Potential assessment of solar power plant: A case study of a small island in Eastern Indonesia

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Abstract. Indonesia as a tropical country has high solar energy potential to generate power. Solar power plant (SPP) using Photovoltaic (PV) is suitable for power generation in a small power system, such as in several small islands in Eastern Indonesia since solar energy is easy to obtain there. The implementation of SPP for power generation needs an examination of energy yield to observe the performance ratio of SPP. Those parameters are important to study to further analyze the economic potential and feasibility of SPP development. This study estimates the performance ratio (PR) and potential energy yield of SPP in a small island in Eastern Indonesia through a self-developed program using MATLAB based Graphical User Interface (GUI). Moreover, this program also provides the levelized cost of energy (LCOE) calculation and land use optimization by readjusting the PV array configuration. According to the simulation result, the implementation of SPP in Eastern Indonesia has 85.4% and 23.54% for annual PR and capacity factor (CF) respectively. The simulation also shows that the optimum distance between PV strings produces higher annual energy yield and CF.

1. Introduction

Electricity demand in Indonesia is always increasing over the year. According to [1], national electricity demand reached 232,296 TWh in 2018 and has a 5.1% growth per year. Those demands spread through all-region in Indonesia from the capital area in big islands to the area in small islands. However, the total electricity production in 2018 only reaches 220,817 TWh which is still dominated by coal and fossil fuel in the amount of 59.6%. Besides, Indonesia as a tropical country that has many islands has great solar energy potential. For instance, the average solar energy potential in small islands in Eastern Indonesia has reached 2,021 kWh/m² per year [2]. Therefore, implementing Solar Power Plant (SPP) in Indonesia especially in small islands might have a promising result since they are well-radiated. However, the land availability in some small islands is limited, so the implementation of SPP needs to be well-configurated to obtain the optimum result [3].

The study of potential implementation assessment of SPP has been being developed from technical to the economic and environmental points of view. The techno-economy point of view determines the feasibility of SPP development through economic parameters such as Net Present Value (NPV) and Internal Rate of Return (IRR). Fathoni et al [4] and Ray et al [5] mapped different site areas to implement SPP in tropical and subtropical humid climate countries such as Indonesia and Australia based on the highest energy potential [4],[5]. Another similar method is used to assess building areas in Pakistan for small-scale SPP implementation [6]. Besides, the environmental point of view also
becomes consideration to assess the impact of SPP implementation through the gas emission reduction parameter [7],[8].

Further assessment needs to be studied to assess the potential to implement SPP. In addition to assessing the potential energy that can be generated by a SPP, this study also provides recommendations for system configuration that has been adapted to the limited availability of land through a self-developed program using MATLAB based Graphical User Interface (GUI). This proposed program uses 3-component (Hay Model) to model solar energy potential for SPP which according to previous study this model gives a better result than other models such as Perez Model for certain albedo and azimuth condition [9]. Moreover, comparing to another similar program, this program offers area optimization scheme with user-defined initial area and considers module distance which affects energy yield calculation for SPP. In the end, the levelized cost of energy (LCOE) will be calculated as one of the parameters for determining the eligibility of an SPP project. The design and sizing method of the SPP is explained in section 2. The potential appraisal of the SPP is accomplished by comparing the calculation result from the proposed program in section 3 for each sizing scenario. The key performance parameters which need to be compared are performance ratio (PR), energy production, capacity factor (CF), and LCOE. At last, section 4 concludes this research.

2. Design and Sizing of SPP

The feasibility of SPP can be assessed by its energy yield, PR, and LCOE. The assessment is accomplished by simulating SPP through MATLAB based GUI program shown in Figure 1(a).

2.1. Solar Energy Potential of SPP

The calculation of solar energy potential for SPP in this study uses the 3-component model to predict the total energy of solar radiation on an inclined plane [10]. The components are direct beam irradiation ($H_{GB}$), diffuse irradiation ($H_{GD}$), and reflected irradiation ($H_{GR}$). The sum of those three components indicates the total energy incident on an inclined PV plane ($H_{G}$) which is expressed as follows.

$$H_{G} [kWh/m^2] = H_{GB} [kWh/m^2] + H_{GD} [kWh/m^2] + H_{GR} [kWh/m^2]$$ (1)

2.2. Normalized Energy Yield of SPP

The previous result is used as a reference yield of SPP ($Y_{R}$) indicates the sun hours with 1 kW/m²-irradiance under Standard Test Conditions ($G_{0,STC}$) to obtain irradiation energy ($H_{G}$) which is expressed by equation (2). The result is multiplied by the nominal power of PV array to determine
reference electrical energy produced by SPP \( (E_{ref}) \), then divided by nominal power \( (P_{an}) \) to get normalized reference yield \( (Y_R) \).

\[
Y_R[kWh/kWp] = \frac{E_{ref}[kWh]}{P_{an}[kWp]}
\]  

(2)

The result before only shows the energy potential number without any losses, but other factors affect the energy yield of SPP which leads to capture losses and system losses. Capture losses rely on PV cell temperature, module quality, low irradiance, and wiring of PV arrays. SPP energy yield after capture losses is determined by normalized array yield \( (Y_A) \) expressed by equation (3), which depends on PV array energy yield after capture losses \( (E_a) \) and \( P_{an} \).

\[
Y_A[kWh/kWp] = \frac{E_a[kWh]}{P_{an}[kWp]}
\]  

(3)

MPPT and inverter have an efficiency that gives an impact on the energy yield of SPP through system losses. The final energy yield \( (Y_F) \) of SPP which is determined after system losses take into the account, can be expressed as equation (4). From this \( Y_F \), the total energy produced by SPP \( (E_{AC}) \) is determined.

\[
Y_F[kWh/kWp] = \frac{E_{AC}[kWh]}{P_{an}[kWp]}
\]  

(4)

2.3. Performance Ratio (PR) and Capacity Factor (CF)

The performance ratio \( (PR) \) is an important parameter to evaluate SPP’s performance as compared to the ideal scenario. This parameter is comparing normalized final yield \( Y_F \) which is lower than the ideal scenario of normalized reference yield \( Y_R \). Moreover, the capacity factor \( (CF) \) is a parameter that captures the actual energy generated by SPP relative to its nominal power output \( (P_{AC}) \).

2.4. Area Optimization and LCOE

Limited land available is often an obstacle to the installation of SPP. This study also proposes an optimization scheme to overcome this issue by readjusting a new PV array configuration through the distance between the PV strings which depends on the tilt angle, as shown in Figure 1(b). The area needed for SPP installation \( (A) \) is determined by equation (5), while the proposed distance between modules \( (d) \) is determined by equation (6). Besides \( d \), \( A \) also depends on the number of modules in each string \( (m_o) \), module dimension \( (l) \), and the number of PV strings \( (s) \). Equation (6) states that distance between PV strings \( (d_o) \) affects the horizon elevation angle which will impact the diffuse and reflected irradiation component. Consequently, optimizing the module configuration based on area availability will give an impact on total energy produced by SPP, but still maintain SPP nominal power. Finally, LCOE depends on the energy yield of SPP so that the LCOE will change for every adjustment [11].

\[
A \ [m^2] = m_o \times l \ [m] \times (s-1) \times d \ [m]
\]  

(5)

\[
d \ [m] = d_o \ [m] \times (\cos \beta + \sin \beta \ \cot \alpha)
\]  

(6)

3. SPP Potential Assessment

The simulation is done by running a self-developed MATLAB based GUI program. The data such as irradiation data, temperature, PV array, module, and inverter have been the input of the program as shown in Figure 2. This program calculates the energy produced by SPP, PR, CF, the area needed to implement SPP with the determined configuration, and LCOE for each scenario as shown in Figure 3. Two different simulations are being compared. The first simulation is to calculate all parameters when the distances between PV string are varied from 1 to 2 meters. Then, the second simulation is to calculate all parameters when the available area is limited. For each scenario, the potential of SPP is tested by simulating small (50 kWp), medium (500 kWp), and large (5 MWp) scale SPP with specified
monocrystalline PV modules and inverters. The PV array is simulated with 10° inclination angle, 0° azimuths, and ground-mounted configuration. The result parameters in Table 1 are being compared for each scenario to determine the best scenario to implement SPP with the studied area’s potential. Moreover, result parameters of this self-developed program using 3-component irradiance model are being compared to two other models, namely the simplified model [10] and Perez model [12]. According to the previous study, the 3-component model has a better result than other models for certain albedo and azimuth conditions [9]. Besides, from Table 1, it can be observed that the 3-component model considers the distance factor (d) in calculating the irradiance model which in turn affects the calculation results of solar energy potential parameters.

Figure 2. Input GUI MATLAB program

Figure 3. GUI MATLAB program result

3.1. PV Configuration
The proposed configuration for each scale of SPP such as distance between PV strings, number of modules, number of inverters, number of modules in each string, and number of PV strings can be shown in Table 1.

3.2. Annual Energy Yield and CF
For each scale of the proposed program with the 3-component model, the highest annual energy yield and CF are obtained when the distance between PV strings is 2 meters. The annual energy yield result reaches 102.89 MWh/year, 926.04 MWh/year, and 8,745.94 MWh/year for the small, medium, and large scale respectively, while the annual CF for all simulated scales are 23.54%. This value is relatively high when compared to other existing SPP in Indonesia which reaches 18%-20% of CF [13]. One can notice that the more optimum distance between PV strings, the more the annual energy yield is obtained.

3.3. PR and Normalized Energy Yield
The simulation result of the proposed program shows the annual PR for all SPP capacities is 85.4%. PR depends on environmental factors and all electrical components of SPP, all of which are the same
for all simulated PV scales. Through 85.4% PR, the simulation shows that the implementation SPP in Eastern Indonesia has high-performance quality.

The monthly PR is varied based on normalized energy yield i.e. reference yield and final yield in every month. Figure 3 shows the normalized energy yield and losses for the highest result i.e. 2 meters PV string distance scenario. From small scale to large SPP, the performance ratio is relatively low in April – May and September – December. This is because the capture losses in those months are relatively high due to a high temperature of over 28 °C.

Table 1. Simulation results

| Scale [kWp] | Model | d [m] | mo | nmo | Area Needed [m²] | LCOE (+Land cost) [$/kWh] | LCOE [$/kWh] |
|-------------|-------|------|----|-----|-----------------|-----------------------------|-------------|
| 30          | 1     | 168  | 1  | 21  | 8               | 101.86                      | 0.1168      |
| 50          | 1     | 168  | 1  | 21  | 8               | 103.64                      | 0.1195      |
| 100         | 1     | 168  | 1  | 21  | 8               | 105.42                      | 0.1195      |
| 300         | 1     | 168  | 1  | 21  | 8               | 107.18                      | 0.1195      |
| 500         | 1     | 168  | 1  | 21  | 8               | 108.94                      | 0.1195      |
| 1000        | 1     | 168  | 1  | 21  | 8               | 110.70                      | 0.1195      |

3.4. LCOE

The LCOE result in Table 1 shows the comparison of LCOE with or without land cost included into the account. For the proposed program, in case without land cost included, the minimum LCOE is obtained by 2 meters distance scenario for each scale of SPP. Meanwhile, by including the land cost, the minimum LCOE is obtained by a 1-meter distance scenario, since the SPP implementation with the 1-meter distance between PV strings needs minimum area.

3.5. Area Optimization

The area optimization scenario result is shown in Table 2. The GUI MATLAB program gives recommendations of the distance between one PV string to another. The program calculates the distance based on the user-defined initial area. However, the program maintains the nominal power capacity by using the same number of module and inverter. Hence, the program optimizes the limited area while the power capacity is being maintained. The annual energy yield is decreasing by 1.43%, 1.11%, and 1.68% for small, medium, and large scales respectively. In result, the CF is also decreasing by 0.33%, 0.26%, and 0.39%. This happens due to the stack configuration gives a shadow effect for the PV module. When the distances are too close or too far, the direct and reflected component irradiation will be affected and reduced the energy yield of SPP.
### Table 2. Area optimization result

| Scale [kWp] | $E_{ac}$ [MWh] | PR [%] | CF [%] | Available Area [m²] | Configuration | $d$ [m] | mo inv | mo/s | s | LCOE (+Land cost) [$/kWh] | LCOE [$/kWh] |
|-------------|----------------|--------|--------|---------------------|---------------|--------|--------|-------|---|----------------------|-------------|
| 50          | 101.44         | 23.2   |        | 500                 |               | 1.74   | 168    | 1     | 21 | 8                    | 0.12085     | 0.11244    |
| 500         | 915.87         | 85.4   | 23.28  | 5,000               |               | 1.71   | 1,512  | 9     | 21 | 72                   | 0.12139     | 0.11208    |
| 5,000       | 8,600.59       | 23.14  | 50,000 |                     |               | 1.79   | 14,280 | 85    | 21 | 680                  | 0.12264     | 0.11272    |

4. Conclusion

Eastern Indonesia has great potential to implement all scale SPP since the predicted PR and CF show high-performance quality in both simulation scenarios. By varying the distance between PV strings, the annual energy yield and CF are changed as well. In the simulation above, the optimum distance between PV strings results in higher annual energy yield and CF for each simulated SPP capacity. Furthermore, the self-developed MATLAB based GUI program of this study proposed a new configuration of the PV array by adjusting the distance between PV strings according to the limited land available. Eventually, this program calculates the LCOE of the selected SPP configuration. Within area limitation, the medium-scale (500 kWp) SPP has the top result in capacity factor and LCOE. This program is providing some techno economy parameters needed to consider the feasibility of SPP installation where this study simulated a planned SPP in a small island with a limited land area of Eastern Indonesia.

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