EREM 80/4
Journal of Environmental Research, Engineering and Management
Vol. 80 / No. 4 / 2024
pp. 21–38
10.5755/j01.erem.80.4.34200

**Performance Analysis Simulation of Urban Rooftop Photovoltaic Potential in Jakarta City, Indonesia**

Received 2023/05 | Accepted after revisions 2024/09

**https://doi.org/10.5755/j01.erem.80.4.34200**

# Performance Analysis Simulation of Urban Rooftop Photovoltaic Potential in Jakarta City, Indonesia

**Donny Triana[1,3*], Iwa Garniwa[2], Asep Husni Yasin Rosadi[3], Dwi Nowo Martono[1]**

[1] School of Environmental Science, University of Indonesia, Indonesia

[2] Department of Electrical Engineering, Faculty of Engineering, University of Indonesia, Indonesia

[3] The National Research and Innovation Agency (BRIN), Indonesia

***Corresponding author:** donny.triana@ui.ac.id

Energy consumption in urban areas is increasing in line with population growth and economic activity. Cities therefore have an important role in the energy transition process. Jakarta, a metropolitan city, has many buildings that can be used for the installation of distributed solar photovoltaic (PV) systems. This study aims to investigate the potential of rooftop solar photovoltaics (RSPV) potential in the city. Available urban rooftop space for installing distributed rooftop solar PV in Jakarta is evaluated by the combination of land use and building footprint analysis using a geographic information system (GIS); consideration of the reduction in shading; and other uses. The study results show that the available roof area suitable for solar PV is 101,297,045 $m^2$ (101.3 $km^2$), 11,236,062 $m^2$ (11.2 $km^2$) and 14,021,862 $m^2$ (14 $km^2$) in residential, industrial and commercial zones respectively. Therefore, potential PV installation capacity based on the available roof area potential ranges from 16,967–21,526 MWp for residential, 1,882–2,388 MWp for industrial, and 2,349–2,980 MWp for commercial areas. Residential electricity potential is 19,089 GWh/year, industrial 2,454 GWh/year, and commercial 3,062 GWh/year, with a scenario of 17.3 percent PV panel efficiency. On the other hand, with 22.8 percent PV panel efficiency, potential residential electricity generation is 26,239 GWh/year, industrial 3,373 GWh/year, and commercial 4,209 GWh/year, representing an annual specific energy yield of 1,161–1,258 kWh/kWp.

**Keywords:** urban rooftop, photovoltaics potential, solar energy, GIS, Indonesia.

## Introduction

Using rooftop solar power plants in urban areas as a source of electrical energy is one of the solutions for reducing carbon emission and easing the burden on traditional power grid, because of their ease of installation, which require a relatively short time, and as they are a source of sustainable and environmentally friendly solar energy (Montealegre et al., 2022). Solar energy, one among other renewable energy sources, is a potential primary resource, which supports sustainable economic development, and is environmentally friendly (Kassem et al., 2021). (Kammen and Sunter, 2016) suggest that integrating solar energy electricity in urban areas can meet the electricity needs of many cities if the photovoltaic (PV) technology being tested in advanced laboratories today becomes competitive in terms of cost.

Cities can accelerate the use of renewable energy in three priority areas: 1) in buildings; 2) in the transport sector; and 3) through the creation of an integrated urban energy system (IRENA, 2016). Cities not only consume energy, but can also produce it through the distribution network. The increase in electrical energy can be generated by variable renewable energy (VRE), especially that sourced from wind and solar energy. By installing solar rooftops connected to the electricity network, households are not only electricity customers, but at the same time can become electricity producers (Martin and Ryor, 2016). The increasing contribution of VRE to the electrical system demands flexible and stable electrical system operators (Guerra et al., 2022).

In the face of the challenges to cities of climate change and sustainable development, mitigation strategies related to increasing the penetration of renewable energy are increasingly attracting the attention of many parties. One low-carbon technology that is experiencing exponential growth is PV energy. Local renewable power generation through rooftop solar PV systems in urban areas provides enormous potential for greenhouse gas emissions mitigation (Mainzer et al., 2017; Zhang et al., 2023).

Regarding the energy transition process, Indonesia has also established the development of clean energy sources as a national policy directive; Government Regulation No. 79/2014 on National Energy Policy has set a target to increase the use of renewable energy in the national primary energy supply (PP 79/2014, 2014). In line with this, the Government is committed to setting a total target reduction of greenhouse gas emissions of 31.89 percent, an increase from the previous target of 29 percent, and a conditional target of up 43.2 percent from the previous 41 percent of the business as usual scenario by 2030 (KLHK, 2022).

The sustainable energy development concept aims for a better future, in which the fulfillment of human needs is kept in balance with nature. Driven primarily by concerns over urban air quality, global warming caused by greenhouse gas (GHG) emissions, and dependence on the depletion of fossil fuel reserves, the transition to alternative energy systems is receiving serious attention. In most cases, energy system decision-makers need to consider several objectives, economic, social and environmental, that may be on a local, regional or global scale, so that energy system management can align with sustainable development (Bazmi and Zahedi, 2011; Olabi et al., 2023; Czerwińska and Pacana, 2024). Key indicators that need to be considered in the drive for sustainable energy include that it is carbon neutral; does not affect the quality, quantity or rational use of natural resources; does not affect biodiversity; does not result in undesirable social consequences; and contributes to economic development and social justice (Singh et al., 2013).

Knowledge of the available potential roof areas is vital for installing solar power plants in urban areas. Several previous studies to assess the potential of solar PV on urban and regional scales have been conducted in different regions of the world using varied methods (Izquierdo et al., 2008; Ordóñez et al., 2010; Wiginton et al., 2010; Bergamasco and Asinari, 2011; Singh and Banerjee, 2015; Mainzer et al., 2017; Gui et al., 2024).

Hierarchically, calculating solar energy potential for urban areas can be addressed in several stages, by estimating the physical or theoretical, geographical, technical, economic, and market possibilities (Izquierdo et al., 2008; Bergamasco and Asinari, 2011; Hong et al., 2016; Assouline et al., 2018). Physical potential includes the total amount of energy received from solar radiation on the roofs of buildings, while geographical potential is the spatial availability of the area where total amount solar energy can be estimated, considers the spatial constraints and practicalities, like shading from other buildings or trees, roof orientation, and the availability of roof space. Technical potential refers to the electrical potential that can be generated from the energy, taking into account the technical performance of the system and the equipment used to convert resources into electrical energy, such as the efficiency of PV modules and inverters.

Assesing the photovoltaic (PV) potential of an urban landscape is a challenging task. Factors such as building elevation, urban density, and diverse urban morphologies, along with limited access to detailed data, make the evaluation more difficult. Although numerous methods have been suggested to address these challenges, they can generally be classified into three main categories (Schallenberg-Rodríguez, 2013; Byrne et al., 2015). Based on data accessibility and consideration of the scope of the study area, these categories described as follows: 1) sample methodology; 2) multivariate sampling-based methodology; and 3) complete census methodology. Melius et al. (2013) reviewed previous related studies and presented a new method for estimating rooftop suitability for PV, while Castellanos et al. (2017) distinguished the methodology for identifying and calculating rooftop solar energy potential into three categories: 1) low-level methods, 2) medium-level methods, and 3) high-level methods. Assouline et al. (2018) further reviewed several methods to estimate the potential of PV rooftop solar power plants on regional and national scales, namely physical/empirical, geostatistical, constant values, sampling, GIS/LiDAR, and machine learning.

The widespread adoption of rooftop solar photovoltaic (RSPV) systems is essential for promoting the transition to renewable energy sources across society. Lowering the costs of such systems enables significant decarbonisation of buildings through the increase in their adoption and deployment. When combined with energy-efficient building envelopes and technical systems, RSPV can achieve net-zero grid electricity consumption at the building level (Kapsalis et al., 2024). The potential for rooftop PV in urban areas can be applied to residential, industrial, commercial, Government, and other buildings. In addition to technical potential (generated electrical energy) and the environment, economic performance is essential for deploying and adopting PV solar system technology (Rose et al., 2016). Because variable renewable energy is site-specific, the potential of each region can differ (Miyake et al., 2024).

Yue and Huang (2011) evaluated solar energy combined with land use analysis, allowing potential exploitation of such energy, considering the limitations of local land use conditions. Their assessment of solar energy potential focused on solar water heaters and photovoltaic systems in the roof areas of buildings in Taiwan. Singh and Banerjee (2015) calculated the potential of rooftop solar PV for the Indian city of Mumbai. Their research used publicly available land use data with a high level of granularity, domain-based imagery analysis, and GIS from satellite imagery samples to estimate the values of the building footprint area ratio. Horan et al. (2020) conducted a study of the potential of rooftop solar PV for industrial and commercial building zones in cities in Ireland, while Kutlu et al. (2022) calculated the technical potential of rooftop solar photovoltaics that could be generated from residential, public and commercial buildings in the city of Ankara, Turkey. Using geospatial modelling and considering the local context, Hasan et al. (2024) reevaluated the geographical and technical potential for solar PV in Bangladesh. A comprehensive exclusion model and a system-specific suitability model were employed to identify appropriate locations and calculate the potential for rooftop PV, ground-mounted PV, floating PV, and agrivoltaic systems.

Indonesia has high solar radiation potential. Jakarta, as a metropolitan city, has many buildings that could be used to locate rooftop solar PV installations. However, the amount of rooftop solar PV installed capacity is still small, and not as expected. The aim of this study is to assess the electricity potential that could be generated from rooftop solar PV in Jakarta, especially in residential, industrial and commercial areas. The results could be used as a reference for stakeholders to create appropriate strategies to increase solar PV system deployment as an environmentally-friendly technology energy source in Jakarta. By making the transition towards renewable energy sources, cities can contribute to reducing $CO_2$ emissions and thus support the net zero emissions commitment made by the Indonesian government and its efforts to overcome the problems of climate change.

## Methods

### A. Study location

This study was conducted in Jakarta, Indonesia, located between latitude 6°12' south and longitude 106°48' east, with a land area of 660.98 km$^2$. Jakarta province consists of five administrative city areas and one administrative regency, namely South Jakarta Municipality, with an area of 144.94 km$^2$. East Jakarta has an area of 185.54 km$^2$; Central Jakarta 47.56 km$^2$; West Jakarta 125.00 km$^2$; North Jakarta with an area of 147.21 km$^2$; and the Kepulauan Seribu Administrative Region 10.73 km$^2$.

Based on data from the Central Statistics Agency of DKI Jakarta Province, the total population of Jakarta in 2023 was 10,672,100, with a population growth rate from 2023 to 2020 of 0.38 percent. Jakarta is the most populous province in Indonesia, with population density reaching 16,165 people per km$^2$ in 2023 (BPS DKI Jakarta, 2024).

In addition to being the location of the provincial Government and central Government, Jakarta is also the business centre of Indonesia. Residential, commercial and industrial buildings require a considerable electrical energy supply; in 2023, the amount of electricity sold was 36,992,354,101 kWh, used by 5,225,077 customers, of whom 92 percent were households.

## B. Solar insolation data

Local solar radiation data for estimating solar radiation on inclined surfaces were obtained from the Meteorological, Climatological, and Geophysical Agency's website (BMKG, 2022). The data included the average monthly solar radiation; hours of bright sunshine (sunshine duration); and clearness index in Jakarta from 2011 to 2020, as shown in *Table 1*. The duration of bright sunshine or sunshine is one of several elements considered in climatology; the World Meteorogical Organization (WMO) defines this the length of time the sun shines brightly on the earth's surface, calculated from sunrise to sunset, and measured by the power of the sun when exceeding 120 W/m$^2$. This is different from peak sun hours, which are defined as the number of hour in the day when the intensity of the sunlight (solar irradiance) reaches an average of 1,000 Watts of energy per square meter of surface area. There are various ways to measure sunshine duration, including direct measurement with sunshine duration recorders; the pyrheliometric method, which uses direct irradiance from pyrheliometers; and pyranometric algorithms, which utilise the global irradiance from pyranometer (Wu et al., 2016). The most common device used to measure sunshine duration is the Campbell-Stokes Recorder.

Global Horizontal Irradiance (GHI) is the total irradiance from the sun on a horizontal surface of the earth. It is the sum of Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). DNI is the level of radiation on a surface that is constantly perpendicular (normal) to the direct solar beam, while DHI is the terrestrial irradiance received by a horizontal surface which has been scattered or diffused by the atmosphere. These three measures are related by the expression $GHI = DHI + (DNI \times \cos\theta)$, where $\theta$ is the solar zenith angle (Pinna and Massidda, 2020). The amounts of GHI and DNI vary due to variations in geographical location and local climate effects.

Throughout the year in Jakarta, the highest solar radiation intensity takes place in August, September and

**Table 1.** *Long term average of Global Horizontal Irradiation (GHI) in Jakarta from 2011 to 2020*

| Month | GHI (kWh/m$^2$) | Bright Sunshine Duration (hour) | Clearness Index | Average temperature (°C) |
|---|---|---|---|---|
| January | 3.70 | 3.50 | 0.3470 | 27.7 |
| February | 4.35 | 4.32 | 0.4050 | 27.4 |
| March | 4.67 | 5.10 | 0.4443 | 28.0 |
| April | 4.72 | 5.94 | 0.4784 | 28.7 |
| May | 4.31 | 5.90 | 0.4765 | 29.2 |
| June | 4.01 | 5.72 | 0.4670 | 28.7 |
| July | 4.30 | 6.22 | 0.4891 | 28.4 |
| August | 4.98 | 7.10 | 0.5251 | 28.4 |
| September | 5.61 | 7.85 | 0.5490 | 28.6 |
| October | 5.26 | 6.60 | 0.4957 | 28.9 |
| November | 4.77 | 5.39 | 0.4485 | 28.7 |
| December | 4.22 | 4.12 | 0.3993 | 28.1 |

October, with sunshine duration of around 7.85 hours per day in September and a clearness index of 0.549. In comparison, the lowest solar radiation intensity is in January and December, with bright sunshine durations of 3.5 and 4.12 hours, and a relative temperature throughout the year of around 28.4°C.

## CV. Solar radiation estimation on inclined surfaces

Calculating solar radiation on inclined surfaces is the key to analysing solar PV systems (Schallenberg-Rodríguez, 2013). (Mousavi Maleki et al., 2017) state that solar radiation measurements on oblique surface are rare; at weather stations, horizontal surfaces are used to measure global solar radiation. Nevertheless, to obtain optimal solar radiation results on the surface of the collector, solar PV panels are installed on an inclined surface, with inclined surface radiation calculated from global horizontal radiation measurement results.

Since estimation models are greatly influenced by latitude, finding the most accurate model for specific regions is vital. In addition, since the number of solar radiation incidents on PV panels is also greatly influenced by the angle and orientation of its installation, finding the optimal tilt angle for receiving maximum solar radiation on photovoltaic modules is the cheapest and most effective method (El-Sebaii et al., 2010; Demain et al., 2013; Khatib et al., 2015; Matius et al., 2021).

In calculating the level of solar radiation on the earth's surface, it is generally necessary to consider the constant of solar radiation and two parameters of the location where the solar radiation is received, namely the solar declination angle and the sunset angle. The earth's rotation on its axis contributes to variations in the intensity of solar radiation received on its surface, while the atmosphere and effects of climate change also both dampen and change the condition of solar energy sources.

The monthly average daily solar radiation incident on a tilted surface ($H_T$) consists of three components, namely: direct (beam) solar radiation incidence on a tilted surface ($H_B$); diffuse solar radiation incidence on a tilted surface ($H_D$); and reflected solar radiation on a tilted surface ($H_R$) (Duffie and Beckman, 2013; Mousavi Maleki et al., 2017; Wang et al., 2018).

$$H_T = H_B + H_D + H_R \tag{1}$$

$$H_T = H_b R_b + H_d\left(\frac{1+\cos\beta}{2}\right) + H\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

To estimate the average of beam solar radiation incidence on a tilted surface, equation (3) is used:

$$H_B = H_b \times R_b \tag{3}$$

$$H_b = H - H_d \tag{4}$$

$$H_d = (1 - 1.13 \times K_T) \times H \tag{5}$$

$$K_T = \frac{H}{H_o} \tag{6}$$

where $H_b$ and $H_d$ are beam and diffuse solar radiation on a horizontal surface; $R_b$ is the ratio of the average beam radiation received by the tilted surface to that on a horizontal surface; $K_T$ is clearness index; $H$ is the global horizontal irradiation obtained from meteorological stations; and $H_0$ is the average daily extraterrestrial radiation on a horizontal surface.

For surfaces in the southern hemisphere, the PV solar panel surface faces the equator with γ = 180°.

$$R_b = \frac{\cos(\phi+\beta)\cos\delta\sin\omega_S' + \left(\frac{\pi}{180}\right)\omega_S'\sin(\phi+\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_S + \left(\frac{\pi}{180}\right)\omega_S\sin\phi\sin\delta} \tag{7}$$

where $\delta$ is the declination angle of the sun; $N$ is the Julian day of the year; $\phi$ is the latitude of the location; $\beta$ is the optimal tilt angle; and $\omega_S'$, $\omega_S$ are sunset hour angle for inclined surfaces and horizontal surfaces.

The values $\delta$, $\omega_S'$ and $\omega_S$ can be calculated using equations (8), (9) and (10) (Duffie and Beckman, 2013).

$$\delta = 23.45\ \sin\left(360\ \times \frac{(284+N)}{365}\right) \tag{8}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{9}$$

$$\omega_S' = \min\{\omega_S, \cos^{-1}(-\tan(\phi+\beta)\tan\delta)\} \tag{10}$$

where min is the smaller value of the two values in parentheses.

To calculate diffusion radiation on an inclined surfaces ($H_D$) using equations (11) (Hay, 1979):

$$H_D = H_d\left(\frac{H-H_d}{H_o}R_b + \frac{1}{2}\left(1-\frac{H-H_d}{H_o}\right)(1+\cos\beta)\right) \tag{11}$$

Reflected radiation on an inclined surfaces ($H_R$) can be calculated by equation (12) (Liu and Jordan, 1961):

$$H_R = \frac{1}{2}\rho H(1 - \cos\beta) \quad (12)$$

where $\rho$ is a measure of surface reflectivity, known as the albedo factor. Depending on the object's composition, albedo values vary from 0.1 (asphalt) to 0.9 (snow). A commonly used assumption is $\rho = 0.2$ (Schallenberg-Rodríguez, 2013).

## D. Estimated building location in Jakarta

The method to estimate rooftop potential was developed from a technique adopted in several previous studies (Yue and Huang, 2011; Singh and Banerjee, 2015; Horan et al., 2020). Based on a review of previous research, this study utilised OSM building footprint vector layers consisting of polygons to estimate the footprint of residential, commercial and industrial buildings in the Special Capital Region of Jakarta Province by intersecting the building footprint layers with vectors layers produced by the base map from the Human Settlements, Spatial Planning and Land Affairs Office of DKI Jakarta Province, which is accessible via the Jakarta Satu website (Jakarta Satu, 2021). The map represents residential, industrial and commercial land use. Analysis was performed using intersection geoprocessing tools and basic statistics in QGIS 3.16 to identify the footprint of the three types of buildings. The roof area of the building is assumed to be equal to its ground area.

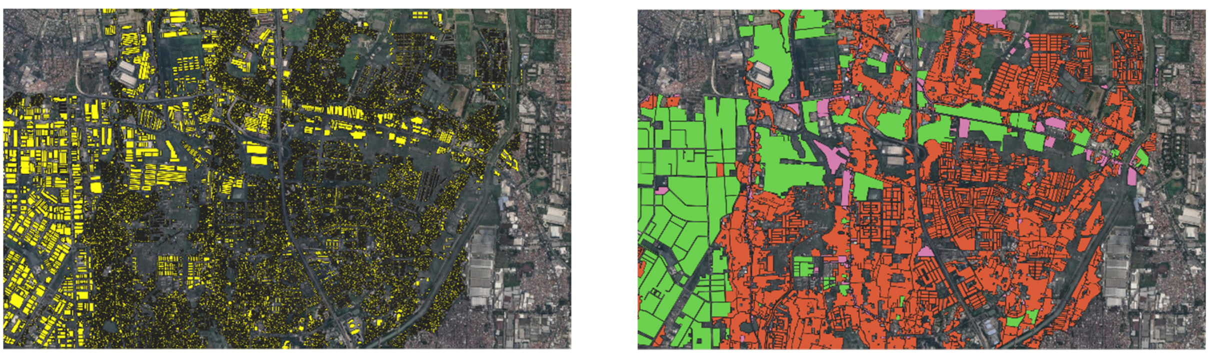
As an output example, screenshots of QGIS applications for building footprint in urban area and land use polygon for residential, industrial, and commercial zones for the city of Jakarta are shown in *Fig. 1*.

## E. Roofing usage correction factor

Assessment of PV potential on buildings starts with determination of the total roof area. However, not all the roof area is suitable for the installation of rooftop solar PV power plants. Many factors influence the proportion of available roof space. Several considerations when estimating the potential roof area, such as the number and height of buildings, population density, and construction typology, affect the usable surface area. Correction or utilisation factors also need to be considered to determine the available roof space for installing PV systems, such as building orientation, roof inclination, location, shadow, and cultural heritage considerations, together with Heating, Ventilation and Air Conditioning (HVAC) installations, water reservoirs, and roof terraces (Schallenberg-Rodríguez, 2013). Several studies have identified a relationship between population density and roof area (Lehmann and Peter, 2003; Wiginton et al., 2010; Hasan et al., 2024). International Energy Agency (IEA) (2016) devised a generic method by performing linear regression in 1600 cities to determine the linear relationship between population density and the roof area available for locating PV solar panels.

According to Gutschner et al. (2002), the total roof area must be reduced or corrected based on architectural and solar suitability to obtain a suitable roof for installing PV panels. Architectural suitability includes

**Fig. 1.** *(a) Building footprint in Jakarta urban area (yellow); (b) Land use polygon in Jakarta (red for residential, green for industrial, pink for commercial zones)*



(a) (b)

limitations caused due to construction restrictions (elevators, HVAC, etc.); protected building status (historical reasons); and shadow effects. Solar suitability refers to the calculation of the relative amount of solar radiation that the surface of a solar panel can receive depending on the inclination, orientation and distance between the PV panels. The term ‘utilisation factors’ refers to solar-architectural suitability.

Several studies have been conducted to determine the value of the reduction fraction of the use of different types of roof. Vardimon (2011), in research on Israel, determined a roof utilisation factor value of 0.3–0.5, while Schallenberg-Rodríguez (2013) set a utilisation value of 0.35–0.48 for flat roofs and < 0.11 for pitched roofs, together with 0.9 for industrial and 0.6 for commercial buildings in the Canary Islands. Horan et al. (2020) examined the decarbonisation potential of industrial and commercial zone buildings in Irish cities, determining utilisation factors 0.4 and 0.5 respectively. Our study refers to several previous studies to estimate the reduction factor for available roof space, adjusted according to climate considerations and building construction typology in Jakarta.

Housing is categorised into four major types: detached houses, semi-detached houses, terraced houses, and apartments, as per the land use map of Jakarta. Roof construction commonly used in housing in the city are gable roofs and hip roofs, with an inclination rates of 30°, together with a small number for flat roofs. To simplify the estimated potential reduction of solar PV due to building orientation, it is assumed that houses with pitched roofs face north or south, while apartments, and industrial and commercial buildings are considered to have flat roofs.

Simulation results with different roof inclination scenarios in the study area were obtained using SAM software; with a change in the orientation of installed solar panels, the potential will decrease by around 10 percent, while a difference in the slope of the roof will have an effect of approximately 12 percent, compared to optimal conditions (Gilman et al., 2018).

Furthermore, the correction factors due to shading and surrounding building construction were determined respectively at 0.64, 0.49, 0.36, 0.49, 0.86, 0.6 for large residential, medium residential, small residential, apartments, industrial buildings, and commercial buildings. The distance between solar panels needs to be considered based on the specified slope angle so that shading, which can cover the arrays of the solar modules, does not occur, so the Ground Coverage Ratio (GCR) value must be calculated. Byrne et al. (2015) determined GCR to be 0.8 for a 5° tilt angle; in this study this value was set at 0.85 for surface latitude angles.

### F. Energy potential estimation

The electrical energy generated from rooftop solar power plants in Jakarta was calculated by considering their technical characteristics, including the performance of the equipment used to convert resources into electrical energy. The output of electrical energy from solar photovoltaic panels was calculated using the following equation:

$$E_{PV} = H_{T,mean} \times A \times \eta_{PV} \times PR \times 365 \qquad (13)$$

where $E_{PV}$ is output of electrical energy from solar panels per year (kWh/year); $H_{T,\,mean}$ is average daily of solar energy radiation at an inclined surfaces (kWh/m$^2$/day); $A$ is available potential roof area (m$^2$); $\eta_{PV}$ is solar module efficiency at standard test conditions (STC) (%); and *PR* is performance ratio calculated using equation (14) (Schallenberg-Rodríguez, 2013; Mansouri Kouhestani et al., 2019).

$$PR = \eta_{th} \times \eta_{inv} \times \eta_{d} \text{ x } \eta_{mm} \qquad (14)$$

where $\eta_{th}$ is thermal efficiency of the solar panels (%); $\eta_{inv}$ is efficiency of the inverter (%); $\eta_{d}$ is losses due to the accumulation of dust or dirt on the surface of the solar panels (%); and $\eta_{mm}$ is losses due to mismatched module parameters (%).

Based on Louwen et al. (2017), $\eta_{d}$ is 98% and $\eta_{mm}$ 98.29%, and these values were adopted for this study. $\eta_{th}$ can be calculated using equation (15) (Singh and Banerjee, 2015):

$$\eta_{th} = 1 + 0{,}01PTC(T_m - T_{stc}) \qquad (15)$$

$$(T_m - T_a)°C = \left(\frac{(NOCT-20)°C}{800}\right) G_s \qquad (16)$$

where *PTC* is power temperature coefficient (%/°C); $T_{stc}$ is temperature of the solar module in standard test conditions (25°C); $T_m$ is solar module photovoltaic cell temperature (°C); $T_a$ is average values of ambient air temperature (°C); *NOCT* is nominal operating cell temperature (°C); $G_s$ is solar irradiation (Wm$^{-2}$), with value of between 800–1000 Wm$^{-2}$.

## Results and Discussion

### A. Estimated residential building roof area

The building layer intersection with the land use layer in the 44 sub-districts in Jakarta indicated a total area value of the residential, industrial and commercial building footprints of 197,482,182 m$^2$, 15,370,810 m$^2$, and 29,457,693 m$^2$ respectively. According to the analysis of the estimated proportions from spatial data on land use in Jakarta, the percentage of land for each house type classification in the residential zone is: large 13 percent, medium 37 percent, small 48 percent, and flats/apartments 2 percent. Therefore, by multiplying the total area of residential buildings by the proportion of each type of housing, the area of large houses is 25,391,041 m$^2$, of medium 72,099,714 m$^2$, of small 95,418,844 m$^2$, and of flats/apartments 4,572,583 m$^2$.

The potential roof area for locating PV panels was calculated by multiplying the value of the roof area of the building by the roof utilisation factor, which is 0.64 for large houses, 0.49 for medium, 0.36 for small, and 0.49 for flats/apartments, 0.86 for industrial, and 0.6 for commercial. The utilisation factor was multiplied by the distance threshold between solar modules arrayed in buildings with flat roofs, such as apartments, industrial and commercial buildings. A threshold of 0.85 was determined for installing a surface latitude slope.

The roof utilisation factor determined in this study was higher than that in the study conducted by Widodo et al. (2020), which estimated the available roof coefficient at around 0.125 and 0.15 for residential areas in the city of Semarang, Indonesia. In addition, Sihotang and Okajima (2017) employed available roof coefficients of 0.58, 0.43 and 0.78 for void rate, shadow rate, and facility rate respectively, in relation to their photovoltaic power potential analysis in Makassar City, Indonesia.

Based on the computed results of multiplying the building roof area value by the roof utilisation factor, it was found that the potential roof space available for installing solar rooftop PV in residential, industrial and commercial areas of Jakarta was 101,297,045 m$^2$ (101.3 km$^2$), 11,236,062 m$^2$ (11.2 km$^2$) and 14,021,862 m$^2$ (14 km$^2$) respectively, as shown in *Table 2*. These results indicate that in the city, roof space in residential areas has the most significant potential for the deployment of rooftop PV, equal to 80 percent of the total roof area in residential, industrial and commercial areas. Assuming that this potential was fully realised for the installation of solar PV, it would significantly contribute to the application of renewable energy in the city, encouraging the achievement of the target of reducing carbon emissions from the energy sector.

The estimated available roof area for installing rooftop solar PV was calculated in more detail based on the administrative areas at the sub-district level in Jakarta for each land use zone. Furthermore, *Table 2* shows the results regarding potential roof availabity for solar PV in residential areas spread across 44 sub-districts in Jakarta, ranging from 100,054 m$^2$ in Kepulauan Seribu Utara sub-district, to 5,022,332 m$^2$ in Duren Sawit sub-district. In the industrial zone, the largest available roof area is in Cakung sub-district, with an area of 2,695,160 m$^2$, while in the commercial zone, the largest is in Cengkareng sub-district, at 1,152,967 m$^2$.

Widodo et al. (2020) estimated the potential electricity production from rooftop solar PV systems in residential areas and calculated the potential for $CO_2$ mitigation in the city of Semarang, Indonesia. Their results show that the area of residential roofs spread across 16 sub-districts in the city of Semarang ranged from 412,987.50 m$^2$ to 2,083,387 m$^2$.

Horan et al. (2020) found that a small number of large industrial and commercial buildings in Irish cities and regions, representing only 4 percent of the sector's facilities, accounted for 38 percent of their decarbonisation potential. To obtain more accurate calculation results which do not require intensive computation, estimation of available roof areas for the installation of PV can be made by integrating GIS with machine learning, which will contribute to estimation of the potential of large-scale rooftop solar PV (Gassar and Cha, 2021).

### B. Solar radiation potential

Calculation of solar radiation on an inclined surface is carried out using equation 1–13. In this study, estimates were carried out for several tilt angle conditions, namely for tilt angles according to surface latitude, 13°, 15°, and 30° facing north. Solar panels must be placed in the right orientation and tilt angle to obtain the most optimal solar energy at the study location.

The calculation results from our study show that for the Jakarta region, the optimal value of annual solar radiation on an inclined surface is obtained if the solar panels are installed with a fixed tilt angle configuration of a latitude angle of around 6° facing north (equator); the value declines with increasing tilt angle. These results are

**Table 2.** *Area of potential residential rooftops for solar PV in Jakarta*

| Sub-District Area | Total roof area (m²) | | | Available roof area (m²) | | |
|---|---|---|---|---|---|---|
| | Residential | Industrial | Commercial | Residential | Industrial | Commercial |
| Kep. Seribu Selatan | 258,260 | - | 2,487 | 107,357 | - | 1,184 |
| Kep. Seribu Utara | 240,692 | - | 81 | 100,054 | - | 39 |
| Gambir | 1,270,590 | 11,776 | 1,117,130 | 662,955 | 8,608 | 531,754 |
| Sawah Besar | 1,501,600 | 35,554 | 781,740 | 730,057 | 25,990 | 372,108 |
| Kemayoran | 3,228,810 | 2,258 | 775,274 | 1,482,233 | 1,651 | 369,030 |
| Senen | 1,506,230 | 628 | 451,319 | 723,112 | 459 | 214,828 |
| Cempaka Putih | 2,071,930 | 29,837 | 312,984 | 1,154,729 | 21,811 | 148,980 |
| Menteng | 2,176,140 | 2,648 | 436,037 | 1,401,749 | 1,936 | 207,554 |
| Tanah Abang | 1,833,240 | 16,454 | 885,596 | 869,535 | 12,028 | 421,544 |
| Johar Baru | 1,415,610 | 1,300 | 104,326 | 705,982 | 950 | 49,659 |
| Penjaringan | 6,342,500 | 2,413,640 | 1,277,320 | 3,527,922 | 1,764,371 | 608,004 |
| Tanjung Priok | 6,902,620 | 1,949,690 | 973,491 | 3,443,500 | 1,425,223 | 463,382 |
| Koja | 4,555,300 | 241,766 | 581.,44 | 2,147,383 | 176,731 | 276,910 |
| Cilincing | 6,210,600 | 1,539,490 | 1,871,830 | 2,871,199 | 1,125,367 | 890,991 |
| Pademangan | 2,170,550 | 736,298 | 629,610 | 1,125,950 | 538,234 | 299,694 |
| Kelapa Gading | 4,442,840 | 501,010 | 954,274 | 2,505,490 | 366,238 | 454,234 |
| Cengkareng | 7,792,470 | 349,316 | 2,422,200 | 3,584,951 | 255,350 | 1,152,967 |
| Grogol Petamburan | 4,469,390 | 38,021 | 653,533 | 2,252,227 | 27,793 | 311,082 |
| Taman Sari | 1,669,570 | 27,534 | 738,376 | 771,646 | 20,127 | 351,467 |
| Tambora | 2,674,160 | 64,444 | 611,241 | 1,220,975 | 47,109 | 290,951 |
| Kebon Jeruk | 7,167,190 | 73,882 | 955,945 | 3,951,352 | 54,008 | 455,030 |
| Kali Deres | 7,420,010 | 1,877,020 | 1,111,630 | 3,289,411 | 1,372,102 | 529,136 |
| Palmerah | 3,451,870 | 5,199 | 402,622 | 1,737,954 | 3,800 | 191,648 |
| Kembangan | 7,558,560 | 148,042 | 717,341 | 4.216.659 | 108,219 | 341,454 |
| Tebet | 4,244,520 | 46,999 | 416,804 | 2,113,216 | 34,356 | 198,399 |
| Setia Budi | 2,308,340 | 42,333 | 666,164 | 1,194,993 | 30,945 | 317,094 |
| Mampang Prapatan | 3,125,560 | - | 517,028 | 1,806,699 | - | 246,105 |
| Pasar Minggu | 7,251,780 | 52,050 | 588,969 | 4,075,136 | 38,049 | 280,349 |
| Kebayoran Lama | 6,677,650 | 49,971 | 931,562 | 3,642,792 | 36,529 | 443,424 |
| Cilandak | 5,966,470 | 12,649 | 599,419 | 3,108,539 | 9,246 | 285,323 |
| Kebayoran Baru | 3,895,390 | - | 742,539 | 2,201,698 | - | 353,449 |
| Pancoran | 3,564,460 | 23,980 | 399,291 | 1,923,555 | 17,529 | 190,063 |
| Jagakarsa | 8,520,390 | 8,040 | 291,627 | 4,307,167 | 5,877 | 138,814 |
| Pesanggrahan | 4,849,850 | 52,382 | 337,204 | 2,643,986 | 38,291 | 160,509 |
| Matraman | 2,607,330 | 8,151 | 323,098 | 1,236,687 | 5,958 | 153,795 |
| Pulo Gadung | 5,541,830 | 137,038 | 598,280 | 2,926,773 | 100,175 | 284,781 |
| Jatinegara | 4,763,710 | 70,821 | 454,839 | 2,413,801 | 51,770 | 216,503 |
| Kramat Jati | 5,596,430 | 51,504 | 485,194 | 2,593,194 | 37,649 | 230,952 |
| Pasar Rebo | 4,417,620 | 226,354 | 193,690 | 2,147,027 | 165,465 | 92,196 |
| Cakung | 9,431,050 | 3,686,950 | 1,489,600 | 4,483,114 | 2,695,160 | 709,050 |
| Duren Sawit | 9,370,840 | 156,430 | 945,639 | 5,022,332 | 114,350 | 450,124 |
| Makasar | 4,446,340 | 40,331 | 158,254 | 2,289,607 | 29,482 | 75,329 |
| Ciracas | 5,643,920 | 596,940 | 367,342 | 2,848,988 | 436,363 | 174,855 |
| Cipayung | 6,927,970 | 42,080 | 183,019 | 3,733,358 | 30,760 | 87,117 |
| Total | 197,482,182 | 15,370,810 | 29,457,693 | 101,297,045 | 11,236,062 | 14,021,862 |

**Table 3.** *Monthly average solar radiation on tilted surfaces in Jakarta (kWh/m²/day)*

| Month | Tilt Angle | | | | |
|---|---|---|---|---|---|
| | Horizontal surface (0°) | Surface Latitude | 13° | 15° | 30° |
| January | 3,697 | 3,575 | 3,383 | 3,319 | 2,715 |
| February | 4,350 | 4,272 | 4,121 | 4,067 | 3,506 |
| March | 4,672 | 4,679 | 4,621 | 4,592 | 4,200 |
| April | 4,716 | 4,827 | 4,891 | 4,895 | 4,741 |
| May | 4,308 | 4,494 | 4,649 | 4,680 | 4,733 |
| June | 4,014 | 4,227 | 4,417 | 4,459 | 4,601 |
| July | 4,300 | 4,509 | 4,690 | 4,729 | 4,836 |
| August | 4,976 | 5,135 | 5,248 | 5,267 | 5,198 |
| September | 5,607 | 5,662 | 5,649 | 5,629 | 5,268 |
| October | 5,257 | 5,195 | 5,051 | 4,996 | 4,395 |
| November | 4,766 | 4,627 | 4,401 | 4,325 | 3,589 |
| December | 4,221 | 4,064 | 3,825 | 3,747 | 3,017 |
| Yearly average | 4,574 | 4,606 | 4,579 | 4,559 | 4,233 |

consistent with the study of Soulayman and Hammoud (2016), who found that the optimal tilt angle is a function of latitude coordinates. In addition, solar radiation data from NASA also shows that tilt surface latitude gives the best results (NASA POWER, 2022). Calculation of monthly average solar radiation at various tilt angle configurations in Jakarta can be seen in *Table 3*.

Setiawan and Setiawan (2017), who investigated solar panel optimisation in three cities in Indonesia using system advisor model (SAM) software, found that the optimal slope angle for Jakarta was 11°. The optimum angle for installing solar panel arrays can be achieved in the range of 0°–15°, with an average annual solar radiation of 4,559 kWh to 4,574 kWh per square meter.

Alhough in ideal conditions solar panels are installed with a slope according to the surface latitude, in real situations pitched roof panels are installed following the slope of the available roof. In general, the typology of residential roofs in Jakarta is gable. This form of hip roof has a certain angle of inclination, generally a slope angle of around 30°, which was used for estimation in this study.

## Technical potential

The angle of inclination in a solar energy system is an essential parameter for capturing the maximum solar radiation that the panels receive. The solar radiation is site specific to each location, depending on the daily, monthly or yearly solar path. The optimal inclination angle is crucial for obtaining maximum energy production from the PV system (Yadav and Chandel, 2013).

The estimation of electric potential in this study was based on two scenarios: assessment using multi-crystalline silicon solar modules with efficiencies of 17.3 percent and 22.8 percent. The electrical parameters of the two types of panel as the basis for calculating electrical potential can be seen in *Table 4*. Electrical output performance was obtained from tests conducted by the manufacturer under standard test conditions, at a cell temperature of 25°C, solar irradiance of 1000 W/m², and air mass of 1.5 (AM 1.5) spectrum (Odeh, 2018). The technical specifications for the calculations in *Table 4* were used to estimate solar rooftop PV power potential in Jakarta.

The potential PV installed capacity from the available roof area in Jakarta ranged from 16,967–21,526 MWp for residential buildings, 1,882–2,388 MWp for industrial, and 2,349–2,980 MWp for commercial. Mathematical equations (14–17) were used to calculate the electrical potential of rooftop solar PV power plants in Jakarta. The residential building zone figure was 19,089 GWh/year, the industrial 2,454 GWh/year, and the commercial 3,062 GWh/year, with a scenario of 17.3 percent PV panel efficiency. With 22.8 percent PV panel efficiency, the electrical generation potential in

**Table 4.** *Electrical parameters of solar PV modules*

| Parameter | Unit | Rated Value | |
|---|---|---|---|
| | | Risen Energy RSM72-6-325P | Sun Power SPR-A-425 G-AC |
| STC Power Rating, Pmax | Wp | 335 | 425 |
| Technology | | Multi-c-Si | Mono-c-Si |
| Dimensions (Length x Width) | mm | 1956 x 992 | 1835 x 1016 |
| Number of cells | | 72 | 66 |
| Maximum Power Voltage, Vmp | V | 37.65 | 41.2 |
| Maximum Power Current, Imp | A | 8.90 | 10.2 |
| Open Circuit Voltage, Voc | V | 42.20 | 48.4 |
| Short Circuit Current, Isc | A | 7.71 | 11 |
| Module efficiency | % | 17.3 | 22.8 |
| NOCT | °C | 45 | 46.4 |
| Power Temperature Coefficient | %/°C | -0.39 | -0.29 |
| Lifespan | years | 25 | 25 |

**Table 5.** *Available roof space, potential installed capacity, solar PV electricity generation*

| Building Type | Available roof space ($km^2$) | Potential installed capacity (MWp) | | Potential yearly electricity generation (GWh) | |
|---|---|---|---|---|---|
| | | Module 17.3 | Module 22.8 | Module 17.3 | Module 22.8 |
| Residential | 101.30 | 16,967 | 21,526 | 19,089 | 26,239 |
| Industrial | 11.24 | 1,882 | 2,388 | 2,454 | 3,373 |
| Commercial | 14.02 | 2,349 | 2,980 | 3,062 | 4,209 |

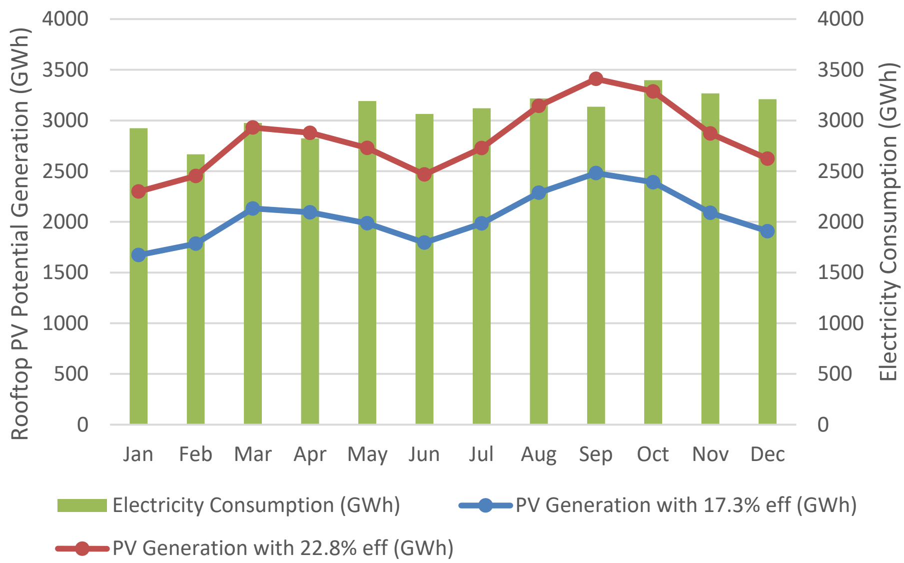
residential buildings was 26,239 GWh/year, in industrial 3,373 GWh/year, and in commercial 4,209 GWh/year, as shown in *Table 5*. This represents an annual specific energy yield for residential, industrial and commercial areas of 1,161–1,258 kWh/kWp.

A comparison between monthly electricity consumption by customers of the State Electricity Company in 2023 and the potential electricity generated by rooftop solar power power plants from residential, commercial and industrial building in Jakarta is shown in *Fig. 2.* The potential electricity production that could be achieved by utilising the entire residential roof area for installing PV is significant. The proportion of PV electricity generated from residential building rooftops would be around 78 percent of the total PV electricity generated from the three zones.

Overall rooftop solar PV electricity generated annually would contribute the equivalent of around 67 percent of Jakarta's total electricity consumption in 2023, with 17.3 percent efficiency solar modules. The lowest figure of 57 percent corresponds to January and the highest of 79 percent to September, when solar radiation intensity reaches its maximum value. If a 22.8 percent efficient module were used, it could contribute 91 percent of Jakarta's total electricity consumption, with the lowest proportion of 79 percent in January and the highest of 109 percent in September, as shown in *Fig. 2*. Even with seasonal changes in sunlight, increasing the efficiency of rooftop photovoltaic systems dramatically increases energy generation. Particularly in the months with the most sunshine, efficient rooftop PV systems have the capacity to match or even surpass monthly electricity usage.

However, there are inconsistencies in the results shown in *Fig. 2* and *Table 1*. *Table 1* shows that the value of sunshine duration for June is higher than for November; however, it is the other way around for PV potential in *Fig. 2*. There may be several factors that influence this, but it is most likely that the distance from the sun to the earth and the declination angle are

**Fig. 2.** *Comparison of electricity consumption by customers of the State Electricity Company with the potential of electricity generated from rooftop solar PV in Jakarta*



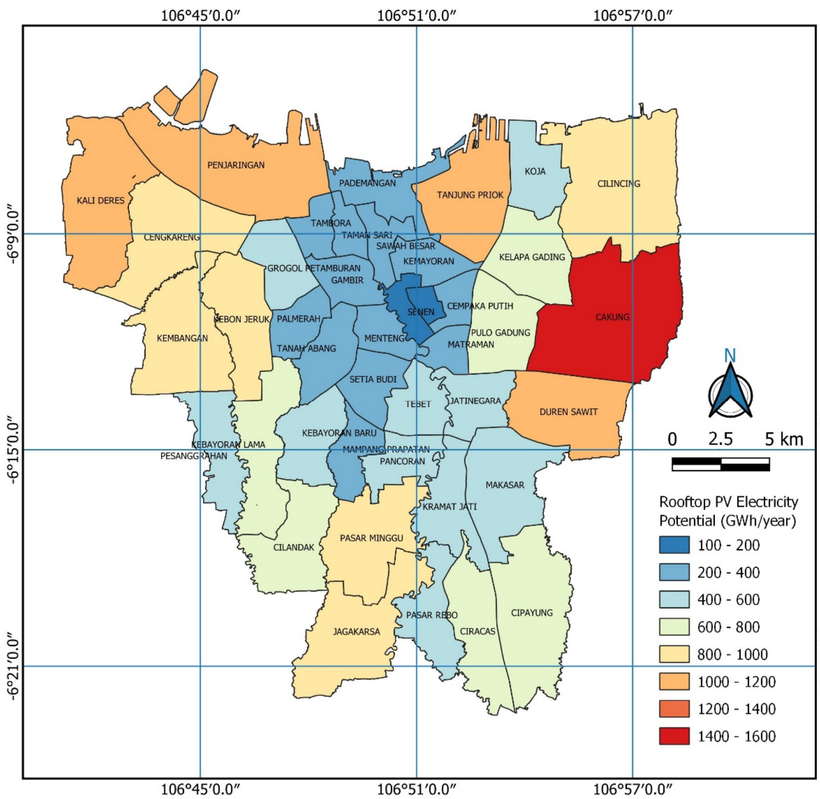

the main contributors. The angle has a maximum value of 23.45° on June 22 and a minimum of –23.45° on December 21–22, which will affected by the distance from the earth to the sun. The geographical location of Jakarta is close to the equator, namely at coordinates latitude –6° 12' south and longitude 106° 48' east, meaning that in August to October the intensity of solar radiation tends to increase as the sun approaches the equator. On the other hand, in June and July the intensity of solar radiation tends to decrease as the sun moves further away from the equator.

The details of the geographical distribution of the potential for rooftop solar power generated by each sub-district in Jakarta are listed in *Fig. 3*. This information shows the areas' potential for rooftop solar PV, from the lowest value of around 100 GWh per annum, to the highest of around 1,600 GWh per annum, with 17.3 percent solar module efficiency. The electricity output will be greater if solar modules with higher efficiency are used. From the calculation results, the potential electricity generated from distributed rooftop solar PV installed on the roofs of available residential, industrial and commercial buildings could provide power to customers, replacing the electricity supplied by the State Electricity Company. The map in *Fig. 3* highlights significant variations in rooftop PV electricity potential across different urban zones. Areas with higher potential, especially those marked in red, are prime candidates for solar energy projects. This finding could be beneficial for all stakeholders in planning and optimising the development of rooftop PV systems to maximise energy generation and efficiency in Jakarta.

Several similar studies have been conducted in Indonesia. Widodo et al. (2020) aimed to provide a quantitative analysis of the potential for electricity production from rooftop solar photovoltaic systems in residential areas and to estimate their potential for $CO_2$ mitigation. Their study found that the residential roof areas across 16 districts in Semarang city ranged from 412,987.50 $m^2$ to 2,083,387 $m^2$, with an average annual solar energy potential of 44,051–222,222 MWh/year. This low-carbon electricity could have accounted for 40.87 percent of the city's total electricity consumption in 2018 and reduced $CO_2$ emissions by 1,394 tons per year.

Sihotang and Okajima (2017) conducted a study of the potential of PV systems in the Makassar region, Indonesia. Their results show that from the 13.8 $km^2$ area available for residential PV systems it was estimated that there was a potential installation capacity of 2,044 MW. The total areas available for large-scale PV systems in and outside Makassar were19.3 $km^2$ and 231.3 $km^2$, estimated to have installed capacities of 851 MW and 10,179 MW respectively. Even though it corresponds to a smaller area, the electricity potential

**Fig. 3.** *Geographical distribution of electricity solar rooftop potential in Jakarta based on sub-district*




per km² produced by the residential area is greater than that of others, at around 44 MW per km², as residential rooftop PV systems can be installed using the available roof area and do not require special land. This figure is lower when compared with the estimation results in this study, which showed that the rooftop solar PV electricity potential capacity in residential areas per km² was 58 MW/km², while that from residential, industrial and commercial areas was around 73 MW/km². In addition, Tarigan (2020) analysed policies for solar rooftop photovoltaic systems in Indonesia, based on the Ministry of Energy and Mineral Resources Regulation No. 49 of 2018, focusing on their implementation in the residential sector. Their simulation results indicate that average total solar irradiation on horizontal surfaces in Surabaya ranged from 4.82 kWh/m² to 6.81 kWh/m², with a daily average of 5.54 kWh/m². A 3 kWp rooftop PV system in Surabaya produced approximately 4,200 kWh annualy, averaging 11.67 kWh per day.

Singh and Banerjee (2015), in their study of Mumbai City, India, concluded that the electrical potential of large-scale solar PV implementation could provide 12.8–20 percent of the average daily electricity demand, reaching 31–60 percent of morning peak load demand during different months by using medium efficiency solar panels. In addition, Ayodele et al. (2021) found that the city of Ibadan in Nigeria had a total roof area of approximately 49.54 square kilometers, with around 7.54 square kilometers available for rooftop PV deployment. This area had a maximum installation capacity of 1734.8 MWp at an optimal fixed tilt of 11°, which could generate approximately 6.67 TWh of electricity annually.

The results of a study conducted by Byrne et al. (2015) show that the technical potential of deploying distributed rooftop solar PV could supply around 30 percent of the annual electricity consumption of Seoul, South Korea. In addition, Gagnon et al. (2016) estimated the technological potential of photovoltaic (PV) systems deployed on rooftops in the continental United States. They found that small buildings (< 5,000 ft²) could supply 25 percent of electricity consumption, medium ones (5,000–25,000 ft²) 5.4 percent, and large ones

(> 25,000 $ft^2$) 8.2 percent, in total contributing 39 percent to national electricity-sector sales. In their research, Bazan et al. (2018) examined the potential of electricity production from urban rooftop solar PV deployment related to the mitigation of GHG emissions in three medium-sized cities in Peru. Their results show that the electricity produced in all three cities would be higher than the required electricity demand based on the historical data series assumed in the case study. Yue and Huang (2011) showed that solar PV and solar water heating systems in Taiwan had the potential to produce 36.1 and 10.2 TWh of electricity and thermal energy annually, representing 16.3 percent and 127.5 percent of the total electricity and energy consumption for household water heating in 2009. Moreover, Kozlovas et al. (2023) found that the potential for rooftop solar PV systems in Lithuanian urban areas was 272 MW in relation to installations on the rooftops of apartment buildings; 78 MW on public buildings; and 67 MW on commercial buildings, while Ranjgar and Niccolai (2023) showed that rooftop PV in Tehran had the potential to generate around 3000 GWh of solar power, accounting for over 14 percent of the city's total electricity consumption. Finally, Hasan et al. (2024) provided a comprehensive picture of Bangladesh's solar PV potential, with estimates of roughly 30 GWp for rooftop PV, 9 GWp for ground-mounted PV, 5 GWp for floating PV, and 81 GWp for agrivoltaic applications.

The discussion presented above reveals the vast potential of rooftop solar PV systems to significantly contribute to electricity generation and sustainability goals across different regions. The large-scale adoption of such systems is essential for advancing the broad move toward renewable energy across society. Lowering the cost of RSPV systems would make it possible to achieve substantial decarbonization of buildings by increasing their adoption and deployment. Therefore, rooftop solar PV would be an attractive option for sustainable energy production in urban areas.

Although the results show that Jakarta has relatively high electricity potential from rooftop solar PV, increasing its adoption, especially amongst residential consumers, remains a challenge. Barriers need to be overcome, including socio-technical, management, economic and policy ones (Karakaya and Sriwannawit, 2015; Setyawati, 2020). To boost the uptake of rooftop solar PV in urban settings, the participation of all stakeholders, including adopters, local communities, business, financial institutions, governments, and international organizations, is essential. Policy measures are also crucial in easing short-term cash flow challenges (Xue et al., 2024).

## Conclusion

This paper has investigated the potential for electricity generated from the available roof area in the residential, industrial and commercial building zones of Jakarta. Land resources assessment has been based on the use of publicly available building and land-use data. Analysis of available roof areas was conducted using intersection geoprocessing tools and basic statistics in QGIS 3.16 to identify the building footprint of the city.

The calculation of available roof area to install RSPV is carried out by taking into account roof utilization factors, such as roof's type of the building, orientation, shading, and other uses. The results reveals that the roof areas of residential, industrial and commercial zones available for the installation of solar rooftop PV were 101,297,045 $m^2$ (101.3 $km^2$), 11,236,062 $m^2$ (11.24 $km^2$), and 14,021,862 $m^2$ (14 $km^2$) respectively.

Depending on solar panels' efficiency, a considerable amount of power can be generated by rooftop solar PV in Jakarta, which varies among residential, industrial, and commercial buildings. For residential areas, the capacity ranged from 16,967–21,526 MWp, industrial area 1,882–2,388 MWp, and commercial areas 2,349–2,980 MWp. Based on 17.3 percent PV panel efficiency, rooftop PV could supply 67% of Jakarta's electricity needs in 2023, rising to 91% with 22.8% efficiency. The solar energy output is highest in September and lowest in January due to variations in sunlight. Increasing PV panel efficiency can greatly boost energy production, potentially exceeding monthly electricity consumption during peak sunlight periods. It's a powerful step towards a more sustainable self-sufficient urban future. With annual specific energy yield of 1,161–1,258 kWh/kWp indicating that Jakarta has relatively good amount of solar radiation.

With increasing energy demand and push for cleaner, renewable energy sources, rooftop solar systems can play a crucial role in reducing reliance on fossil fuels and lowering greenhouse gas emissions. Additionally, Jakarta's favourable solar radiation levels enable efficient energy generation throughout the year, with the potential to meet a large portion of the city's electricity needs. Jakarta can improve its energy security, lower consumer electricity costs, and advance local and national sustainability goals by putting distributed rooftop solar PV into place. Furthermore, this is a financially feasible option due to improvements in solar panel technology and falling costs, with potential for private sector investments and government incentives to hasten its implementation.

In the context of national decarbonization policy, this study highlights the potential for technological deployment in each local administrative region to support national decarbonization goals, an aspect that is currently insufficiently addressed in Indonesia's national planning. It should be helpful for stakeholders related to renewable energy development and serve as a reference for developing strategies and policies for implementing distributed solar power systems in Jakarta. Subsequent research could examine the economic feasibility and levels of carbon emissions reduction that could be achieved in urban areas from the adoption and deployment of rooftop solar PV.

## References

Assouline D., Mohajeri N., Scartezzini J.-L. (2018) Estimation of large-scale solar rooftop PV potential for smart grid integration: A methodological review. In: Amini M., Boroojeni K., Iyengar S., Pardalos P., Blaabjerg, F., Madni, A. (eds) Sustainable Interdependent Networks. Studies in Systems, Decision and Control, vol 145. Springer, Cham. https://doi.org/10.1007/978-3-319-74412-4_11

Ayodele T. R., Ogunjuyigbe A. S. O., and Nwakanma, K. C. (2021) Solar energy harvesting on building's rooftops: A case of a Nigeria cosmopolitan city. Renewable Energy Focus 38: 57-70. https://doi.org/10.1016/j.ref.2021.06.001

Bazmi A. A. and Zahedi G. (2011) Sustainable energy systems: Role of optimization modeling techniques in power generation and supply-A review. Renewable and Sustainable Energy Reviews 15(8): 3480-3500. https://doi.org/10.1016/j.rser.2011.05.003

Bergamasco L. and Asinari P. (2011) Scalable methodology for the photovoltaic solar energy potential assessment based on available roof surface area: Application to Piedmont Region (Italy). Solar Energy 85: 1041-1055. https://doi.org/10.1016/j.solener.2011.02.022

BMKG (2022) Potensi Energi Surya Stasiun [Station Solar Energy Potential]. Badan Meteorologi, Klimatologi, dan Geofisika. Available: https://iklim.bmkg.go.id/id/ (Accessed 15 October 2022) (in Indonesian).

BPS DKI Jakarta (2024). Provinsi DKI Jakarta Dalam Angka 2024 [DKI Jakarta Province in Figures 2024]. Badan Pusat Statistik Provinsi DKI Jakarta (in Indonesian).

Byrne J., Taminiau J., Kurdgelashvili L. and Kim K. N. (2015) A review of the solar city concept and methods to assess rooftop solar electric potential, with an illustrative application to the city of Seoul. Renewable and Sustainable Energy Reviews 41: 830-844. https://doi.org/10.1016/j.rser.2014.08.023

Castellanos S., Sunter,D. A. and Kammen D. M. (2017) Rooftop solar photovoltaic potential in cities: how scalable are assessment approaches? Environmental Research Letters 12: 125005. https://doi.org/10.1088/1748-9326/aa7857

Czerwińska K. and Pacana A. (2024) Analysis of Energy Security Based on Level of Alignment with the Goals of Agenda 2030. Energies 17: 2813. https://doi.org/10.3390/en17122813

Demain C., Journée M. and Bertrand C. (2013) Evaluation of different models to estimate the global solar radiation on inclined surfaces. Renewable energy 50: 710-721. https://doi.org/10.1016/j.renene.2012.07.031

Duffie J. A. and Beckman W. A. (2013) Solar engineering of thermal processes, John Wiley and Sons. https://doi.org/10.1002/9781118671603

El-Sebaii A., Al-Hazmi F., Al-Ghamdi A. and Yaghmour S. J. (2010) Global, direct and diffuse solar radiation on horizontal and tilted surfaces in Jeddah, Saudi Arabia. Applied energy 87: 568-576. https://doi.org/10.1016/j.apenergy.2009.06.032

Gagnon P., Margolis R., Melius J., Phillips C. and Elmore R. (2016) Rooftop solar photovoltaic technical potential in the United States. A detailed assessment. National Renewable Energy Lab.(NREL), Golden, CO (United States). https://doi.org/10.2172/1236153

Gassar A. A. A. and Cha S. H. (2021) Review of geographic information systems-based rooftop solar photovoltaic potential estimation approaches at urban scales. Applied Energy 291. https://doi.org/10.1016/j.apenergy.2021.116817

Gilman P., DiOrio N. A., Freeman J. M., Janzou S., Dobos A. and Ryberg D. (2018) SAM photovoltaic model technical reference 2016 update. National Renewable Energy Lab.(NREL), Golden, CO (United States). https://doi.org/10.2172/1429291

Guerra K., Haro P., Gutiérrez R. and Gómez-Barea A. (2022) Facing the high share of variable renewable energy in the power system: Flexibility and stability requirements. Applied Energy 310: 118561. https://doi.org/10.1016/j.apenergy.2022.118561

Gui B., Sam L. and Bhardwaj A. (2024) From roofs to renewables: Deep learning and geographic information systems insights into a comprehensive urban solar photovoltaic assessment for Stonehaven. Energy 360 1: 100006. https://doi.org/10.1016/j.energ.2024.100006

Gutschner M., Nowak S. and Toggweiler P. (2002) Potential for building integrated photovoltaics.: IEA - PVPS T7-4 : 2002.

Hasan A. M., Kesapabutr P. and Möller B. (2024) Bangladesh's pathways to net-zero transition: Reassessing country's solar PV potential with high-resolution GIS data. Energy for Sustainable Development 81: 101511. https://doi.org/10.1016/j.esd.2024.101511

Hay J. E. (1979) Calculation of monthly mean solar radiation for horizontal and inclined surfaces. Solar energy 23: 301-307. https://doi.org/10.1016/0038-092X(79)90123-3

Hong T., Lee M., Koo C., Kim J. and Jeong K. (2016) Estimation of the Available Rooftop Area for Installing the Rooftop Solar Photovoltaic (PV) System by Analyzing the Building Shadow Using Hillshade Analysis. Energy Procedia 88: 408-413. https://doi.org/10.1016/j.egypro.2016.06.013

Horan W., Byrne S., Shawe R., Moles R. and O'Regan B. (2020) A geospatial assessment of the rooftop decarbonisation potential of industrial and commercial zoned buildings: An example of Irish cities and regions. Sustainable Energy Technologies and Assessments 38. https://doi.org/10.1016/j.seta.2020.100651

International Energy Agency (IEA) (2016) Energy technology perspectives 2016: towards sustainable urban energy systems. Annex H.

IRENA (2016) Renewable Energy in Cities. Abu Dhabi, United Arab Emirates: International Renewable Energy Agency (IRENA)

Izquierdo S., Rodrigues M. and Fueyo N. (2008) A method for estimating the geographical distribution of the available roof surface area for large-scale photovoltaic energy-potential evaluations. Solar Energy 82: 929-939. https://doi.org/10.1016/j.solener.2008.03.007

Jakarta Satu (2021) Data Penggunaan Lahan dan Bangunan per Kecamatan DKI Jakarta [Land Use and Building Data per Sub-district of DKI Jakarta]. Available: https://jakartasatu.jakarta.go.id/portal/apps/sites/#/public/pages/unduh-kecamatan (Accessed 08 July 2021) (in Indonesian).

Kammen D. M. and Sunter D. A. (2016) City-integrated renewable energy for urban sustainability. Science 352: 922-928. https://doi.org/10.1126/science.aad9302

Kapsalis V., Maduta C., Skandalos N., Wang M., Bhuvad S. S., D'Agostino D., Ma T., Raj U., Parker D. and Peng J. (2024) Critical assessment of large-scale rooftop photovoltaics deployment in the global urban environment. Renewable and Sustainable Energy Reviews 189: 114005. https://doi.org/10.1016/j.rser.2023.114005

Karakaya E. and Sriwannawit P. (2015) Barriers to the adoption of photovoltaic systems: The state of the art. Renewable and Sustainable Energy Reviews 49: 60-66. https://doi.org/10.1016/j.rser.2015.04.058

Kassem Y., Gökçekuş H. and Güvensoy A. (2021) Techno-economic feasibility of grid-connected solar PV system at Near East University hospital, Northern Cyprus. Energies 14: 7627. https://doi.org/10.3390/en14227627

Khatib T., Mohamed A., Mahmoud M. and Sopian K. (2015) Optimization of the tilt angle of solar panels for Malaysia. Energy sources, part A: Recovery, utilization, and environmental effects 37: 606-613. https://doi.org/10.1080/15567036.2011.588680

KLHK (2022) Enhanced Nationally Determined Contribution Republik of Indonesia. Kementerian Lingkungan Hidup dan Kehutanan, Indonesia.

Kozlovas P., Gudzius S., Ciurlionis J., Jonaitis A., Konstantinaviciute I. and Bobinaite V. (2023) Assessment of technical and economic potential of urban rooftop solar photovoltaic systems in Lithuania. Energies 16: 5410. https://doi.org/10.3390/en16145410

Kutlu E. C., Durusoy B., Ozden T. and Akinoglu B. G. (2022) Technical potential of rooftop solar photovoltaic for Ankara. Renewable Energy 185: 779-789. https://doi.org/10.1016/j.renene.2021.12.079

Lehmann H. and Peter S. (2003) Assessment of roof and façade potentials for solar use in Europe. Institute for sustainable solutions and innovations (ISUSI): Aachen, Germany.

Liu B. and Jordan R. (1961) Daily insolation on surfaces tilted towards equator. ASHRAE J.;(United States), 10.

Louwen A., Schropp R. E. I., van Sark W. G. J. H. M. and Faaij A. P. C. (2017) Geospatial analysis of the energy yield and environmental footprint of different photovoltaic module technologies. Solar Energy 155: 1339-1353. https://doi.org/10.1016/j.solener.2017.07.056

Mainzer K., Killinger S., McKenna R. and Fichtner W. (2017) Assessment of rooftop photovoltaic potentials at the urban level using publicly available geodata and image recognition techniques. Solar Energy 155: 561-573. https://doi.org/10.1016/j.solener.2017.06.065

Mansouri Kouhestani F., Byrne J., Johnson D., Spencer L., Hazendonk P. and Brown B. (2019) Evaluating solar energy technical and economic potential on rooftops in an urban setting: the city of Lethbridge, Canada. International Journal of Energy and Environmental Engineering 10: 13-32. https://doi.org/10.1007/s40095-018-0289-1

Martin, S. and Ryor, J. (2016). Prosumers in Bengaluru: Lessons for scaling rooftop solar PV.

Matius M. E., Ismail M. A., Farm Y. Y., Amaludin A. E., Radzali M. A., Fazlizan A. and Muzammil W. K. (2021) On the Optimal Tilt Angle and Orientation of an On-Site Solar Photovoltaic Energy Generation System for Sabah's Rural Electrification. Sustainability 13. https://doi.org/10.3390/su13105730

Melius J., Margolis R. and Ong S. (2013). Estimating rooftop suitability for PV: a review of methods, patents, and validation techniques. https://doi.org/10.2172/1117057

Miyake S., Teske S., Rispler J. and Feenstra M. (2024) Solar and wind energy potential under land-resource constrained conditions in the Group of Twenty (G20). Renewable and Sustainable Energy Reviews 202: 114622. https://doi.org/10.1016/j.rser.2024.114622

Montealegre A. L., Garcia-Perez S., Guillen-Lambea S., Monzon-Chavarrias M. and Sierra-Perez J. (2022) GIS-based assessment for the potential of implementation of food-energy-water systems on building rooftops at the urban level. Sci Total Environ 803: 149963. https://doi.org/10.1016/j.scitotenv.2021.149963

Mousavi Maleki S. A., Hizam H. and Gomes C. (2017) Estimation of hourly, daily and monthly global solar radiation on inclined surfaces: Models re-visited. Energies 10: 134. https://doi.org/10.3390/en10010134

NASA POWER (2022) Prediction of Worldwide Energy Resource (POWER). Available: https://power.larc.nasa.gov/ (Accessed 20 September 2022).

Odeh S. (2018) Analysis of the performance indicators of the PV power system. Journal of Power and Energy Engineering 6: 59-75. https://doi.org/10.4236/jpee.2018.66005

Olabi A., Elsaid K., Obaideen K., Abdelkareem M. A., Rezk H., Wilberforce T., Maghrabie H. M. and Sayed E. T. (2023) Renewable energy systems: Comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals. International Journal of Thermofluids 20: 100498. https://doi.org/10.1016/j.ijft.2023.100498

Ordóñez J., Jadraque E., Alegre J. and Martínez G. (2010) Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain). Renewable and Sustainable Energy Reviews 14: 2122-2130. https://doi.org/10.1016/j.rser.2010.01.001

Pinna A. and Massidda L. (2020) A Procedure for Complete Census Estimation of Rooftop Photovoltaic Potential in Urban Areas. Smart Cities 3: 873-893. https://doi.org/10.3390/smartcities3030045

PP 79/2014 (2014). Government Regulation of The Republic of Indonesia No. 79/2014 on National Energy Policy.

Ranjgar B. and Niccolai A. (2023) Large-scale rooftop solar photovoltaic power production potential assessment: A case study for tehran metropolitan area, iran. Energies 16: 7111. https://doi.org/10.3390/en16207111

Rose A., Stoner R. and Pérez-Arriaga I. (2016) Prospects for grid-connected solar PV in Kenya: A systems approach. Applied Energy, 161, 583-590. https://doi.org/10.1016/j.apenergy.2015.07.052

Schallenberg-Rodríguez J. (2013) Photovoltaic techno-economical potential on roofs in regions and islands: The case of the Canary Islands. Methodological review and methodology proposal. Renewable and Sustainable Energy Reviews, 20, 219-239. https://doi.org/10.1016/j.rser.2012.11.078

Setiawan A. and Setiawan E. A. (2017) Optimization of a photovoltaic power Plant in Indonesia with proper tilt angle and photovoltaic type using a system advisor model. International Journal of Technology 8: 539-548. https://doi.org/10.14716/ijtech.v8i3.8076

Setyawati D. (2020) Analysis of perceptions towards the rooftop photovoltaic solar system policy in Indonesia. Energy Policy 144. https://doi.org/10.1016/j.enpol.2020.111569

Sihotang M. A. and Okajima K. (2017) Photovoltaic Power Potential Analysis in Equator Territorial: Case Study of Makassar City, Indonesia. Journal of Power and Energy Engineering 05: 15-29. https://doi.org/10.4236/jpee.2017.51002

Singh A., Olsen S. I. and Pant D. (2013) Importance of life cycle assessment of renewable energy sources. Life cycle assessment of renewable energy sources. Springer. https://doi.org/10.1007/978-1-4471-5364-1

Singh R. and Banerjee R. (2015) Estimation of rooftop solar photovoltaic potential of a city. Solar Energy 115: 589-602. https://doi.org/10.1016/j.solener.2015.03.016

Soulayman S. and Hammoud M. (2016) Optimum tilt angle of solar collectors for building applications in mid-latitude zone. Energy Conversion and Management 124: 20-28. https://doi.org/10.1016/j.enconman.2016.06.066

Tarigan E. (2020) Rooftop PV system policy and implementation study for a household in Indonesia. International Journal of Energy Economics and Policy 10: 110-115. https://doi.org/10.32479/ijeep.9539

Vardimon R. (2011) Assessment of the potential for distributed photovoltaic electricity production in Israel. Renewable Energy 36: 591-594. https://doi.org/10.1016/j.renene.2010.07.030

Wang M., Mao X., Gao Y. and He F. (2018) Potential of carbon emission reduction and financial feasibility of urban rooftop photovoltaic power generation in Beijing. Journal of Cleaner Production 203: 1119-1131. https://doi.org/10.1016/j.jclepro.2018.08.350

Widodo D. A., Purwanto P. and Hermawan H. (2020) Potential of solar energy in residential rooftop surface area in Semarang city, Indonesia. Advances in Science, Technology and Engineering Systems Journal 5: 397-404. https://doi.org/10.25046/aj050446

Wiginton L. K., Nguyen H. T. and Pearce J. M. (2010) Quantifying rooftop solar photovoltaic potential for regional renewable energy policy. Computers, Environment and Urban Systems 34: 345-357. https://doi.org/10.1016/j.compenvurbsys.2010.01.001

Wu B., Liu S., Zhu W., Yu M., Yan N. and Qiang X. (2016) Method to Estimate Sunshine Duration Using Cloud Classification Data from a Geostationary Meteorological Satellite (FY-2D) over the Heihe River Basin. . Sensors (Basel). 2016 Nov 4;16(11):1859. https://doi.org/10.3390/s16111859

Xue L., Liu J., Lin X., Li M. and Kobashi T. (2024) Assessing urban rooftop PV economics for regional deployment by integrating local socioeconomic, technological, and policy conditions. Applied Energy 353: 122058. https://doi.org/10.1016/j.apenergy.2023.122058

Yadav A. K. and Chandel S. (2013) Tilt angle optimization to maximize incident solar radiation: A review. Renewable and Sustainable Energy Reviews 23: 503-513. https://doi.org/10.1016/j.rser.2013.02.027

Yue C.-D. and Huang G.-R. (2011) An evaluation of domestic solar energy potential in Taiwan incorporating land use analysis. Energy Policy 39: 7988-8002. https://doi.org/10.1016/j.enpol.2011.09.054

Zhang Z., Chen M., Zhong T., Zhu R., Qian Z., Zhang F., Yang Y., Zhang K., Santi P. and Wang K. (2023) Carbon mitigation potential afforded by rooftop photovoltaic in China. Nature Communications 14: 2347. https://doi.org/10.1038/s41467-023-38079-3