Box	https://www.food4rhino.com/en/app/lunchbox
Pufferfish	https://www.food4rhino.com/en/app/pufferfish
Tree Sloth	https://www.food4rhino.com/en/app/treesloth
TT Toolbox	https://www.food4rhino.com/en/app/tt-toolbox

- **Script of developed map table tool**

This section overviews the scripts of the tool design's front and back end. The front-end scripts are displayed in Table 25, and the back-end scripts are displayed in Figure 65. Nevertheless, the overview of the overall scene can be found in Figure 66.

Table 25 Front-end design scripts

Frontend	
User Interface main box design	
	The main box of the User Interface is designed to be a vessel for buttons of the operation, such as selecting geometry, orientation, panel, run simulation, and overview of the result information. The script of the user interface main box design can be found below in Figure 56.

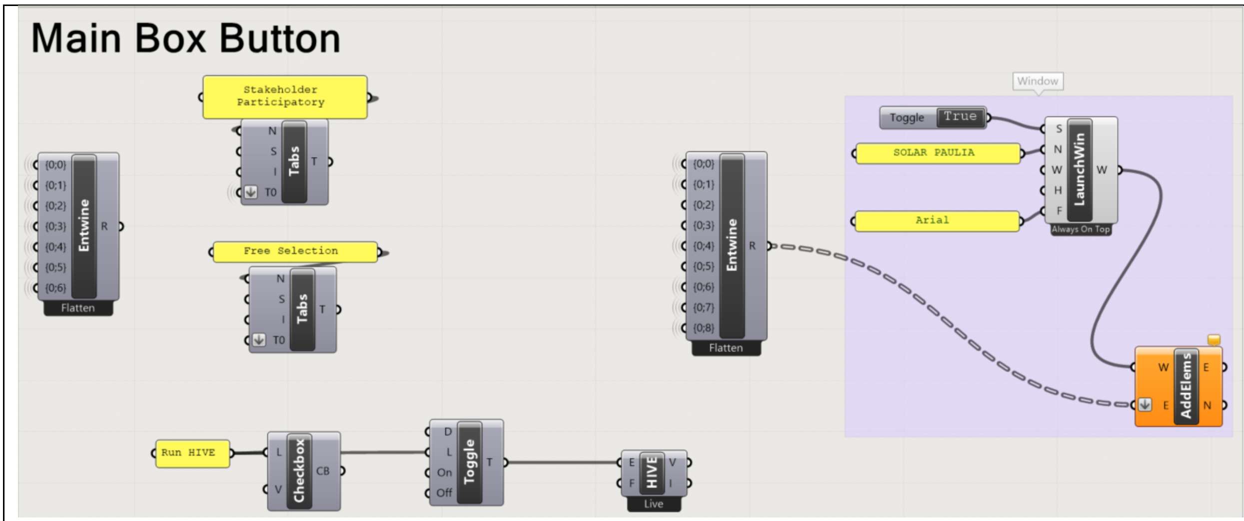
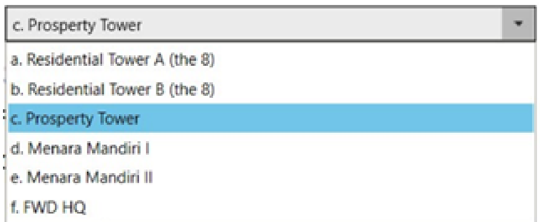


Figure 56 The script of User Interface design

The overview of the building's figures and Geometry selection



The overview of the building's pictures for each building is associated with pull down-menu that directly selects the 3D geometry of the building. The script of input images and geometry selection with the pull-down menu shows in Figure 57 and Figure 58.

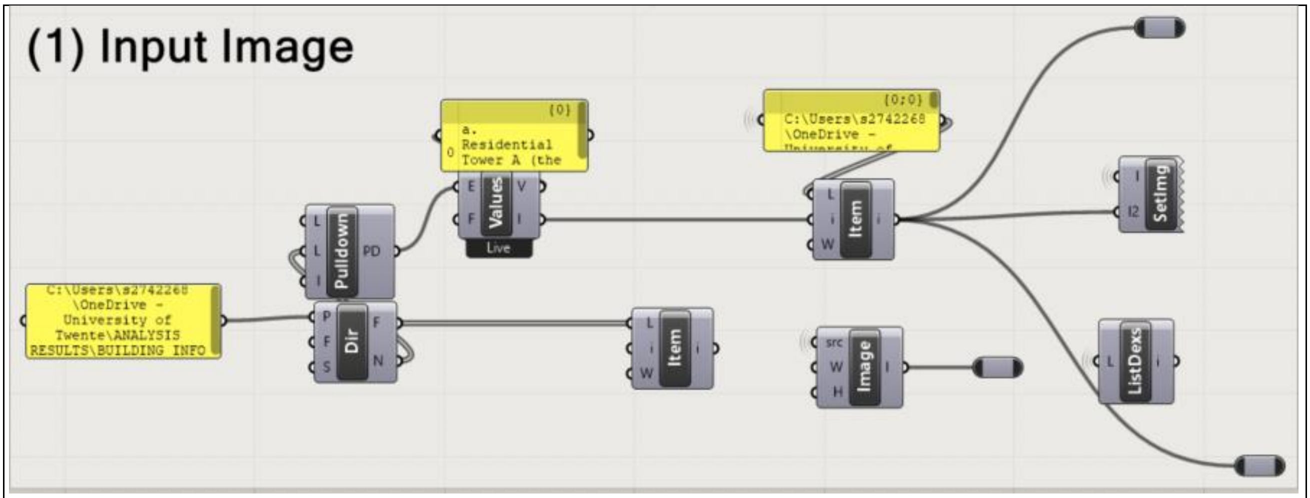


Figure 57 The script for inputting the building's images

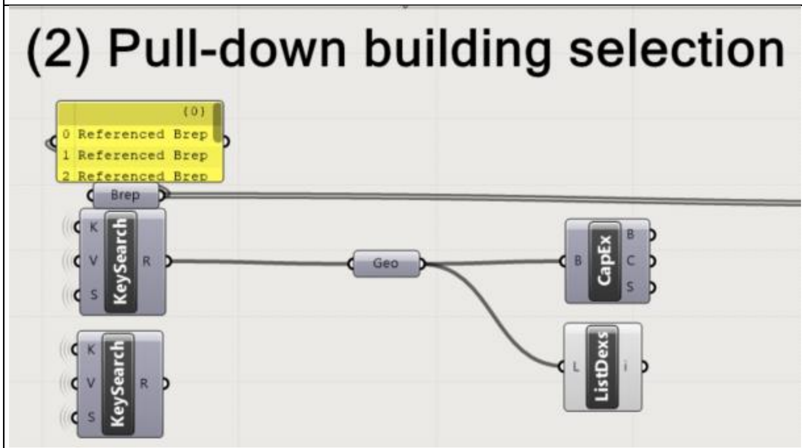
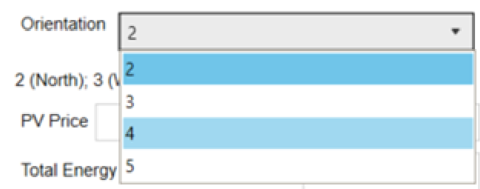


Figure 58 The script of geometry selection with a pull-down menu

The façade orientation selection



The façade orientation selection is designed in a pull-down menu representing the number. The script of orientation selection is displayed in Figure 59.

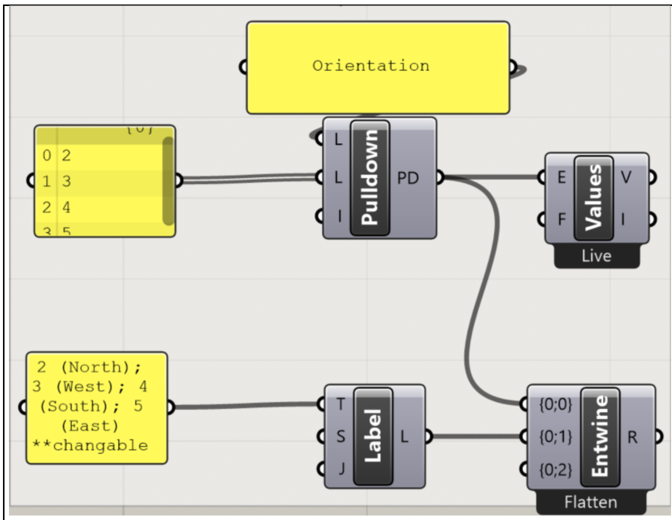
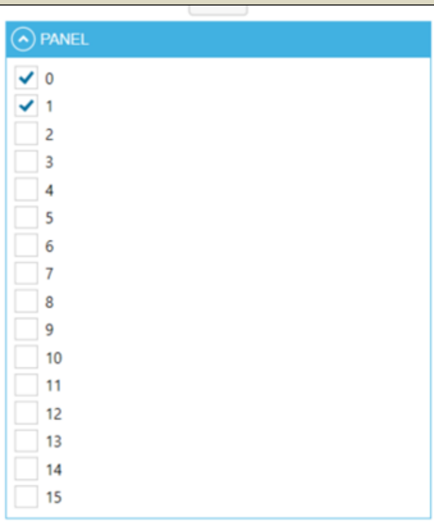


Figure 59 The script of façade orientation selection with a pull-down menu

Panel selection



The panel selection is designed with tick boxes; the script to create it shows in Figure 60.

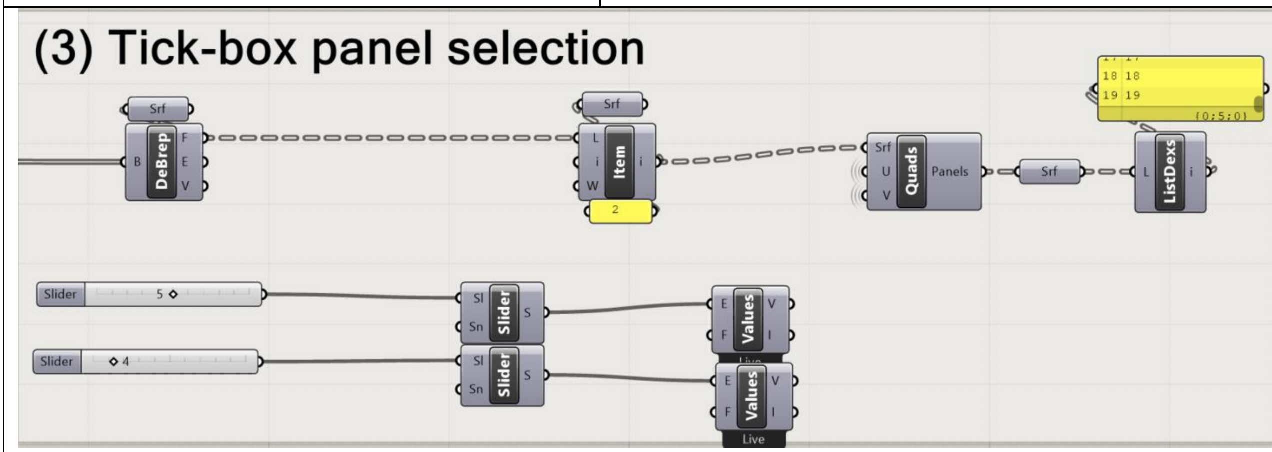


Figure 60 The script of panel selection with tick boxes design

Panel area information

After selecting panels, the area per panel and total area for all panels selected show directly on the user interface. The script for providing the panel area information is displayed in Figure 61.

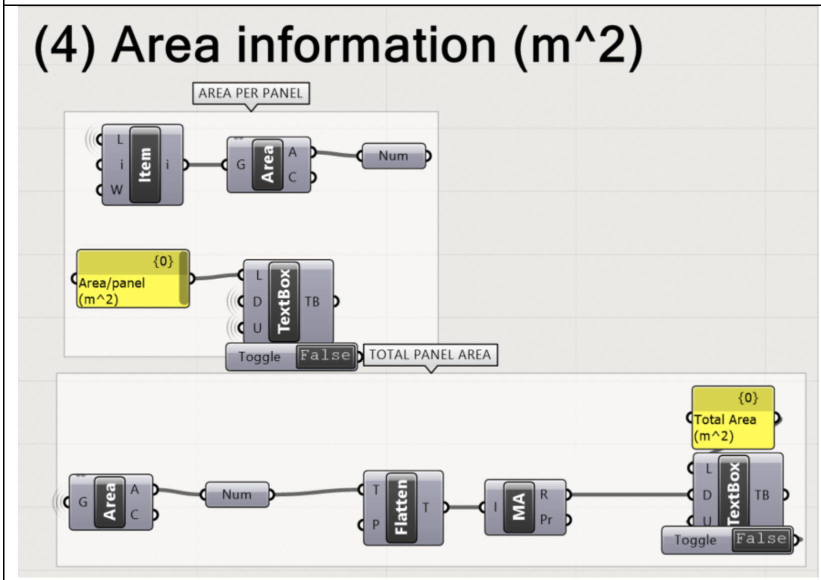
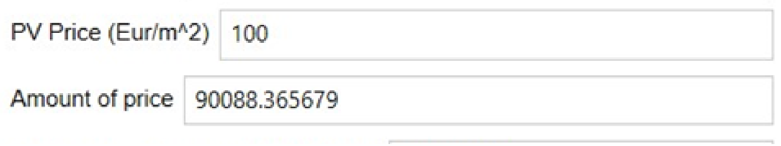


Figure 61 The script of panel selection with tick boxes design

Estimation of BIPV price information



The BIPV price information is designed with the possibility of the users putting the price directly, and it will associate with the amount of price that shows the total estimation of the price. The script of the estimation of the BIPV price can be found in Figure 62.

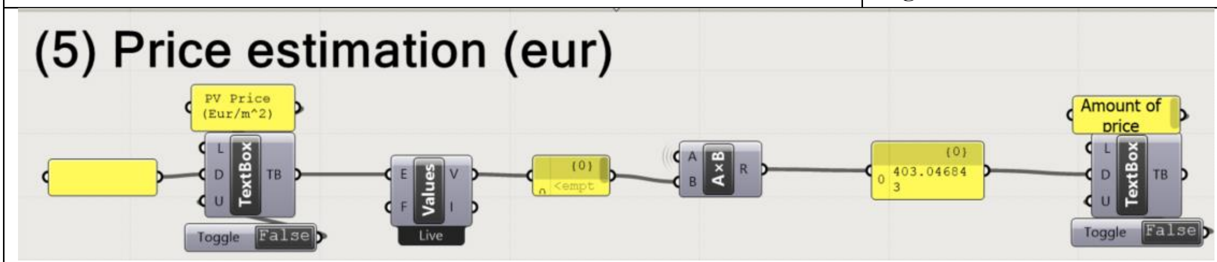


Figure 62 The script of BIPV price estimation

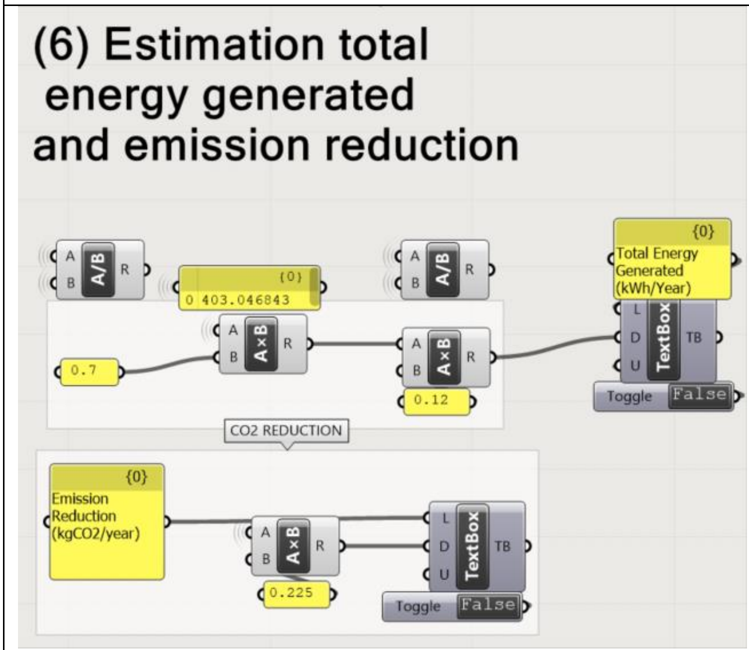
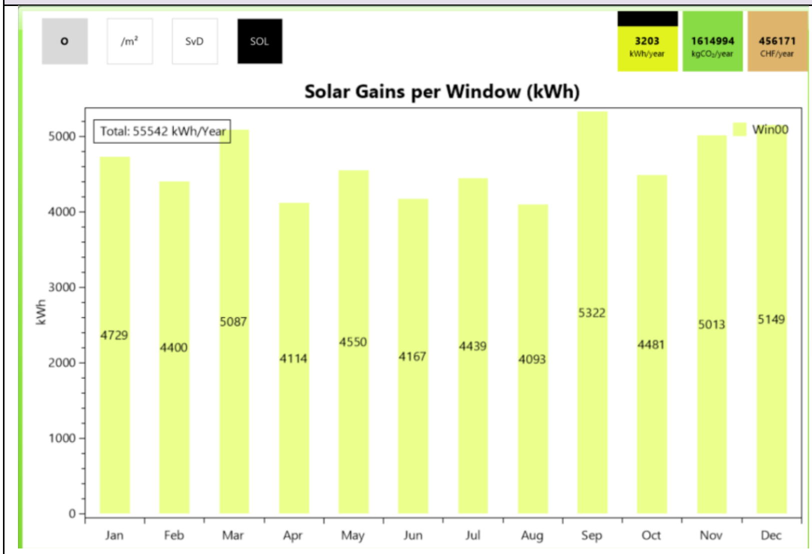
<table>
<tr><th colspan="2">Estimation of total energy generated and emission reduction information</th></tr>
<tr><td>
</td><td>The information on the estimation of BIPV annual yield and annual emission reduction was directly generated after the simulation. The script to show this information is displayed in Figure 63.</td></tr>
<tr><td colspan="2">

Figure 63 The script of information overview of annual energy yield and emission reduction</td></tr>
</table>

Annual solar gain information



The annual solar gain information is displayed in graph view. The script to create the graph information can be found in Figure 64.

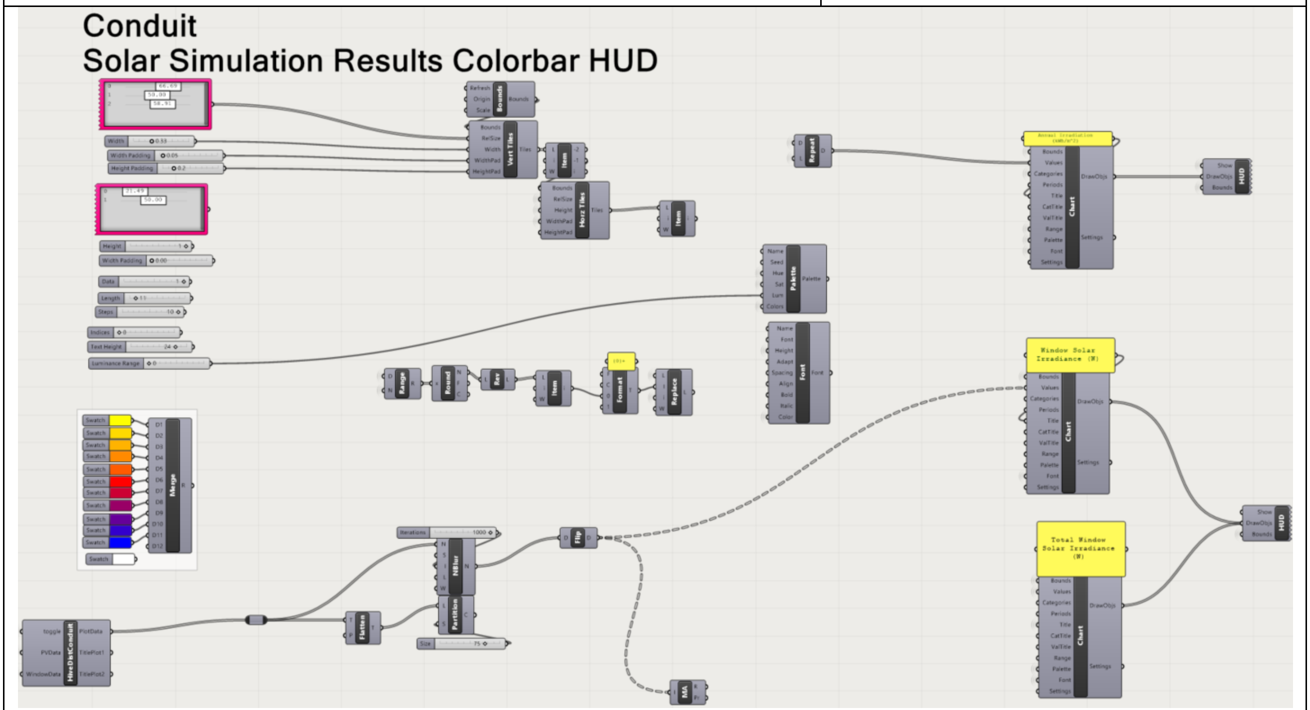


Figure 64 The script to display the graph information

Backend grasshopper script

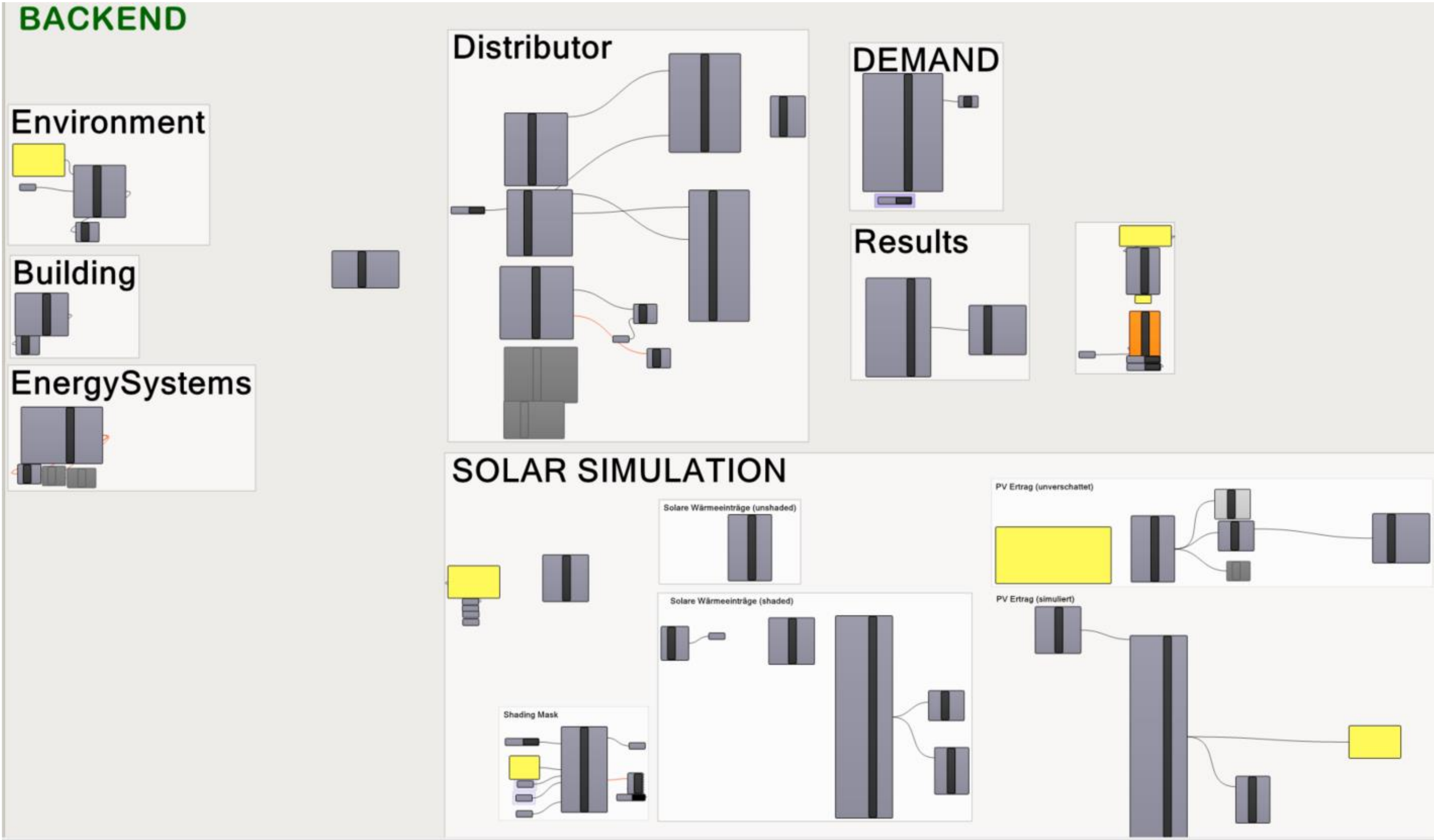


Figure 65 The script of backend simulation

Overview of the whole script

Figure 66 The overview of whole script for map table tool development

ANNEX D: Stakeholder participation workshop in Jakarta

The stakeholder workshops were held in Jakarta for about one month, as shown in Figure 67. All the activities were documented, both videos and images, with the consent of the stakeholders. The subsequent parts displayed the questionnaire distributed during the stakeholder participation in Jakarta, the detailed open-question feedback from the participants, and the ac.

Figure 67 Stakeholder workshop in Jakarta scheduled from March to May 2023 (Figure source: Author)

- **Questionnaire**

Questioner:

This survey is part of the thesis research activity: "*Not Enough Space In Your City? Vertical Photovoltaic Suitability Analysis On Building Façade Using 3d Model And Psscience Tool In Jakarta*".

Your participation in the survey going to be a great help for the research. All the information perceived will only be utilized for the research objectives and not for any other purpose. Additionally, the research will make proper acknowledgment and reference to the source of information in the final document and the response will be kept anonymous.

Please complete this survey before you leave. Thank you for your participation!

Part 1: About the participatory, including tools and model

1. Question about Usability of the tool

About the participatory digital Tool Please answer the following questions by selecting the option on the right.	Very Easy	Easy	Neutral	Difficult	Very difficult
1. How was it to interact with the interface (e.g., button and slider)?	1	2	3	4	5
2. How was it to navigate the model (e.g., zoom in-out, rotate, pan)?	1	2	3	4	5
About the model and information provided **Please agree or disagree with the following statements**	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
3. The information provided is easy to understand	1	2	3	4	5
4. The model result take long time to be done	1	2	3	4	5

2. Question on Added value

About the model and information provided Please agree or disagree with the following statements	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
6. I learned about the renewable energy issue in urban dense area	1	2	3	4	5
7. After the participatory session my knowledge about BIPV as one of climate technology is increasing	1	2	3	4	5
8. I find the tool presented can help the planning and discussion process	1	2	3	4	5
9. I prefer the participatory using maptable than the paper based participatory	1	2	3	4	5

3. How long did it take to understand how to choose the panel and run the simulation ?

☐ Very Long ☐ Long ☐ Neutral ☐ Short ☐ Very short

4. How satisfied are you with the model, tools, and information provided during the activity?

☐ Very dissatisfied ☐ Dissatisfied ☐ Unsure ☐ Satisfied ☐ Very satisfied

About the added value (Object learning and efficiency indicators)

5. Can you please describe What are most important thing that you learned through the participatory session?

6. Do you think using the current tool and model is applicable in Indonesia during the decision-making process in comparison with the current contemporary-paper-based solution? Please provide the reason.

About the Usability of the tool

7. What do you think are the strength and limitation of the model and the tools?

Strength:

Limitation:

8. If you can add or change the model or the tools, What could it be?

(Optional)

9. If the current intervention is applied in Indonesia. What could be potentially the obstacle to implement it?

- **The feedback from stakeholders**

The detailed feedback from stakeholders regarding the strength and limitations of the model and tool developed (See Table 26), to add and/or change the model and tool (See Table 27), object learning (See Table 28), efficiency (See Table 29), the barriers and limitation (See Table 30), and the feedback of the developed framework (See Table 31) are explained in this section.

Table 26 Strength and limitation feedback on the model and tool developed

Strength	Limitation
P1:" *The* ***interaction*** *among stakeholders and the* ***visual*** *aspect."*	"*More dynamic and colorful, so that* ***more interactive****, and the simulation process can be* ***faster.***"
P2: "*The* ***varied features*** *and* ***detailed information.***"	"*The overall looks seem* ***complex*** *for the inexperienced people.*"
P3: "*The* ***3D model*** *displayed helps to see the building's form, model, and orientation*	"*(i) need more* ***supporting data****; (ii) need an* ***improvement*** *for the* ***interface*** *design in order all-users can* ***easily understand.***"
P4: "*It gives lots of* ***visual information*** *and helps for the* ***simulation.***"	"*There is no information for the* ***price calculation*** *(this is related to the* ***cost-benefit analysis****), and running the model* ***takes time.***"
P5: "*Technology makes it easy to provide an* ***overview*** *of* ***problems*** *and* ***solutions."***	"*Many other factors, such as risk factors, need to be considered.*"
P6: "*Technology-based is more* ***efficient*** *than paper-based.*"	"*Relatively* ***high device specifications*** *are required for interface changes to* ***run smoothly.***"
P7: "***Interactive***"	"***Hardware specification***"
P8: "*Information can be* ***displayed optimally."***	"*It gives some* ***crashes****, and the output of the running model is difficult to read because the* ***window is small*** *(compared to the entire window)."*
P9: "***Informative*** *and* ***interactive*** *in providing essential information.*"	"*require a* ***high*** *intensive* ***computational power*** *to* ***obtain quicker results.***"
P10: "*Simple enough for non-energy stakeholders (who do not hold any background in renewable energy and technical)."*	"*need* ***a powerful computer*** *to run it."*
P11: "***Interactive****,* ***applicative****,* ***easy to learn*** *and* ***use.***"	"*takes a* ***long time*** *for processing, data and* ***scope*** *are* ***limited.***"
P12: "*Lots of* ***information*** *can be* ***generated.***"	"*requires a* ***long process*** *to select and run an option.*"
P13: "***supports the decision-making process, saves time,*** *and can provide general* ***information*** *for PV installation plans*	-
P14: *"****Easy to use*** *in model changes and makes it easier to run model results.* "	"*the model and tool can only be used on* ***high-spec laptops.***"

P15: "*It can **help for the process of participatory decision making.***"	"*the building **model** does not represent the real situation.*"
P16[9]: N/A	N/A

Table 27 Feedback on adding or changing the model and tool design.

Addition to the tool/model
P1:" *The option to pick the panel directly from the building's façade."*
P2: "*Make the visual view and features more simple."*
P3: "*Create the phone application that can be downloaded and accessed.*"
P4: "*Everything is enough."*
P5: "*Adding the legend."*
P6: "*Make the interface changing smoother.*"
P7: "*(1) Filed of **price** better only show the numbers, (2) when choosing a panel there is a function that can calculate energy directly (similar to filling in an excel function)."*
P8: "(i) *Enlarge the modeling output window; (ii) Added information regarding the floor dimensions of each building so that panels can be selected based on floors (instead of per unit panel).*"
P9: "*Selecting the panel PV in the working display window rather than on the list of panel number id.*"
P10: "*Add **cost analysis** and the choice option of BIPV module technology.*"
P11: "***Economic analysis**, IRR/NPV analysis.*"
P12: "*Adding the name of each building, making it easier to find buildings on the interface.*"
P13: "*Maybe just changing from the side of the building's identity to be named directly on the design.*"
P14: *"(i) may be able to add to BIPV maintenance recommendations in the modeling.; (ii) Adds BIPV return on **investment calculations** for buildings.* "
P15: "*Legend instructions for use, compass directions per building.*"
P16: "S*how the **cost-benefit** relation (for instance, how much energy buildings used that can be covered by the BIPV); (ii) make the area simulation on a larger scale; (iii) show the direction of incoming sunlight.*"

Table 28 Added values indicator: Object learning feedback.

Object Learning
P1:" *The interaction with the selected object to give the **visual aspect** and **in-depth understanding of the information.**"*
P2: "*The **ease of participatory** using digital tools, in order all-users (everybody), can make use of the tool."*
P3: "*(i) **Learned** the integrated **PV on façade**; (ii) Learned the **energy transition solution** that can be applied in the **densely populated city.***"
P4: "***Solar BIPV** can be applied and used in the **dense area; BIPV** can be one of the **alternative technology** for renewable energy; There is a more efficient option to simulate the PV installment, which from the navigation model developed by the researcher."*
P5: "*The **use of technology** in one of the processes of **problem analysis**. This technical assistance can facilitate analysis and provide a **visual** picture. However, it is necessary to pay attention to the level of accuracy and precision.*"
P6: "*The **information** needed for **discussion in our unit** can be obtained through this model.*"
P7: "*The selection of **BIPV installment** affecting the amount of energy generated*

[9] P16 meeting was held online, and impossible to test the model and tool directly. Some questions were also adjusted that suit the online meeting environment.

P8: "*The tools are very helpful for the user to have basic information regarding production capacity, which will later become a consideration variable in the* ***decision-making*** *process for* ***BIPV development.***"
P9: "***Visual*** *information and* ***interactive*** *platform is easier to understand.*"
P10: "***I just knew there is a BIPV technology,*** *and an interactive explanatory process (****participatory****) can catch stakeholder interest.*"
P11: "*(i) information about* ***BIPV*** *and* ***BAPV****; (ii) different PV energy yields; (iii)* ***PV use case for buildings in the urban area.***"
P12: "***Not all parts of the building can produce the same yield****, and it turns out that a lot of energy can be produced from a single panel.*"
P13: "*Get an* ***overview of BIPV technology.***"
P14: "*The application is very easy to use. It is* ***easier for new people to use.*** "
P15: "***BIPV technology*** *and the simulation tool.*"
P16[10]: N/A

Table 29 Added value indicator: Efficiency feedback

Efficiency
P1:" *The presented tool and model is* ***useful*** *for the* ***decision-makers,*** *which helps them to have a clear figure/context for the policy planning they will create."*
P2: "***Absolutely****! The map table as a medium increases the efficiency and effectivity of the discussion process.*"
P3: "***It is applicable in Indonesia*** *but needs further development to support the low-emission development (goal).*"
P4: "***Yes, it can****, and it can help the planning more efficiently because it provides the information visually just in case there is no need to come directly to the site project.*"
P5: "*In general, the map table touch screen provides an interactive* ***visual*** *overview, but in the decision-making process, other factors are needed with detailed consideration so that the use of* ***map table and paper is complementary.****"*
P6: "Al*ong with technological developments, this map table touch screen is* ***very applicable*** *and can streamline the work or analysis from stakeholders.*"
P7: "***Yes*** *(1) It is faster, (2) easy to operate, (3) no longer paper use, (4) the result of the discussion can be saved (safety option)."*
P8: "***High probability it can be implemented in Indonesia****. Decision-making using the paper-based certainly has limitations that can reduce the decisions' credibility. The tools and models offered will provide information that is easily understood by the user and directly impacts the decision-making process."*
P9: "***Yes****, as the model is easier to understand, especially for those who do not have a strong background in the particular field.*"
P10: "*Able to force stakeholders to be more active and have a deep understanding.*"
P11: "***It can*** *because software like this is also widely used for modeling or simulating PV installation at home. If it looks better, it will sell more to the stakeholders.*"
P12: "***I think it can*** *because the information produced is very informative and can be used in decision-making.*"
P13: "***Yes****, in my opinion, the map table touch screen tool and model* ***can be applied in Indonesia*** *for decision making because it saves time and is more flexible.*"

[10] P16 meeting was held online, and impossible to test the model and tool directly. Some questions were also adjusted that suit the online meeting environment.

P14: *"These tools and models can be* ***made for decision-making*** *because the model can be changed instantly.* "
P15: "***Yes, it is applicable****, as technology development in Indonesia keeps increasing. There will be more of this kind of practice in the future compared to paper-based.*"
P16: "***Yes****, nowadays, people are more engaged in technology, and for the time being, preferably, people are going to choose digital over paper.*"

Table 30 Barriers and limitation Evaluation

Barriers and limitation
P1:" *The* ***policy*** *that nowadays still in pre-clean energy, and the national electricity corporate that still in the situation of* ***oversupply*** *(for electricity)."*
P2: "*The* ***initiative*** *from* ***government*** *to implement the technology, and* ***conflict of interest*** *in* ***regulation*** *making.*"
P3: "*(i) There is not yet a* ***regulation*** *that can support the implementation of vertical PV on building façade; (ii) There is not yet the* ***industry*** *that can support the use of vertical PV on building's façade as the green building solution.*"
P4: "*The* ***cost*** *installment is expensive; There should be an* ***incentive*** *for users (buildings used for BIPV installment)."*
P5: "***Cost*** *and* ***effectivity.***"
P6: "*(i) the* ***cost*** *of procuring equipment is still relatively high; (ii) Anticipate demand for* ***incentives*** *for the development of this technology, given the limited state budget.*"
P7: "*(1)* ***Cost****, (2) collective agreement of building* ***tenants****, (3) continuous* ***maintenance*** *construction, which is difficult because of the* ***jurisdiction*** *of the building.*"
P8:
P9: "*(i) Solar panel* ***regulation*** *from PLN that hinders 100% generation of electricity from PV (max 15%); (ii)* ***affordability*** *of solar panel in Indonesia; (iii) window* ***technology*** *in Indonesia that can integrate the PV is most likely still limited.*"
P10: "*PLN* ***regulations*** *regarding the maximum installation of rooftop PV.*"
P11: "*(i)* ***Resistance*** *to change; (ii)* ***unfamiliarity*** *of stakeholders so that it may be necessary to pay attention to the use case or real case first.*"
P12: "*The* ***high price*** *is the biggest barrier. Moreover, the existing* ***technology*** *in Indonesia is still not much developed.*"
P13: "*Which will be a possible obstacle in terms of* ***costs*** *that may be greater than ordinary facades.*"
P14: *"(i) oversupply of the* ***electrical system****; (ii) Minister of Energy and Mineral Resources* ***policy*** *number 26 of 2021; (iii)* ***Intermittent*** *of BIPV.* "
P15: "*Mostly the* ***price*** *and* ***regulation.***"
P16: "*The* ***cost*** *and* ***trade benefits*** *from users' perspective.*"

Table 31 The feedback for developed framework

Feedback for developed framework
Greenpeace: *"Better involve stakeholder involvement both in the beginning and end."*
Ministry of Economic and Finance of Indonesia : *"Include the stakeholder participation at the beginning of the phase. To find out the request from stakeholders. Because if it is only I the end of the cycle, it is more monitoring purpose."*
State Electricity Company (PLN): *"I think the feedback evaluation should be between phase two – four. Because during that time is the development of model and tool."*
Audit Board of the Republic of Indonesia: *"In our monitoring system, the control check is always in every phase whenever there is a national project. The involvement of stakeholder feedback should be in every stage."*
IESR: *"Overall, the framework is perfect. Because the aim of developing the model and tool is to inform the stakeholder."*
Ministry of State-Owned Enterprises: *"The process should involve the stakeholder initially and at the end. Because some stakeholder might have the requirement to add on."*
Ministry Of National Development Planning Agency: *"The framework is already perfect."*
National Research And Innovation Agency (BRIN): *"To make a perfect loop, better to place the stakeholder feedback in every phase."*
IPB University: *"The stakeholder feedback should also be included in the beginning to create user requirements, so it will make a perfect looping."*

- **Stakeholder's participation documentation**

The documentation of stakeholder participation with nine different institutions in Jakarta, Indonesia, is displayed in Table 32.

Table 32 Documentation of stakeholder participation in Jakarta

Documentation of stakeholder participation
Ministry of Economic and Finance - (29th March 2023: 1 pm – 3pm)
  Figure 68 Stakeholder participation with the representatives from the Ministry of Economic and Finance
Audit Board of the Republic of Indonesia and State Electricity Company (PLN) - (29th March 2023: 4 pm – 6pm)
  Figure 69 Stakeholder participation with the representative from the Audit Board of the Republic of Indonesian and State Electricity Company
Green Peace Indonesia – (30th March 2023: 10 am to 12 am)
  Figure 70 Stakeholder participation session with the representatives of Green Peace Indonesia
Institute for Essential Services Reform (IESR) – (3rd April 2023) **Due to a technical issue, the pictures captured could not be found

Ministry of National Development Planning of the Republic of Indonesia (Bappenas) – (14th April 2023: 9 am to 12 am)

Figure 71 Stakeholder participation with the Ministry of National Development Planning of the Republic of Indonesia

Ministry of State-Owned (BUMN) – (17th April 2023: 10 am to 12 am)

Figure 72 Stakeholder participation session with the representatives of the Ministry of State-Owned

National Research and Innovation Agency (BRIN) – (18th April 2023)

Figure 73 Stakeholder participation with BRIN

IPB University – (2nd Mei 2023)

**Due to a technical issue, the pictures captured could not be found