Techno-economic analysis of stand-alone PV system: a case study of public street lighting for remote area in Indonesia

T A Ajiwiguna, A Qurthobi
Engineering Physics Department, Telkom University, Jalan Terusan Buah Batu, Bandung, Indonesia

triayodha@telkomuniversity.ac.id

Abstract. Stand-alone Photovoltaic (PV) system is mostly required for the remote areas where the electricity is limited or not available from the grid. This study presents the simplified method to design system and analyse the economic aspect of the stand-alone PV system. The case study of providing electricity for public street lighting using PV system for remote area in Indonesia was conducted. First, the size of PV system was estimated based on the daily electricity consumption and the peak solar hour (PSH) on the site location of the project, so the requirements of the components were obtained. Second, the components selection was performed by surveying the information from the components manufacturers which met with the requirement of the system. Third, economic analysis was performed by considering the capital cost and the final specific energy electric cost. The public street lighting used 80 W lamp and was operated for 12 hours per day. The result showed that the total capital cost for the system was 8,031,400 IDR (551 USD) and the final specific energy cost at 1,960 IDR/kWh (0.13 USD/kWh). The largest portion of capital cost was for the battery as energy storage which took 38% of the total capital cost.

1. Introduction
Due to the decreasing of price and improvement efficiency, solar photovoltaic (PV) has become one the most popular of renewable energy (RE) technology compared with the other system [1]. The flexibility of the size is one of the advantages of solar PV technology so that it can be applied even in residential scale. Some areas in Indonesia suffer from unavailability or limited of electricity such as in small island or remote area. Since the high cost to build the connection grid to those areas, the use of stand-alone PV system is one of the solution for this problem. This system needs battery as energy storage so the electricity can be supplied to the demand in low or unavailable radiation time.

The capacity of PV system must be determined so that the system can meet the demand. On the other hand, the electricity produced by PV module depends on the weather at the site location. Therefore, the method for sizing the capacity of PV system is needed by considering the demand and weather condition. Another important thing for applying PV system is the economic analysis so that it can decide the feasibility of the system. The proper capacity of PV system is important because it will affect the economic point of view which is the most important thing for proposing the project to the investor. Khatib et al. [2] reviewed the methodologies for sizing the PV system. They presented the several methods start from very simple (intuitive) to advanced (artificial intelligence). However, in the very first design step, the estimation of economic aspect is also needed. Therefore, this study presents...
the simplified method for sizing and economic analysis for stand-alone PV system. The case study of providing electricity for public street lighting in one remote area is discussed.

2. Design methodology
The case study of providing public street light in Cisoka Village, west Java, Indonesia was chosen. The main components of the systems were PV modules, inverter and battery. The system was designed for 20 years of lifetime. First step is estimation of the solar insolation at the site location. Second step is calculation of the daily electrical energy required. Third step is the sizing of main components so that the system could satisfy the energy load. Fourth step is the economic analysis to estimate the total capital cost and energy cost.

2.1. Estimation of solar insolation
In this study, the concept of peak sun hours (PSH) was used. PSH is defined as the duration of constant solar irradiation at 1 kW/m$^2$ to produce the same amount of energy in a day [3]. The value of PSH is the same with solar daily solar insolation in kWh/m$^2$ unit. To get the value PSH, the global solar atlas website was used. The site is located at -6.8° latitude and 107.8° longitude. By inputting this coordinate to the website, the daily average value of PSH was obtained to be 4.8 as shown in figure 1.

![Figure 1. Site location of case study and solar insolation data](image)

2.2. Estimation of daily electrical energy consumption
The system used 80 W of LED street light bulb that is operated 12 hours per day from 6 pm to 6 am. The electrical energy required was calculated by using equation 1.

$$E_{day} = P_{light} \cdot D$$

where $E_{day}$ is daily energy consumption, $P_{light}$ is the wattage of the light bulb (W) and $D$ is the daily operation time of the light bulb (h). The daily electrical energy consumption was obtained at 960 Wh.
2.3. Estimation of the sizes of main components

The size of PV modules was estimated by considering the daily insolation data and electrical energy consumption which were obtained from the two previous steps. The rated capacity of PV modules required was calculated by using equation 2.

\[
P_{PV} = \frac{E_{day}}{PSH \cdot PR}
\]  

(2)

where \( P_{PV} \) is the required rated capacity of PV modules and \( PR \) is the performance ratio of the system which includes the total losses of the system and efficiency of battery. The total loss of the system was assumed at 24% from the total solar energy input due to dust, shading, wire loss, array mismatch, etc [4]. The value of \( PR \) was obtained by considering the total loss of system and battery efficiency. The typical battery efficiency was assumed 85% [4]. Then, the value of \( PR \) was calculated by using equation 3.

\[
PR = \eta_{batt} \times (1 - L)
\]  

(3)

where \( \eta_{batt} \) is the battery efficiency and \( L \) is the total loss of the system. The required capacity of PV modules was obtained to be 310 W. Therefore, a PV module with the specification shown in table 1 was used. On the other hand, the minimum required capacity of inverter was based on the rated capacity of PV module.

Table 1. Specification of PV modules

| Parameters     | Value  |
|----------------|--------|
| Power rating   | 330 W  |
| \( V_{oc} \)   | 45.9 V |
| \( I_{sc} \)   | 9.31 A |
| \( V_{mp} \)   | 37.5 V |
| \( I_{mp} \)   | 8.8 A  |
| NOCT           | 45 °C  |
| Temperature Coefficient | -0.41%/°C |

The required battery capacity was estimated so that it can store energy as much as daily energy consumption. For safety, the assumption of two autonomous days was used. Considering the depth of discharge which is assumed 80% [5], the required capacity of battery was calculated by equation 4.

\[
B_{cap} = \frac{AD \times E_{day}}{DoD}
\]  

(4)

where \( B_{cap} \) is the required battery capacity, \( AD \) the number of autonomous days, and \( DoD \) is the depth of discharge of battery. The required battery capacity of the system was obtained to be 2260 Wh.

2.4. Economic analysis

Once the size of each component was calculated, the economic analysis was performed. The main objectives of this step are to estimate the capital cost and the specific energy cost of the system. The former objective is important to give information related to the funding that should be provided at the
beginning of the project. The later one is important to give fair comparison with other energy sources such as grid.

The total capital cost consists of the prices of components and the installation cost which was assumed 30% from the total price of component [6]. Therefore, it was calculated by equation 5.

\[
CC = 1.3 \times (P_{pv} + P_{inv} + P_{Bat})
\]  

(5)

where \(CC, P_{ pv}, P_{ bat}, P_{ inv}\) are total capital cost, total price of PV module, battery unit, and inverter unit respectively.

To estimate the specific energy cost (SEC) of this system, the evaluation was conducted by considering the total annual cost (\(\sum C_{ann}\)) and total annual energy production (\(E_{ann}\)). The SEC was calculated by equation 6.

\[
SEC = \frac{\sum C_{ann}}{E_{ann}}
\]

(6)

The annual inflation rate \((i)\) was also considered to estimate the annual cost for each component [7]. \(C_{ann}\) and \(E_{ann}\) were calculated by using equation 8 and 9 respectively.

\[
C_{ann} = \left(\frac{P_{comp}}{L_T} + C_{omn}\right) \times (1 + i)
\]

(8)

\[
E_{ann} = P_{pv} \times PR \times PSH \times 365
\]

(9)

where \(P_{comp}\) is the price of component, \(L_T\) is the life time of component, \(C_{omn}\) is the operational and maintenance cost component, and \(i\) is the annual inflation rate. The assumptions in this study were summarized in the table 2.

| Parameters                  | Assumption                  |
|-----------------------------|-----------------------------|
| Lifetime of PV module       | 25 years                    |
| Lifetime of inverter        | 10 years                    |
| Lifetime of battery         | 7 years                     |
| Operational and maintenance cost | 185,000 IDR/kW/year (12.6 USD/kW/year) |
| O&M cost of Battery         | 2% of price                 |
| O&M cost of Battery         | 1% of price                 |
| Installation cost           | 30% from total price        |
| Inflation rate per year     | 7%                          |

Table 3 shows the result of economic analysis. The total capital cost was obtained at 8,031,400 IDR (551 USD). The specific energy was obtained to be 2,055 IDR/kWh (0.14 USD/kWh). Based on these results, the capital cost is relatively cheap comparing with building the connection grid to the site location. However, the energy cost is higher than using grid. The portion of capital cost was dominated by battery system (38%) and followed by the PV module (34%). The disadvantages of battery are the price is expensive and its lifetime is relatively short compared with other component.
Table 3. Result of economic analysis

| System part   | Price (IDR) | Life time | Annual On M Cost (IDR) | Annual cost (IDR) |
|---------------|-------------|-----------|------------------------|-------------------|
| PV module     | 2,750,000   | 25        | 61,050                 | 184,734           |
| Battery       | 3,078,000   | 7         | 61,560                 | 541,376           |
| Inverter      | 350,000     | 10        | 3,500                  | 41,580            |
| Installation cost | 1,853,400 | -         |                        |                   |
| **Total capital cost** | **8,031,400** |           |                        | **767,690** |

3. Conclusion
In this study, the simplified method to for sizing the stand alone PV system and its economic analysis was presented. This method is very helpful to give estimation for feasibility of the project. The case study of providing energy source for public street light was discussed. The system is projected for 20 years of lifetime. The results show that the total capital cost was 551 USD for one unit of public street light system using 80 W of light bulb. The specific energy cost was obtained at 0.14 USD/kWh

References
[1] Parida B, Iniyan S, Goic R 2011 A review of solar photovoltaic technologies Renewable and Sustainable Energy Reviews 15 1625–1636
[2] Khatib T, Ibrahim IA, Mohamed A 2016 A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system Energy Conversion and Management 120 430–448
[3] Markvart T and Castaner L 2003 Practical Handbook of Photovoltaics Fundamentals and Applications Elsevier
[4] Ekici S, Kopru MA 2017 Investigation of PV System Cable Losses International Journal of Renewable Energy Research 7 807-815
[5] Hlal MI, Ramachandaramurthy VK, Sarhan A, Pouryekta A, Subramaniam U 2019 Optimum battery depth of discharge for off-grid solar PV/battery system Journal of Energy Storage 26 100999
[6] Bakos GC and Soursos M 2002 Techno-economic assessment of a stand-alone PV/hybrid installation for low-cost electrification of a tourist resort in Greece Applied Energy 73 183–193
[7] Mohamed ES and Papadakis G 2004 Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics Desalination 164 87-97