Jurnal Sosial dan Teknologi (SOSTECH)
Volume 4, Number 7, *Juli* 2024
p-ISSN **2774-5147** ; e-ISSN **2774-5155**

Design and Implementation of Self-Cleaning Coated Rooftop Photovoltaic System Supporting Energy Conservation in Small-Medium Enterprises

Ruri Agung Wahyuono[*1], Miga Magenika Julian[2]
[1] Institut Teknologi Sepuluh Nopember, Jalan Arif Rahman Hakim, 60111, Surabaya, Indonesia
[2]Hydrography Research Group, Institut Teknologi Bandung, Jl. Ganesha No. 10, 40123 Bandung, Indonesia
[*]e-mail: wahyuono@its.ac.id

Abstract

The implementation of rooftop solar power system for SMEs is one step to provide an examplified pilot project so that the clean energy transition in the economic sector can also be realized. However, difficult operations and maintenance for rooftop solar power plant require a self-cleaning coating design to passively clean the surface of the solar cell module and hence, the performance of rooftop solar power system is maintained. In this research, the design of a rooftop solar power system utilizes global climate data, i.e., air temperature data and duration of sunlight. Long-term trends in solar radiation levels were analyzed using the Mann-Kendall test and Sen's slope analysis to assess the long-term solar energy potential. The self-cleaning layer utilized a mixture of ZnO/TiO$_2$ (1:1) dispersed in water/ethanol (7:3). The results of implementing the solar energy system for food-based SMEs in Indramayu showed a positive response. Solar energy supply from rooftop solar power system with the application of ZnO/TiO$_2$ self-cleaning coating can save energy usage by up to 30% of the monthly electricity costs charged for MSME operations and domestic needs. The ZnO/TiO$_2$ self-cleaning layer is found to be able to maintain rooftop solar power system performance of up to 85% during 9 months of observation.

Keywords: Energy conservation, ZnO/TiO$_2$, Self cleaning, Rooftop solar power system

INTRODUCTION

Currently, clean, renewable energy has become a global issue following the emergence of the fossil energy crisis. Indonesia's abundant natural resource potential provides reserves of renewable energy potential that need to be explored and exploited (Wahyuono & Julian, 2018); (Pusdatin, 2014). According to Pusdatin (2014) Indonesia is able to develop clean energy sources such as hydropower (75,000 MW), geothermal (29,164 MW), biomass (49,810 MW), marine (46 GW), solar (4.80 kWh·m^{-2}·day^{-1}), and wind energy (3 - 6 m·s^{-1}). The level of energy consumption in Indonesia has averaged around 7% in the last decade, while the level of energy supply is limited. Indonesia relies heavily on fossil fuels, i.e., petroleum which dominates 50% of the primary energy mix, followed by coal at 32%, gas at 19%, geothermal at 1.3%, hydro at 2.9% and the remainder is supplied by other renewable energy sources (Pusdatin, 2014). Apart from that, the high growth in fossil energy consumption will cause environmental problems, especially high CO_2 emissions which cause global warming.

The large potential for renewable energy is not in line with the slow diffusion of the application of renewable energy technology in Indonesia due to the lack of insight into the potential for clean, sustainable energy. In fact, particularly solar energy, the application of a solar energy system (photovoltaic–PV), for example a grid-connected system and/or off-grid, can be an alternative solution for providing sources. clean and sustainable energy (Tarigan & Kartikasari, 2015); (Reinders et al., 2011). In general, PV-based solar energy systems are widely used to provide domestic electricity including Small and Medium Enterprises (SMEs) or household businesses. Due to COVID-19 pandemic that has hit Indonesia since early March 2020, it has certainly had an impact on SME

e-ISSN 2774-5155
p-ISSN 2774-5147

activities. It is estimated that around 87.5% of SMEs have been significantly affected by the COVID-19 pandemic (Victoria, 2021), so that many SMEs have switched transactions to digital market platforms. Since the majority of SMEs in Indonesia are food- and textile-based business, the economic burden on SMEs roots from the production costs and the human resources that must be met for the sustainability of SMEs are becoming increasingly difficult as the number of requests tends to decrease significantly. As an example, a total of 43,475 SMEs in Indramayu were significantly affected in the midst of the COVID-19 pandemic, of which only 15,834 SMEs received assistance from the Central Government.

In this work, the implementation of a solar power system has been proposed as an alternative solution to reduce production costs for a SME as an effort to recover the economy affected by the pandemic. In particular, the SME in Indramayu, which is partner in this study, is engaged in the production of snacks. As the owner of the SME has no background in solar power system, operation and maintenance limits both technology and knowledge transfer. One of few options for improving the solar power system performance while reducing the maintenance activities is the implementation of self-cleaning coating. This self-cleaning coating could be made from photocatalytic active materials such as TiO_2 and ZnO removing dust and organic compounds deposited on the solar cell surface that are activated by solar irradiation, rainfall, and wind. The work at hand presents the design and installation of a 1 kWp rooftop solar power system for a SME in Indramayu with an improved and maintained system performance utilizing ZnO/TiO_2 self-cleaning coating.

METHOD

Climate data where the solar panels were installed was obtained from the Indramayu Meteorological Station (-6.327518° Latitude; 108.334695° Longitude) which is located 5 m above sea level. This station is located 5 km from UKM and is operated by the Indonesian Meteorology, Climatology and Geophysics Agency. To estimate the daily output of solar energy, sunlight duration data is used from 1975 to 2020. Estimation of daily solar radiation (Rs) uses data on the duration of sunlight. Details of the estimation procedure have been published (Ismail et al., 2019) and the calculation of Rs is reproduced as follows. First, R_s is estimated using two local Angstrm coefficients (a and b) (Angstrom, 1924); (Kermani et al., 2021):

$$R_s = \left(a + b\frac{S}{S_0}\right) R_a$$

where S is the actual sunlight hours, and R_a is the extra-terrestrial radiation. Here, *a* and *b* are adjusted to 0.25 and 0.75 respectively. S_0 is the maximum possible sunshine hours (0.133ω), where is the sunset hour angle at a given geographic latitude (φ) and declination (δ). The hour angle and declination are calculated as follows:

$$\omega = cos^{-1}(-1 \cdot tan\,\varphi \cdot tan\,\delta)$$

$$\delta = 23.45 \cdot sin\left[\frac{360}{365} \cdot (n + 284)\right]$$

where n is the number of days in one year while extraterrestrial radiation (R_a) is calculated as follows (Z. Sen, 2008):

$$Ra = \frac{24}{\pi} \cdot I_{SC} \cdot \left(1 + 0.033 \cdot cos\frac{360n}{365}\right) \cdot \left(cos\,\varphi \cdot cos\,\varphi \cdot sin\,\omega + \frac{\pi}{180} \cdot \omega \cdot sin\,\varphi \cdot sin\,\delta\right)$$

where Isc is the solar constant, 1367 Wm^{-2}.

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p-ISSN 2774-5147

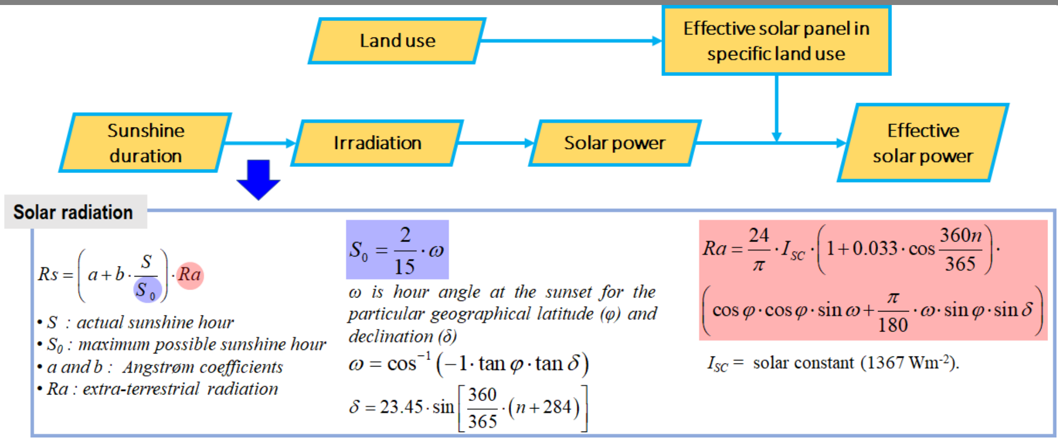

Figure 1. Stages in estimating solar energy potential from exposure duration and air temperature.

The Mann-Kendall and Sen's slope tests examine long-term solar energy output. Sen's method is used to estimate trends in climate time series data (P. K. Sen, 1968). Then, the Mann-Kendall method evaluates the significance of the increasing or decreasing trend of the Sen gradient (Mann, 1945); (Kendall, 1948); (Zar, 2014). The off-grid rooftop solar power system was modeled and simulated using PVsyst 7.2. The output of this modeling and simulation is the annual energy yield and designed PV performance. The main components used in the designed rooftop solar PV system are shown in the wiring diagram (Figure 2). The system includes PV modules, inverters, fuse boxes, MCBs, batteries, and grid lines.

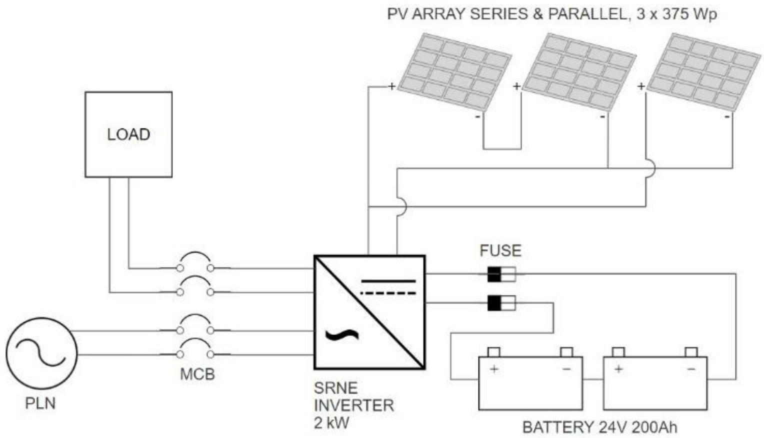

Figure 2. Wiring diagram for the solar power system installed at SME in Indramayu.

In PVsyst simulation, there are several input variables including meteorological data, incident radiation on the collector field, incident energy factor, PV array (field) behavior, inverter losses, system operating conditions, energy use, efficiency, and normalized performance index (Rahardjo & Fitriana, 2005); (Winardi et al., 2019); (Afif & Martin, 2022); (Kermani et al., 2021).The simulation parameters were set as follows: the location of the simulated PV system is located, as mentioned before, at -6.327518 °S (latitude) and 108.334695 °E (longitude). The tilt angle, at which the solar panels were installed facing the sunlight, was set at 12°. The azimuth angle, which indicates the direction of the sun's rays, was set to 110°. The PV module used in the simulation was Si-poly (Model MPE 375 MP 0, manufactured by Schueco) with a maximum peak power output of 375 W. The inverter was based on the model SR-HF2420S60-100 manufactured by SRNE with an operating voltage of 22 V DC and the unit normal power 2 kW AC. Based on field surveys, SMEs require up to 5.62 kWh of electrical power.

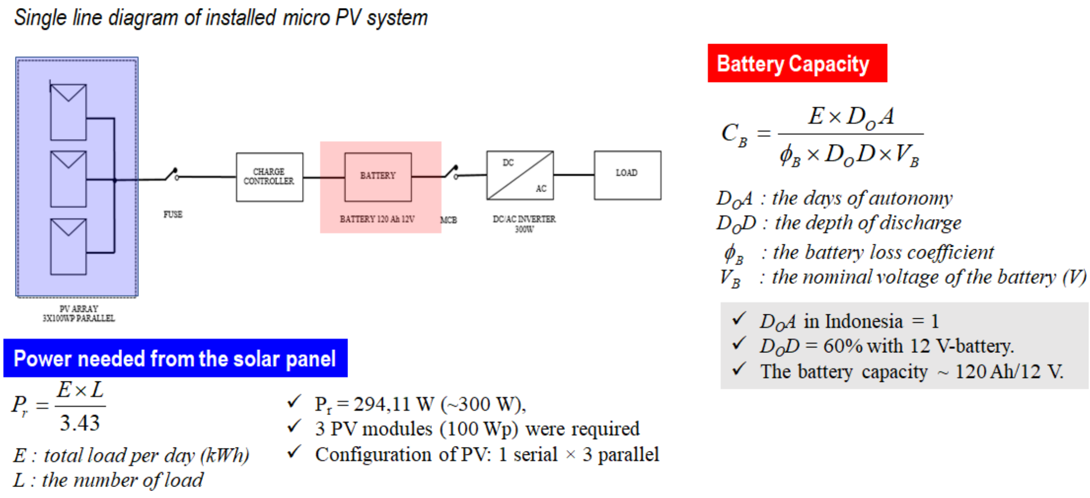

Figure 3. Schematic of off-grid rooftop solar power system components.

The power required from the solar panels (Pr) for this system was calculated as follows:

$$P_r = \frac{E \times L}{3.43}$$

where E is the total load per day (kWh), and L is the total load. Therefore, Pr is 6.55 kWh, and three PV modules (375 Wp) were required. The PV array configuration was 1 serial × 3 parallel keeping the system voltage identical (see Figure 3). Since the PV array has been determined, the battery capacity (CB in Ah/V) is estimated as follows:

$$C_B = \frac{E \times D_O A}{\phi_B \times D_O D \times V_B}$$

where DOA is the days of autonomy, DOD is the depth of discharge, ϕ_B is the battery loss coefficient, and V_B is the nominal voltage of the battery (V). DOA in Indonesia was set 1. Battery DOD was set at 60% with a 24 V battery. Therefore, the required battery capacity was around 200 Ah/24 V. When the solar power syste, has been installed, a one-day evaluation was carried out on the system.

For self-cleaning coating, a mixture of ZnO and TiO_2 nanoparticles was prepared. The ZnO and TiO_2 nanoparticles were purchased from Merck (Germany). A composite of ZnO/TiO_2 with a weight ratio of 1:1 was mechanically grounded. The resulting nanocomposite was dissolved into a mixture solvent compossed of water and ethanol with a ratio of 7:3. The solution of ZnO/TiO_2 nanocomposite was then ultrasonicated for 30 minutes and stored before application to the solar cell panel surface.

RESULTS AND DISCUSSION

Long-term historical solar radiation data from 1978 to 2020 is used to estimate solar energy potential at UKM locations in Indramayu (Figure 4a). The annual average daily sunshine duration was found to be 5.35 hours, where the average daily sunshine duration was found to be 4.37 and 6.31 hours/day for the rainy and dry seasons, respectively. The longest duration of sunlight occurs in August, namely 6.89 hours/day. Assuming there are no meteorological disturbances, the highest duration of sunlight occurs between 11.99 and 12.00 hours/day in the rainy and dry seasons. During the observation period, the effective solar radiation duration was only 47.5% of the maximum possible solar radiation duration. The estimated irradiance obtained from the duration of sunlight ranges from 2.6 – 6.9 kWh/m²/day, with an average of 5.4 kWh/m²/day. This amount is comparable to the average solar radiation in Indonesia of 4.8 kWh/m²/day [17]. Seasonally, the estimated irradiance during the rainy and dry seasons is 4.53 kWh/m²/day and 6.33 kWh/m²/day respectively.

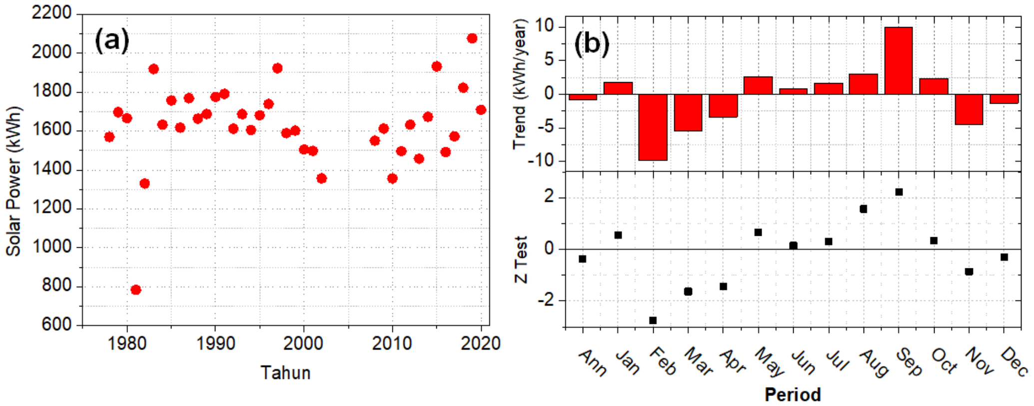

Figure 4. (a) Statistical data on annual solar energy potential in Indramayu, and (b) monthly solar irradiation trends.

It has been shown that solar irradiance can be estimated using sunshine duration dates. Trends in solar irradiance profiles derived from long-term historical climatological data are presented in Figure 4(b) and spatial maps of daily and annual direct normal irradiation (DNI) derived from long-term climatological data are presented in Figure 5. As discussed previously, differences the average solar radiation between the dry season and the rainy season is not significant. This shows the potential for solar energy which is quite constant throughout the year in the study area. On a monthly basis, the variability of solar radiation is greater during the rainy season, namely in December, January and April. During the rainy season, variability in cloudy and rainy days can occur locally and on a short-term daily basis. In general, the long-term annual irradiance according to the Mann-Kendall and Sen slope analysis (summarized in Figure 4b) does not show a significant trend. However, positive and negative trends were found in Jan, May, Jun, Jul, Aug, Sept, Oct, and Feb, Mar, Apr, Nov, Dec. This shows that solar power systems in periods with positive trends should be operated in optimal conditions for long-term use. The climate-induced potential of solar energy is strategically beneficial for MSME production activities, for example, electricity for lighting, frying and cooling devices.

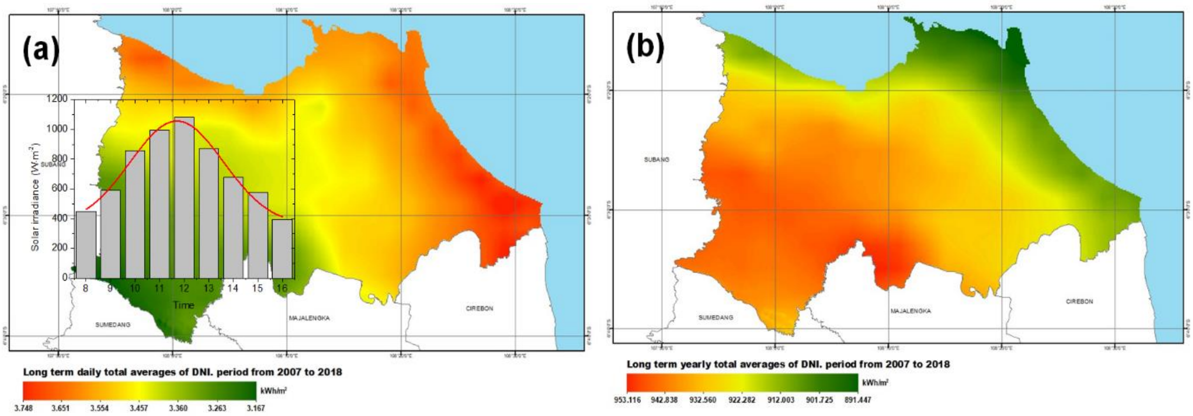

Figure 5. Spatial distribution of total average direct normal irradiation, Direct Normal Irradiation DNI, (a) daily and (b) yearly from 2008-2017 data. The inset image shows the daily average irradiation profile at the SME location.

The results of the solar power system installation on the roof of the SME building are shown in Figure 6. In accordance with the wiring diagram, the solar power system consists of 3 PV panels with a capacity of 350 Wp each. In this study, selected areas around SMEs are proposed that have the

e-ISSN 2774-5155
p-ISSN 2774-5147

potential to install solar power systems. In total, 94 m^2 of area including roofs and unused fields can be utilized for the installation of solar power systems. The solar power design is optimized by considering the grid structure (serial × parallel connection of PV modules), PV module installation tilt angle, and operating temperature. Using estimated monthly irradiation data, a solar power system occupying the proposed area can generate a total of up to 12.6 MWh/year of electricity from 3 solar panels with different off-grid structures.

Figure 6. PV panels installed on the roof of SME's house and an electrical system that has been installed in a room dedicated to solar power system.

The PVsyst simulation results are divided into three main parameters: The total amount of energy produced by the photovoltaic system each year, the specific annual production per installed kWp, and the average annual performance ratio (Q). An example of the balance and main results of a PV system is shown in Table 1, which contains several variables: global irradiance in the horizontal plane, average ambient temperature, effective global irradiance taking into account dirt/impurity losses and shade losses, energy put into network by considering losses in electrical components, availability of photovoltaic energy and system efficiency. These variables are presented in the form of monthly and annual values. The annual global irradiance in the horizontal plane (GlobHorr) is 1351.7 kWh·m^{-2} and the effective global irradiance after optical loss (GlobEff) is 1330.7 kWh·m^{-2}. The annual DC energy generated from the PV array and the annual AC energy that can be fed into the grid is 12.6 MWh.

Tabel 1. Neraca dan hasil utama simulasi PVsyst untuk SHS di Indramayu

Month	GlobHorr kWh/m²	T Amb (°C)	GlobInc kWh/m²	GlobEff kWh/m2	E_Avail kWh	E_Unused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac
JAN	78.0	30	108.8	69.1	60.7	0	34.24	59.50	93.74	0.635
FEB	66.8	29	107.7	60.1	52.7	0	33.41	51.27	84.67	0.605
MAR	105.4	30	137.8	99.3	86.8	5.45	13.22	80.53	93.74	0.859
APR	104.8	31	150.7	104.0	90.6	3.41	7.19	83.53	90.72	0.921
MAY	121.5	32	171.4	127.7	112.2	16.02	6.35	87.40	93.74	0.932
JUN	122.8	32	163.2	133.4	117.5	20.07	0	90.72	90.72	1
JUL	140.6	32	167.9	153.5	134.7	36.64	0	93.74	93.74	1
AUG	159	34	165.9	166.7	145.2	47.51	0	93.74	93.74	1
SEP	154.8	35	159.1	151.4	131.4	36.75	0	90.72	90.72	1
OCT	125.5	35	147.2	114.3	99.4	2.67	0	93.74	93.74	1
NOV	95.1	33	123.6	84.1	74.2	1.39	14.12	76.60	90.72	0.844
DEC	77.4	31	109.2	67.2	58.3	0	37.10	56.64	93.74	0.604
YEAR	1351.7	32.0	1712.3	1330.7	1163.7	169.93	13.47	958.15	1103.76	0.868

e-ISSN 2774-5155
p-ISSN 2774-5147

Legends: GlobHorr (Horizontal global irradiation), T Amb (Ambient Temperature), GlobInc (Global Incident in coll. Plane), GlobEff (Effective Global, corr. For IAM and shading), EAvail (Available solar energy at the output of the PV array), E_Unused (Unused energy(battery full)), E Miss (Missing energy), E User (Energy supplied to the user), E Load (Energy need of the user(load)), SolFrac (Solar fraction (E Used/E Load)).

The PVsyst simulation results are divided into three main parameters: The total amount of energy produced by the photovoltaic system each year, the specific annual production per installed kWp, and the average annual performance ratio (Q). An example of the balance and main results of a PV system is shown in Table 1, which contains several variables: global irradiance in the horizontal plane, average ambient temperature, effective global irradiance taking into account dirt/impurity losses and shade losses, energy put into network by considering losses in electrical components, availability of photovoltaic energy and system efficiency. These variables are presented in the form of monthly and annual values. The annual global irradiance in the horizontal plane (GlobHorr) is 1351.7 kWh·m^{-2} and the effective global irradiance after optical loss (GlobEff) is 1330.7 kWh·m^{-2}. Figure 7 depicts that the annual DC energy generated from the PV array and the annual AC energy which can be transferred into the grid is 12.6 MWh.

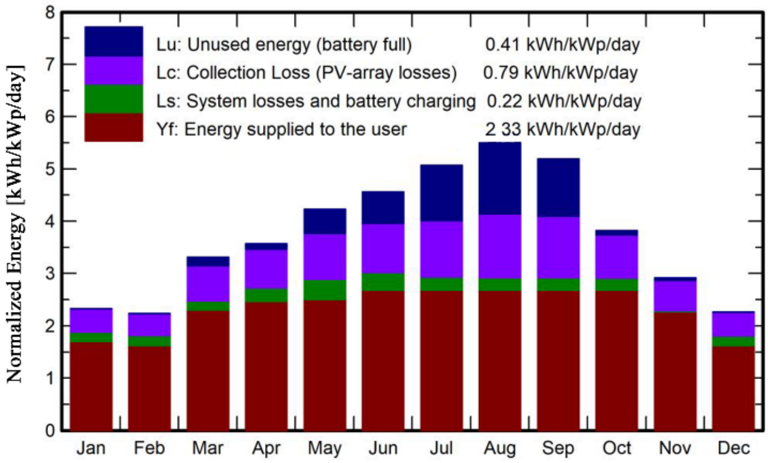

Figure 7. Normalized energy production in SHS installed at Indramayu SMEs.

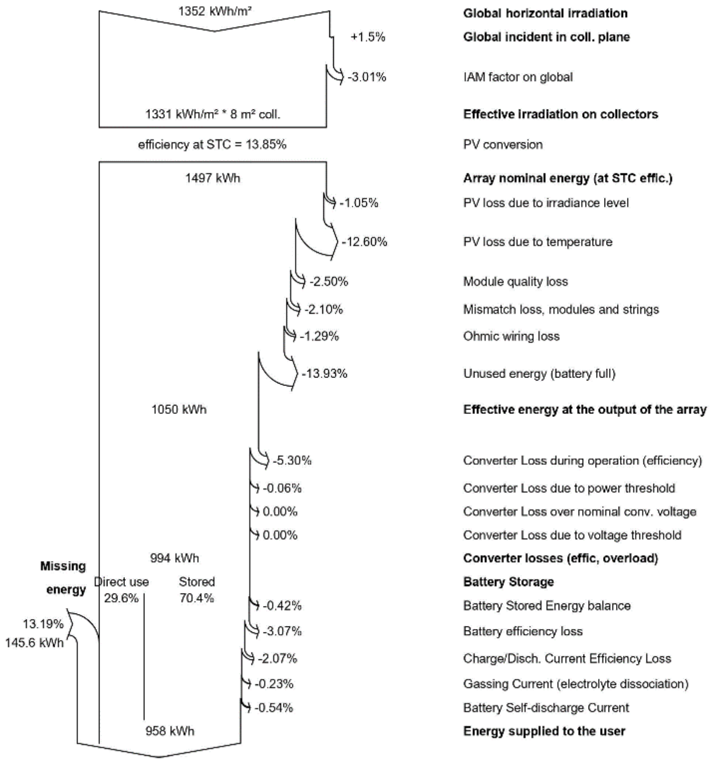

Figure 8. Sankey diagram of losses on the off-grid solar power system installed at SME in Indramayu.

Important variables for evaluating PV system performance include: Collection losses (L_c 0.79 kWh/kWp/day), system losses (L_s 0.22 kWh/kWp/day), and useful energy (Y_f 2.33 kWh /kWp/day). Simulation results in performance ratio (quality factor) > 70%. This ratio shows the ratio between the AC current inverter output and the DC current PV output. A higher quality factor reflects higher useful generated current and higher power conversion efficiency (Reinders et al., 2011). Additionally, the resulting useful energy profile resembles the solar irradiance estimates discussed previously, where peak performance occurs between July and September. Meanwhile, energy losses come from collection losses and system losses which are relatively constant throughout one year. The detailed energy loss channels in the designed rooftop solar PV system are depicted in the Sankey diagram (Figure 8). The Sankey loss diagram reveals various losses that must be considered as constraints when optimizing system design. For example, for the analysis of energy loss at an SME site, the annual global radiation on the horizontal plane is 1352 $kWh{\cdot}m^{-2}$, while the effective radiation on the collector is found 1331 $kWh{\cdot}m^{-2}$. This means that energy loss of up to 3.01% is caused by the level of illumination.

After irradiation, the PV array converts solar irradiation into electrical energy, where the nominal energy of the array at standard test conditions (STC) is 12.6 MWh (PV array efficiency at STC is 13.85%). Meanwhile, the annual array of virtual energy at the maximum power point is 11.5 MWh. It is also worth noting that some channel losses under STC are observed: 12.6% loss due to temperature, 2.5% loss due to module layout mismatch, 1.05% loss due to light-induced degradation, and 1.29% Ohmic loss. The annual energy available from the inverter is 11.5 MWh. One loss mechanism is found due to inverter losses during inverter operation which is up to 5.3%. In general, the highest losses are found to be due to operating temperature. It is generally known for the use of crystalline silicon-based PV that power conversion efficiency drops significantly at operating temperatures above 50 ^{o}C.

e-ISSN 2774-5155
p-ISSN 2774-5147

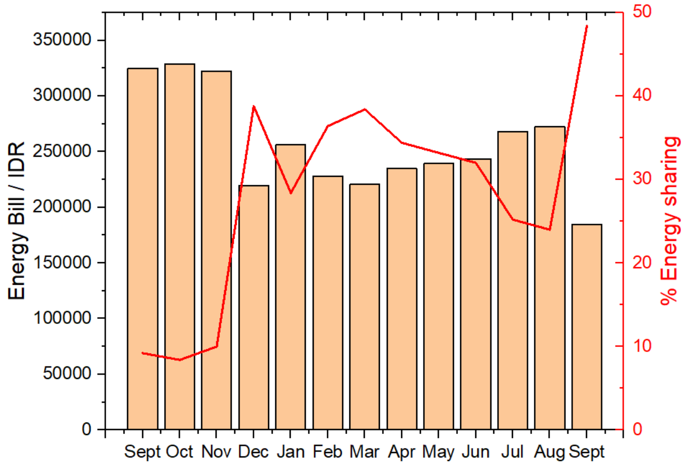

Figure 9. Electricity bill of SME in Indramayu tends to decrease while benefitting additional energy from rooftop solar power system and the percentage of energy sharing from the solar power system.

The effect of self-cleaning coating on the performance of the installed rooftop solar power system can be deduced from billing of energy for the SME in Indramayu and the % energy sharing as shown in Figure 9. The first three months exhibit the baseline energy billing for typical electricity utilization while the following nine months show the energy saving after installation of rooftop solar power system. The almost unchanged energy sharing percentage during the implementation of self-cleaning coated solar power systems indicates that ZnO/TiO_2 coating on the solar cell surface works throughout the year (dry and wet season). Despite almost 85% maintained power generation, self-cleaning coating based on ZnO/TiO_2 needs to be further optimized.

CONCLUSION

An off-grid solar power system with a capacity of 1050 Wp for SME production has been designed and implemented. Long-term observed sunlight duration data is very important to obtain solar energy potential for designing systems. In the case of solar radiation model calculations derived from sunlight duration data, observed solar radiation is very necessary to assess model performance. The observed solar radiation must be in various locations, especially at latitudes where the higher the latitude, the higher the sunlight. The results of implementing the solar energy system at SME in Indramayu showed a positive response. The supply of solar energy from solar power system can save energy usage by up to 30% of the monthly electricity costs charged for SME operations and domestic needs. The application of self-cleaning coating enables 85% stable electricity generation during both dry and wet season.

e-ISSN 2774-5155
p-ISSN 2774-5147

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