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# Energy-yield Assessment Based on the Orientations and the Inclinations of the Solar Photovoltaic Rooftop Mounted in Jakarta, Indonesia

Ahmad Afandi [a], M. Danang Birowosuto [b], Kiky Corneliasari Sembiring [c,*]

*[a] Research Center for Physics, National Research and Innovation Agency (BRIN), Puspiptek Serpong, Tangerang Selatan, Indonesia*
*[b] Department of Renewable Energy Engineeringn, Universitas Prasetiya Mulya, DSD City, Tangerang, Indonesia*
*[c] Research Center for Chemistry, National Research and Innovation Agency (BRIN), Puspiptek Serpong, Tangerang Selatan, Indonesia*
*Corresponding author: *kiky001@lipi.go.id*

***Abstract*— Solar rooftop is a new trend in harnessing renewable energy in Indonesia. In this work, energy yield assessment was simulated from the solar photovoltaic (PV) installed on the rooftop from the urban housing in Jakarta, Indonesia. The selection of the capital city is because of the high energy consumption from the residence. In this simulation, the orientations of solar PV were varied from four main cardinal directions with inclination variation six points (i.e., 0, 10°, 15°, 20°, 30°, and 45°), respectively. For the important parameters, we set the installed capacity, the calculation area, the module type, and the number of modules as 2 kWp, 16.8 m$^2$, Polysilicon 200 Wp, and 10, respectively. The maximum energy yield of 2497 kWh/year is obtained for North orientation with 10° inclination, while the minimum of 1740 kWh/year was simulated at South with 45° inclination. In general South-facing orientation has a weak energy yield compared to others, and the 0° inclination has relatively high energy yield, and 45° inclination is the weakest energy yield annually. With those energy yields, the Peak Sun Hours (PSH) average is more than 6 kWh m$^{-2}$ d$^{-1}$. The Cost of Solar Energy (*CSE*) has been calculated, and it showed that the reduced *CSE* to US$ 2000 will have a payback time of 4 years with the respective *PSH*.***

***Keywords*— Energy yield; orientation; inclination; cost of solar energy; peak sun hours.**

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## I. INTRODUCTION

In the last decade, solar photovoltaic (PV) system has gained greater attention as a global sustainable source of electrical energy. Tremendous development has been done to utilize PV systems in remote locations and densely populated areas. In the cities, space has greater value and opportunity costs. Suitable space is an essential consideration to implement solar system technologies. The orientation of PV system can be defined on their PV arrays, which consist of azimuth angle (the angle measured clockwise from North) and the tilt angle (the angle above the horizontal plane). Geographic information systems (GIS) and light detection and ranging (LiDAR) can approach the rooftop photovoltaic electricity potential of building in the urban environment.

The Government of Indonesia has set the share of renewable energy sources (RES) by 23 % in 2025 [1]. The government is increasing energy development in all sectors. Solar PV system has been planned to overcome the rise of electricity demand. As a tropical country located in the equator line, Indonesia has abundant solar energy potential. From the solar energy mapping data, Indonesia has global horizontal irradiation (GHI) annually between 1600-2200 kWh/m$^2$ [2], [3]. Although it has not been massively adopted, the solar PV system application is increasing due to the competitiveness improvement and cost parity with other technologies.

The installed capacity of a solar-based power plant in Indonesia's state-owned utility company (Perusahaan Listrik Negara, PLN) was reported to be about 40.78 MW in 2019 [4]. This capacity was only a 0.06% contribution to the total installment of electricity power in Indonesia. From this tiny contribution, most of the solar PV plants are built outside Java Island. This was due to the low electrification ratio is outside of Java Island.

Developing solar energy in rural areas has faced significant barriers [5]. The lack of social acceptances [6], unreliable electricity generations [7], and the low energy demands are some factors that make on-grid solar energy less attractive economically. A successful example of solar energy development in Indonesia is off-grid applications. According to the annual report that MEMR issued, the installed capacities of solar PV systems have reached 48 MWp [7], and this amount is mostly government-incubated programs. Off-grid solar energy Indonesia has benefited many villagers, but its utilization is limited to the solar home system, solar lanterns, and other standalone solar mini-grids [8], [9].

A new strategy needs to be regulated to implement commercial solar PV for urban areas. It is also interesting to see how solar PV could reduce global warming and further mitigate the urban heat island (UHI) phenomena on the city scale. UHI is the phenomenon where the cities are warmer than surrounding rural areas. The study had shown that the urban area is hotter by 2.5°C compared to the countryside [10].

Mitigating UHI has been a great challenge, and several strategies are planting more trees and opening more space for vegetation [11], [12], green roofs technology [13], [14], cooling roofs materials [15], and new cool pavements [16]. All those strategies were applied to reduce albedo, the reflectivity index of the shortwave solar radiation onto the Earth. High albedo means high reflectivity, such as myriads of ice crystals, which will reflect most of the solar radiation to the sky. In comparison, low albedo corresponds to the high adsorption of shortwave solar radiations, which generate slow heat propagation to the sky.

Solar PV panels with high reflectivity could theoretically reduce UHI, which has been reported by Altan *et al.* [17] and Burg *et al.* [18]. Thus, by developing solar rooftop-mounted applications, it is expected that the UHI in Jakarta could be mitigated. As the capital city of Indonesia, Jakarta occupies an area of 664 km$^2$, with some inhabitants of about 10.5 million people in 2020. Jakarta currently holds the highest energy consumption per capita (3,300 kWh/a), and the level of electrification ratio reached 100% in 2013 [4]. From the total energy consumption, the residence consumed annually 14,576.96 GWh/a, which accounted for 45.32%, as shown in Fig 1.

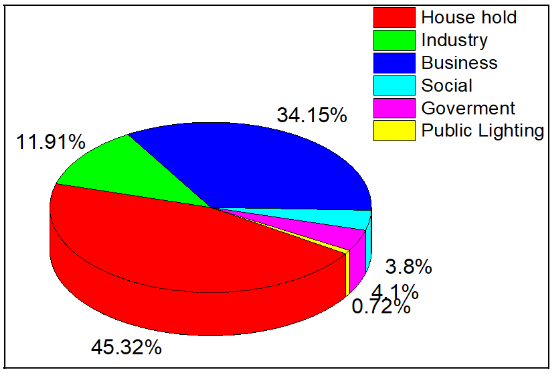

Fig. 1 Energy consumption in Jakarta

Business and industrial sectors came into second and third in energy consumption, with the total energy consumption in Jakarta accounted for 40 GWh/a in 2013. The high energy consumption in Jakarta directly affects the greenhouse gasses (GHG) emissions as the electricity generation in the Java grid is still 100% supported by fossil fuels. The utilization of solar energy for rooftop applications will help reduce GHG and eventually mitigate global warming. This study evaluated and simulated the technical and financial study of the commercial solar PV rooftop. The results determined the benefits of sustainable solar PV deployment in large cities with the rooftop mounted application.

## II. MATERIAL AND METHOD

The solar rooftop-mounted in Jakarta was simulated using PV*SOL software. The project location, which corresponds to the available solar radiation data, was taken from a weather Metronome database. The historical data used was from 1990-2005. The yield energy from the solar insolation is simulated in Jakarta, with the specific location described by the global positioning system (GPS) of the latitude and longitude -6.18°and 106.82°, respectively. Four main cardinal directions are selected from East, North, West, and South. The inclination was varied from 0°, 10°, 15°, 20°, 30°, and 45°. The inclinations were selected to adapt the residential rooftops' real situation, which could face any directions and inclinations.

The result of the energy yield simulation was used for the financial feasibility study. The daily insolation from the simulation was compared with the four scenarios of insolation from 4 to 6 kWh/m$^2$.day, and the cost of solar energy was designed with four different bases from 2000 to 3500 USD/kWh. The calculation of the return of investment (ROI) as the payback time was based on Earnings Before Interest, Tax, and Amortization (EBITA) value. The detail of the methodology can be seen in Fig 2.

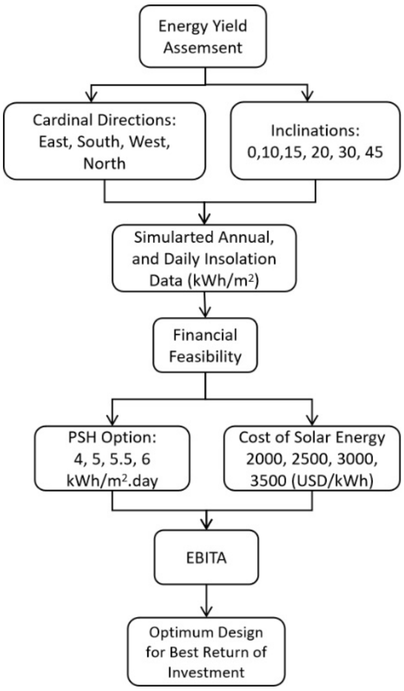

Fig. 2 Methodology of research

## III. RESULTS AND DISCUSSION

### *A. Simulation Design of the Solar Rooftop Mounted in Jakarta and Financial Feasibility*

The proposed solar PV system for the simulation comprises 10 solar PV modules, each with 200 Wp. The yield energy is sold entirely to the grid in this scenario, i.e., the full feed-in metering. As opposed to net-metering, only excess energy is sold to PLN as the sole electricity company. The total 2 kWp solar system occupies 16.8 m$^2$, mounted onto the rooftop. The result of the simulations will be compared for each inclination in all directions to see the most preferred setup.

There are four main steps to simulate yield energy using PV*SOL software. The first is to determine the project location, which corresponds to the available solar radiation data from a weather Metronome database. The second is to select whether the solar energy generated is net-metering or full-feed in the mechanism. The third is to select the type of panels, thin-film or crystalline Silicon, and then select the appropriate Balance of System (BOS). This step is crucial to match between the solar PV panel and the inverter. Most of the failure design comes from the mismatch between PV panel and the inverter. Finally, is to select the orientation and inclinations in order to get the highest possible yield energy.

In this simulation, a solar PV panel is arranged in series with only one inverter used. A simple illustration of the system is given in Fig 3. PV panels captured the solar energy, then the solar cell of polycrystalline Silicon (Poly-Si) converted it into DC. The DC current was converted to AC and then flowed into the electricity meter before 100% was sold to the grids. Since the weather and irradiance govern PV performance, the more data collected, the more accurate the yield energy simulation. There are two parameters related to solar irradiance, direct normal insolation (DNI) and diffuse horizontal insolation (DHI). Those two parameters are combined to get the global horizontal insolation (GHI) using the equation below:

$$\text{GHI}=\text{DHI Cos}\ (\Theta_z)+\text{DHI} \tag{1}$$

where $\Theta_z$ is the solar zenith angle, the angle between the sun and the normal vertical line to the Earth. GHI is a terrestrial irradiance received by the horizontal surface of Earth, which is the combined value of direct irradiance and scattering from the atmosphere. However, GHI does not reflect the amount of solar irradiance received by solar PV panels on the ground.

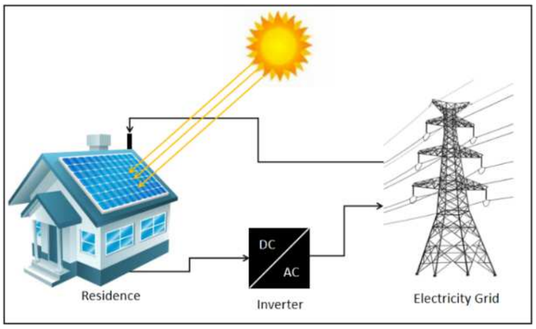

Fig. 3 Solar PV panel with one inverter.

The state of irradiance that falls on the PV panels is called the *plane of array* (*POA*) irradiance, which can be expressed by:

$$E_{POA} = E_b + E_g + E_d \tag{2}$$

More parameters will increase the insolation, such as additional irradiance scatterings from surrounding objects such as soils, buildings, dust, water, etc. $E_b$ is *POA* beam component that adjusts the value from *DNI,* and the following equation gives it.

$$E_b = DNI\ \times\ cos\ (AOI) \tag{3}$$

*AOI* is the incident angle of the solar array that arrives on the PV panels. $E_g$ is *POA* of ground component that measure albedo contribution, and it is stated by:

$$E_g = GHI\ x\ albedo\ x\ \frac{(1-\cos(\Theta_t))}{2} \tag{4}$$

The expression of $\Theta_t$ is the tilt angle of the solar PV panels. And the last expression $E_d$ from the Eq. 2 is POA sky-diffuse component, given by:

$$E_d = DHI\ x\ \frac{(1-\cos(\Theta_t))}{2} \tag{5}$$

Many models calculate POA irradiance [19], [20], but only a few models calculate sky-diffuse irradiance $E_d$, and the one that has been extensively used is the Perez model [21]. The detailed calculation from PV*SOL software is not open for the public, but it can generally be traced back to the calculation procedure through Eq. 1-5.

To demonstrate the economic feasibility of the solar PV for the rooftop-mounted system, it is important to see how well the small solar PV system can be applied commercially. Few scenarios have been proposed with two primary variables; the cost of solar energy (CSE) indicated in US$ per kilowatt peak (kWp), and the daily solar insolation (kWh m$^{-2}$ day$^{-1}$). CSE corresponds to the upfront investment covering both solar PV modules and BOS, which comprise cabling and charge controller. CSE is varied respectively from 2,000, 2,500, 3,000, and 3,500 US$/kWp. The selection of those CSE comes from the consideration that the system installations might vary across Indonesia due to different costs of shipping and other logistic costs. In addition, the survey conducted by the international renewable energy agency (IRENA) reported the cost of solar PV for a resident in the selected countries [22], as shown in Fig 4.

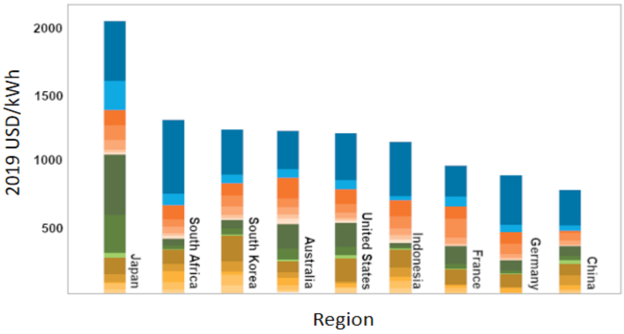

Fig. 4 The cost of solar energy installation with different power capacity in various countries [21].

The insolation expresses the amount of the solar energy received by the solar panel measured in 1 m$^2$. Solar insolation is sometimes called the peak sun hours (*PSH*) when the solar energy is measured daily. To see how *PSH* will influence the payback period, four variables of *PSH* were used to simulate the energy yield and the associated income when the energy is sold to the grid. The selling energy to the grid was assumed based on the ministry of energy and mineral resources (MEMR) regulation no. 17 of 2013. The regulation mentions that the energy to the grid from solar photovoltaic (PV) is 0.25 US$/kWh, with additional incentive to become 0.30

US$/kWh if the local contents of the solar PV system investment reach 40%.

The detail of the financial calculation parameters is given in Table 1. For the first parameter, the system lifetime ($T_L$) is 25 years, and this corresponds to the lifetime of the solar PV modules for the Poly-Si. The performance degradation of a solar PV module ($S_d$) is set 0.5%/year, and the inverter lifetime ($I_L$) is 10 years, and the replacement needs to be done accordingly. The cost of the inverter is included in the simulation as the component of BOS. However, the replacement cost of the inverter will account for 540 US$ for the small home system.

TABLE I
PARAMETERS OF FINANCIAL CALCULATIONS

| Remark | Notation | Value |
|---|---|---|
| Watt-peak (Wp)/module | *Ewp* | 200 |
| No. Module | $N_m$ | 10 |
| System Lifetime (years) | $T_L$ | 25 |
| Solar PV degradation (%/years) | $S_d$ | 0.5 |
| Inverter Lifetime (years) | $I_L$ | 10 |
| System Loses (%) | $\eta$ | 23 |
| Feed in Tariff (US$/kWh) | *FIT* | 0.25 |
| Electricity Cost Inflation (%/year) | *CEI* | 3.00 |
| Maintenance Cost (%/year) | $C_m$ | 0.50 |
| Inflation Rate (%/year) | *CIR* | 8 |

The loss of a solar PV system ($\eta$) is set conservatively at 23% due to cable losses, inverter losses, temperatures, shading, sun tracking, etc. A feed-in tariff (*FIT)* is 0.25 US$/kWh, electricity cost inflation (*CEI*) is standard 3%, maintenance cost ($C_m$) 0.5% from the total investment, which will rise due to economic inflation 8% (*CIR*) annually. The daily solar radiation or *PSH* is varied from 4, 5, 5.5, and 6 kWh/m$^2$ day. Those *PSH* selections consider the variability of solar radiation Jakarta due to variables that can reduce energy conversion.

Numerical simulations are made with the input parameters from Table 1 and the PSH variables with the following steps. First is calculating the specific yield energy ($E_{SY}$), which is done with the following equation.

$$\mathrm{ESY} = \mathrm{PSH} \times 365 \times (1 - \eta) \tag{6}$$

The solar energy output ($E_o$) as the function of time is multiplied by the total capacity of PV panels ($E_{kwp}$) with specific yield energy ESY from Eq. 6.

$$E_o(t) = (E_{kwp}\ x\ E_{sy}(t) x\ (t - S_d)^{t_{t+1} - t_t} \tag{7}$$

The income from solar energy generation is stated by earning before tax and amortization (*EBITA*). Numerical simulation of *EBITA* is obtained with

$$\mathrm{EBITA}(t) = (\mathrm{Eo}(t) \times \mathrm{FIT}) - \mathrm{C}(t) \tag{8}$$

where $C(t)$ is the annual cost from the periodic maintenance and inverter cost replacement every 10 years. To compare the economic feasibility, *EBITA* is normalized to become:

$$EBITA_{std}(t) = \frac{EBITA\ (t)}{CES}\ x\ 100 \tag{9}$$

### *B. The energy yield simulation using PV*SOL*

The energy yield simulation using PV*SOL found the weakest direction to generate solar energy comes from the South. In all the variable inclinations, 45° gets the lowest yield energy. The trend indicates that the energy yield drops significantly when the inclination risen-up, and this is expected. The result of annual yield energy ($E_{SY}$) is exhibited in Fig. 5.

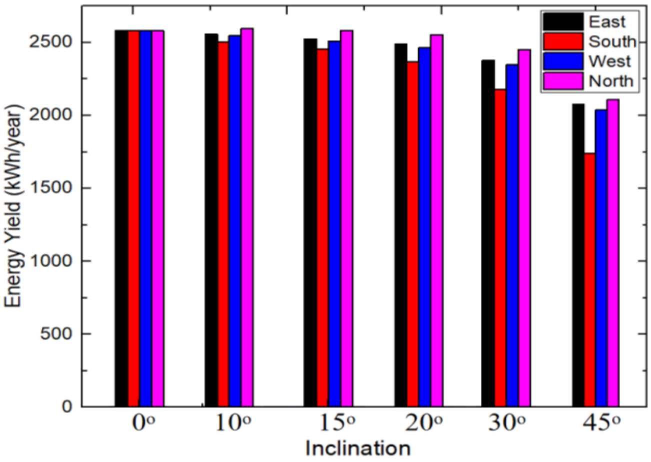

Fig. 5 Annual yield energy from the rooftop solar PV simulation.

The PSH for each direction with a different inclination is shown in Table 2 below.

TABLE II
DAILY INSOLATION OF DIFFERENT INCLINATIONS AND DIRECTIONS

| Inclination | East | South | West | North |
|---|---|---|---|---|
| | PSH (kWh m$^{-2}$ day$^{-1}$) | | | |
| **0** | 6.80 | 6.80 | 6.80 | 6.80 |
| **10** | 6.74 | 6.60 | 6.71 | 6.84 |
| **15** | 6.65 | 6.47 | 6.62 | 6.80 |
| **20** | 6.55 | 6.24 | 6.49 | 6.73 |
| **30** | 6.26 | 5.74 | 6.18 | 6.46 |
| **45** | 5.69 | 4.77 | 5.59 | 5.78 |

A polar plot of Fig. 6 shows the differences of the annual yield energy with its minimum ($E_{SY}$, min = 1740 kWh/year). The optimum direction to gain solar energy is obtained when the PV panel faces the North direction. Inclination variations of the data from the North direction show relatively stable yield energy from 0 to the 20° inclination. The yield energy starts to drop significantly when the inclination is set to 30°. Data show a strong decrease in yield energy for the South direction. Presumably, since the solar PV faces the North, the energy yield was strongly affected by the contribution from the Northern Hemisphere. The effect from the Southern Hemisphere can be inferred from the energy yield in March, and the effect was not strong. The 45° inclination PV gives the minimum yield energy, $E_{SY}$, min.

The zero inclination shows steady yield energy irrespective of the direction, as expected. However, the zero inclination is generally avoided due to difficulty cleaning the surface of the PV module. The accumulation of dust on the surface of PV module can decrease the solar PV performance. Therefore, the scheduled cleaning is mandatory. Little inclination from zero, as we can see from Fig. 5, such as 10° inclination has practically little difference in the annual energy yield compared to zero inclination. However, the 10° inclination gives better maintenance and operation.

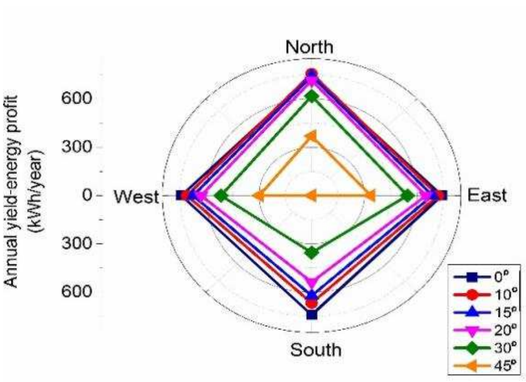

Fig. 6 Annual yield-energy profit for four main cardinal directions and six inclinations.

The trend of the energy shifted due to seasonal is shown in Fig. 7. The highest yield energy is obtained in October, followed by June, September, and March to May. When the solar PV panels are orientated to the North, energy yield shows maximum from May to June and September-October. Energy yields drop from November to January. On the contrary, stable energy yield from November to January is obtained when solar PV panels face the South direction. However, for the South direction, energy yield is relatively lower than others when the inclinations are varied. This is the reason the South direction is the weakest. East and West directions show similar characteristics of energy yield, with East being slightly higher.

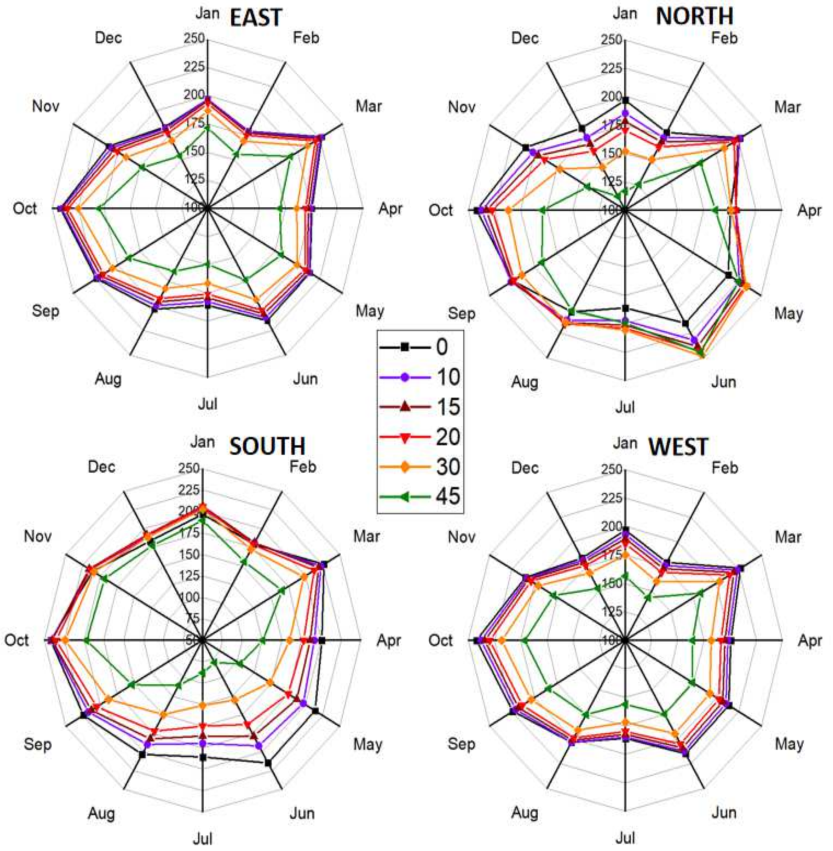

Fig. 7 Seasonal yield energy of solar PV system in one month with 2 kWp capacity as the function of directions and inclinations. Monthly yield energy is presented with the different inclinations.

### *C. The Financial Simulation of the Solar PV*

After the yield energy from the solar PV rooftop was obtained by simulation, the insolation daily was determined, as shown in Table 2. The average daily insolation is around 6 kWh $m^{-2}day^{-1}$, which is the maximum value from PSH scenarios between 4 to 6 kWh $m^{-2}day^{-1}$. The result of the financial simulation was calculated from Eq.7 to 9, and it is demonstrated in Fig. 8. With the maximum scenario cost of solar electricity (CSE) of 3,000 US$/kWp and 3,500 US$/kWp, respectively. The CSE value is taken from the IRENA data in Fig. 4. The scenario that has been proposed for CSE 3,500 US$/kWp. This study obtained the return of investment (ROI) or the payback time between 9-16 years, depending on the PSH. Meanwhile, for the CSE of about 3,000 US$/kWp, the payback time is 7.5-13 years.

It is clear that the installation of solar PV rooftops indeed influences the performance of PSH, thus influencing the return of investment. The worst installation procedure with 45° inclination and facing South direction as seen in Table 2 still obtaining 4.77 kWh $m^{-2}day^{-1}$ and the ROI can be between 13-16 years depending on the CSE value. Indeed, the ROI for more than 10 years is unfavorable for the business, and consumers may be reluctant to invest in the system. However, with the better installation procedure, for instance, the inclination is set the maximum to 30° and the direction toward North, East, and West for the best PSH value as seen in Table 2, the ROI can be obtained 7-9 years.

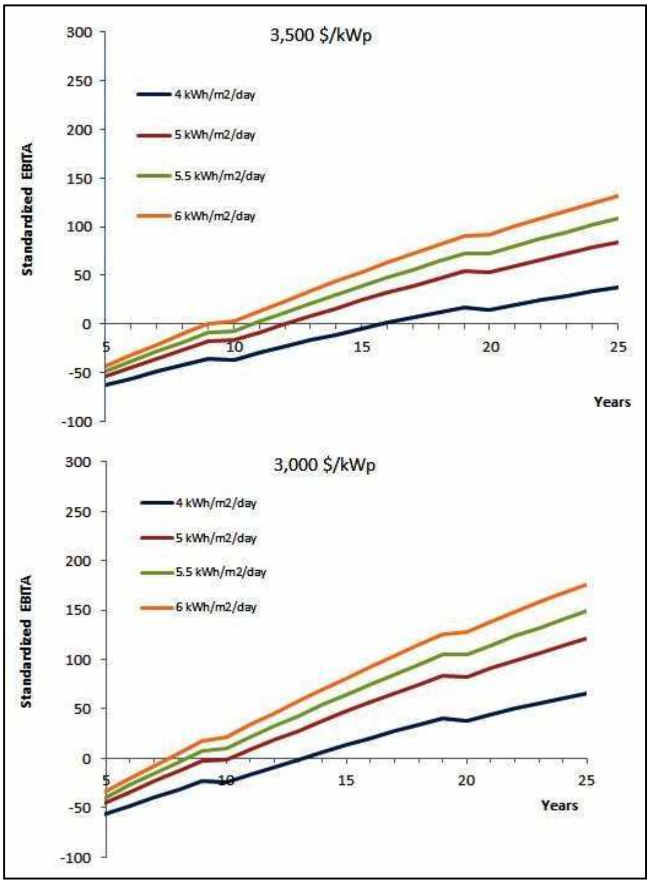

Fig. 8 Financial simulation for the CSE 3,500 and 3,000 US$/kWp.

Meanwhile, for the scenario of lower CSE between 2,000 to 2,500 US$/kWp showed more promising solar PV rooftop-mounted applications for an urban area. With CSE at 2,500 US$/kWp the best expectation of ROI as measured by EBITA, it is 6 years and the longest payback time becomes 11 years with PSH respectively 6 and 4 kWh $m^{-2}$ $day^{-1}$ as shown in Figure 9. In general, the CSE value is expected to be cheaper when technology is massively implemented, especially in the case of solar PV. Therefore, with the most economical CSE value of 2,000 US$/kWp, the ROI time becomes 4 and 8 years concerning the PSH 6 and 4 kWh $m^{-2}day^{-1}$.

The overall simulation from energy yield assessment and financial aspect has demonstrated that the solar PV rooftop has potential application in an urban area in Indonesia. The careful installation is critical in obtaining the best energy from the sun, and therefore the ROI value can be obtained faster, which can be beneficial for the potential customers.

## IV. CONCLUSION

In this study, the energy yield simulation for the solar PV mounted on the rooftop in Jakarta, Indonesia, has been demonstrated. The energy yield decreases with the solar PV inclination from 0° to 45°, and this occurred for all main directions of North, South, West, and East. The financial simulation using $PSH$ at 6 kWh $m^{-2}$ $d^{-1}$ resulted in the payback time can be as low as 4 years, and this can be extended to 7 years of the ROI if the actual PSH is only 5 kWh $m^{-2}$ $day^{-1}$. The simulation has shown the potential of the solar PV system application in Indonesia from economic and technical feasibility studies.

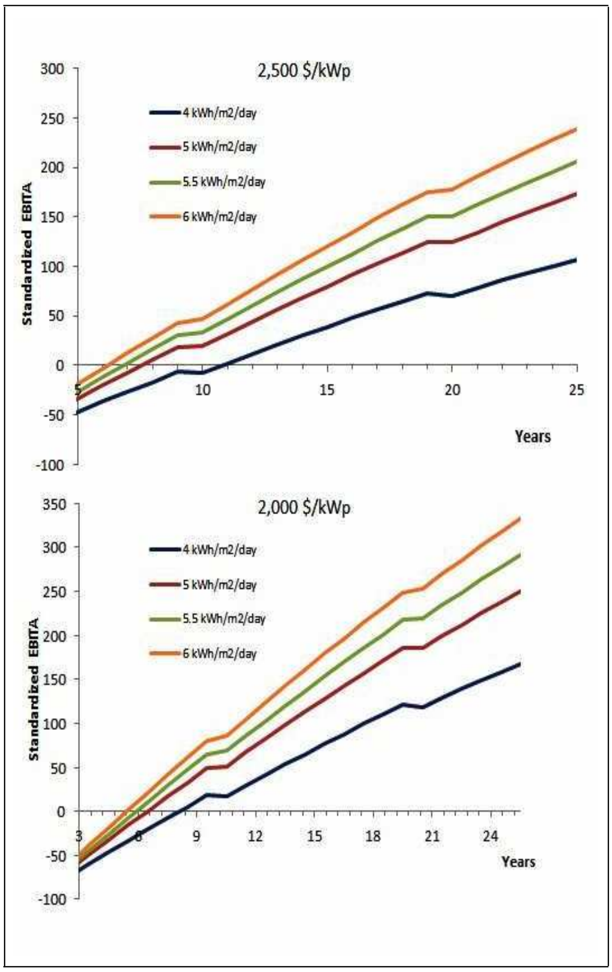

Fig. 9 Financial simulation for the CSE 2,500 and 2,000 US$/kWp.

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