Reliability and performance analysis of a mini solar home system installed in Indonesian household

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ABSTRACT

During the COVID-19 pandemic since early 2020 in Indonesia, the demand for electrical energy in the housing sector has increased significantly. This is due to the government’s recommendation to reduce activities on the outside and work from home, specifically for educational and entertainment activities. Those are almost recommended to be done online. Many people complain about the increase in monthly electricity payments compared to before the pandemic. The construction of solar power plants in housing/solar home systems (SHS) will reduce the electricity consumption from the public grid. This SHS installation can be used to supply some household electricity needs, such as computers, televisions, internet facilities, lighting, et cetera. In this article, the researchers discuss the performance testing of SHS with a capacity of 300 Wp. It is installed in the house buildings accompanied by the design and measurement of solar energy potential.

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1. INTRODUCTION

Solar power generation systems have been applied to various locations that require a supply of electrical energy apart from the public electricity grid. In Indonesia, solar power plants mostly use photovoltaic technology. This technology uses silicon wafers to convert solar energy into electrical ones [1]-[6]. The application of solar power generation systems is very diverse, such as centralized generation, distributed generation, solar home system (SHS) [7]-[10], solar water pump system [11]-[14], public street lighting [15]-[17] and also solar-powered electric vehicles [18].

The SHS is usually used to reduce electrical energy consumption from the public grid with a smart-grid topology [19]. This application allows solar power generation systems to increase the availability of electricity for the users [20]. The demand for building SHS in the housing sector in Indonesia is also increasing. It is related to the government’s policy of buying and selling electricity with the state electricity company (PLN). Apart from being a backup power source, this system is also useful for reducing electricity bills for the public grid. In designing this system, it is always necessary to use the right calculation method so that the solar power plant system built can operate optimally. The conducted calculations must also consider the topology of the installation location and the specifications of the solar power generation system.

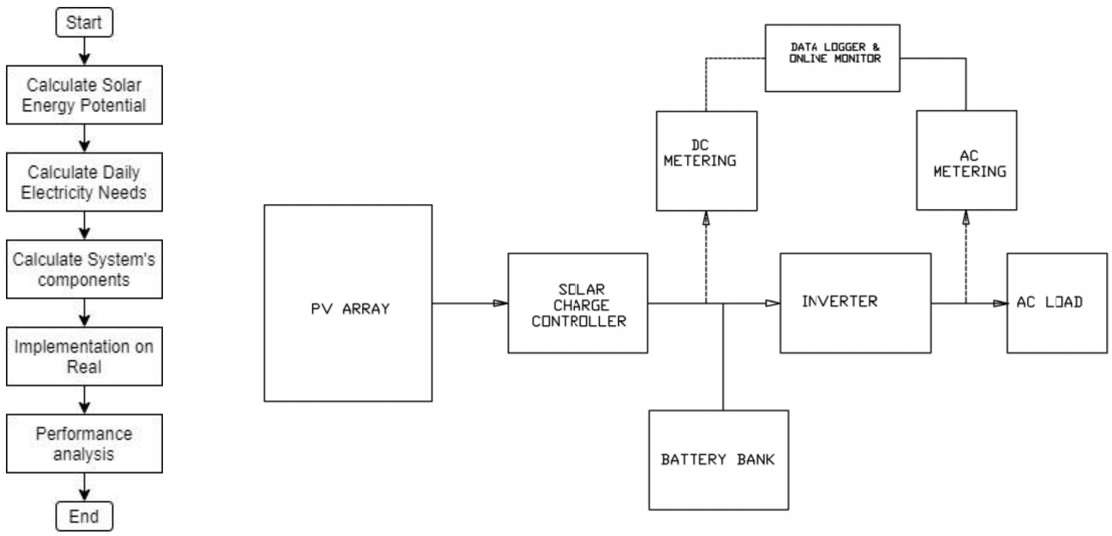
Several studies related to the method of calculating the SHS design have been done. One of them is the research conducted by the researchers in designing a solar water pump system for the residential sector [21]. Another research was also conducted by Diantari and Pujotomo [22], in designing a solar power system with a capacity of 5 kW. Furthermore, Khin *et al*. [23], estimated solar radiation and optimal tilt angle in a photovoltaic system in a college building. About the software, Paluch *et al*. [24], design a sizing tool for solar photovolatic system. Beside that, Bukvina *et al*. [25] has developed a software used to calculate the potential for solar radiation and based on location coordinates.

2. RESEARCH METHOD

The method of this study is to determine the performance of the SHS installed in the housing with an adjustable capacity. The SHS is designed to have an off-grid or stand-alone topology without a connection to the public electricity network. The electrical connection from SHS is only for certain electrical loads that are separate from the electrical ones, which are connected to the public electricity network.

The research method is shown in Figure 1(a) begins with the calculation of the potential for solar energy in Indonesia with a case study of Surabaya city. The solar energy potential data is secondary data obtained from RETScreen. The second stage is calculating the need for electrical energy per day for 24 hours, day and night. The third one is the calculation of the number and specifications of each system component. Finally, the last one measures the system performance based on the results of direct measurements in the field with an adjusting electrical load.

Figure 1(b) shows a block diagram of an SHS, consisting of the system's main components. Photovoltaic solar panels are generating units that are used to harvest solar energy into electrical ones. The solar charge controller (SCC) is used to optimize energy harvest from solar panels with the maximum power point tracking (MPPT) feature. Part of the storage unit used a VRLA battery. Inverters are used to convert direct current (DC) electricity into alternating current (AC) electricity. Hence, they can be used to supply electrical loads. As an additional component, SHS also has a pair of miniature circuit breakers (MCB) mounted on both the DC and AC sides. In addition, there are monitoring devices and dataloggers for monitoring system parameters.



(a) (b)

Figure 1. Design of research method (a) SHS design workflow and (b) SHS block diagram

2.1. Solar energy potential

Surabaya is located at the coordinates of 07°09'00"-07°21'00" south latitude and 112°36'-112°54' east longitude. In this study, the value of direct normal insolation (DNI) was obtained by direct measurement in the field using a solar power meter. The determination of DNI is the lowest solar insolation value during peak sun hours (PSH). The PSH is a parameter to express the ratio of the maximum solar radiation duration (in hours) per day to the standard solar radiation intensity, which is 1 kW/m^2. The PSH start from the time when the intensity is raising to more than 60% of the highest intensity and ends when the intensity is lower than 60% of the highest intensity of that day. According to [26], the value of PSH in Indonesia is 4-5 hours. In this study, the determination of the PSH value is seen from the insolation graph resulting from the measurement of the sunlight power. PSH starts and ends when the solar insolation reaches a point above 60% or about 600 W/m^2.

By taking the minimum value of DNI, it is hoped that the SHS system can work optimally even in the worst conditions. Furthermore, the analysis of the demand for electrical energy harvested by the solar panels is obtained from the amount of energy consumed by the load every day. Therefore, the DNI value can be used as a reference for the estimated output power generated by the solar panels in the array when installed on-site.

2.2. Daily electricity needs

The total need for electrical energy used in several buildings in a day can be calculated by (1).

$$E_{total} = \sum n \ x \ t \quad (1)$$

where E_{total} of the electrical energy total amount needed for each electrical device per day, *n* is the number of each electrical device that has been used per day. *t* is the time of use of each device per day.

2.3. System specification

The first thing calculated from the SHS component is the number and specifications of the solar panels. This calculation involves the PSH value. Then, with the total electrical energy consumption that has been calculated, the total capacity required for P_pv array PV panels can be calculated in (2).

$$P_{pv\_com} = \frac{E_{total}}{PSH \ x \ P_{minimum\_DNI}} \quad (2)$$

With the solar panel capacity expressed in P_{pv_com}, it will be possible to design series and parallel connection configurations in the solar panel array. The number and type of connections are used as a reference to determine the operating voltage and current in the generating unit. Afterward, the SHS design also considers the electrical losses that occur in each component of the system, which in this study is 6.5%. By considering the formula, the calculation in (3).

$$P_{pv\_total} = \frac{P_{pv\_com}}{(100\% - Loss_{Total}\%)} \quad (3)$$

The configuration of the solar panel array is expressed by the number of series and parallel connections. Each parallel connection (n_p) will double the current. Meanwhile, the series connection (n_s) will double the voltage.

$$n_{s\_pv} = \frac{V_{system}}{V_{mp}} \quad (4)$$

where V_{system} is the operating voltage. On the other hand, V_{mp} is the maximum voltage of the solar panel array.

$$n_{p\_pv} = \frac{P_{pv\_total}}{P_{pv}} \quad (5)$$

where P_{pv} is the maximum electric power of the solar panel array.

This SHS is activated to meet the electricity needs for 24 hours. Therefore, a storage unit is needed. It uses a battery array to store the electrical energy generated by the generating unit. The storage unit capacity considers the total energy generated by the generating unit during PSH and the hourly load power. The energy that the battery must store is described in (6).

$$W_{battery} = P_{pv\_com} \ x \ PSH \quad (6)$$

where $W_{battery}$ is the capacity of the storage system stated in the energy (Wh/kWh).

Moreover, this energy is the product of the battery voltage ($V_{battery}$)), which is stated in volts multiplied by the current capacity of the battery. The solar power generation system is indeed suitable for using VRLA type batteries, both dry and gel with a deep discharge (*DoD*) 80%. The current capacity of the battery is described in (7).

$$I_{bat\_total} = \frac{W_{battery}}{V_{system} \ x \ DoD} \quad (7)$$

SCC has a maximum power point tracking (MPPT) feature, in which this feature serves to track the maximum power point voltage of the solar panel array (V_{mpp}). The DC/DC converter on the SCC will convert the charging voltage into a V_{mpp} Voltage. This will increase the production of electrical energy and the efficiency of the system. This MPPT feature usually uses certain programming algorithms to conduct its functions, such as genetic algorithms [27]-[30]. The calculation of the capacity and specifications of the SCC considers the system voltage and the specifications of the solar panels used. Therefore, the calculation of voltage and current specifications must be met according to (8) and (9).

$$V_{scc} = n_p \; x \; V_{oc} \tag{8}$$

where; V_{scc} is the SCC voltage. Meanwhile, n_p is the number of solar panels connected in parallel. As for the V_{oc}, it is the open-circuit voltage.

$$I_{scc} = I_{sc} \; x \; n_s \; x \; 1.5 \tag{9}$$

I_{scc} is the current required SCC capacity and n_s is the number of PV panels connected in series. Moreover, the current capacity of the SCC must be multiplied by 1.5 to compensate for 50%. This 50% compensation is required to prevent overcurrent from the solar panel array.

Determination of inverter capacity in solar power plants only considers the total power used by all loads plus 25% compensation. This is considered to avoid overload or "in-rush" current generated by inductive electrical loads. The inverter capacity is calculated by (10).

$$P_{inverter} = (\sum V_{load} \; x \; I_{load}) \; x \; 1.25 \tag{10}$$

where V_{load} is the voltage of each electrical load, which is about 220 V. Meanwhile, I_{load} is the RMS current of each electrical load.

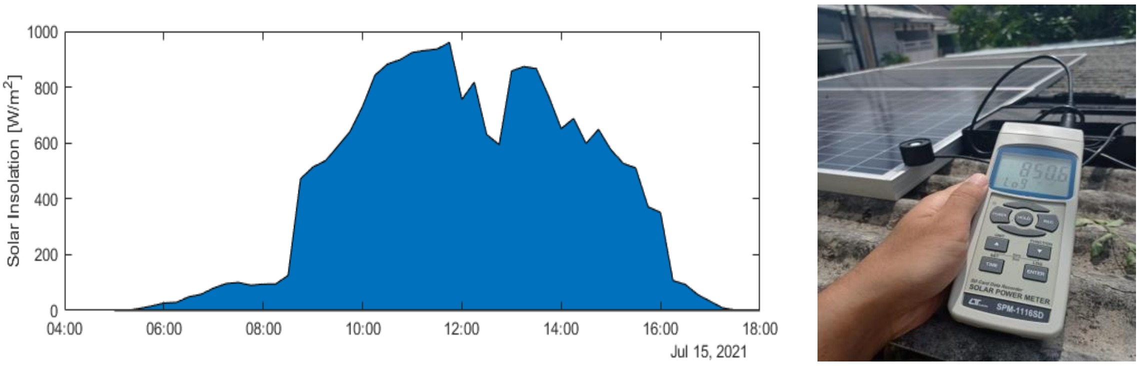
2.4. System performance

SHS is built with a design following the calculation of energy potential, electricity demand, and component specifications. Before being fully operational, it is necessary to test the reliability of the system. This is conducted to determine that the SHS can harvest enough energy to supply electricity to the load. At the same time, it reveals that SHS can store electrical energy appropriately and not excessive or lacking. This analysis was conducted by measuring for a full 24 hours. The parameters observed are from the generation unit to the distribution one. From the generation unit, there is a solar panel current and voltage. Afterward, the battery current and voltage are controlled by the SCC. The output power of the SCC will determine the quality level of the power harvest from the solar panels. In addition, from the AC side, current, voltage, power, frequency, and energy are the outputs of the inverter. The output of this inverter will determine the quality of the electrical energy supply to the load.

3. IMPLEMENTATION

The SHS design calculation method is applied to its construction with a capacity of 300 Wp. This SHS is used to supply household entertainment devices: wifi router, tv box, and LED tv. SHS is operated for 24 hours with non-stop loading.

Figure 2(a) shows a graph of the solar insolation on a daily cycle from 05.00 to 18.00. This graph is used to determine the PSH and the maximum and minimum solar insolation points. If this SHS is used to power the wifi router and tv box with a power of 5.5 W–that is turned on for 24 hours per day– as well as a 27 W LED television–that is turned on for 12 hours per day–then the total power that must be met is 456 Wh per day with a PSH value of 3.5 hours. That is during 10.00-13.00. Calculated in (2), the power value (P_{pv_com}) is 200 Wp. If the value of losses is entered into (3), then the total capacity of the solar panel array required is 308 Wp and rounded up to 300 Wp. According to the standard, a solar power plant with a capacity below 1 kWp must have an operating voltage (V_{system}) of 12 V. Therefore, the arrangement of the PV panels is configured into three series to meet the minimum input voltage requirements for SCC. The same data described in the previous subchapter were taken using a Lutron brand solar power meter with SPM 116SD type. As shown in Figure 2(b), the solar insolation measurements are carried out near the solar panel installation on the roof of the house/building.



(a) (b)

Figure 2. Solar insulation measurement (a) solar insolation occurred in location and (b) data collection process

The calculation of the number and specifications of the battery can be seen from the stored electrical energy. Furthermore, based on (6), the electrical energy that must be stored by the battery ($W_{battery}$) is 700 Wh. In addition, the value of I_(I_{bat_total}) in this SHS is 58.33 Ah. Therefore, it is rounded up according to the battery stock on the market to 55 Ah.

The calculation of SCC specifications is seen from the specifications, configuration, and the number of the used PV panels. Based on (8), with V_{oc} on the solar panel is 21.24 V, a minimum voltage specification of 63.72 V is required. As shown in (7), with the I_{sc} value on the PV panel of 6.22 A, a minimum current specification of 6.22 A is required.

The calculation of inverter specifications is only considered from the total electrical load power. In this study, the total load power for the wifi router, tv box, and LED tv is 34 W. Coupled with a power compensation of 25%, it is safe for SHS to use an inverter with a power not less than 42.5 W. Because SHS has an operational voltage 12 V, the inverter must also have an input voltage specification of 12 V.

4. RESULTS AND ANALYSIS

4.1. SHS installation

The results of the calculation implementation of each SHS component are contained in this section, along with the detailed engineering design (DED) for each SHS configuration. The design uses a solar panel with a P_pv of 100 Wp. Based on (4) and (5); hence, three series configurations are required. The number of solar panels needed is three units. The cable used in the PV panel array uses the NYYHY type with 2 x 1.5 mm square size. The choice of this type of cable is suitable for use in outdoor areas and is more resistant to air and weather. The size of the cable is, of course, adjusted to the current from the solar panel. Based on the calculation results of the storage unit, only 1 unit of 12 V 55 Ah VRLA type battery with a DoD level of 80% is needed.

Figure 3 shows the SHS design with a single line diagram based on the following design, and the cable specifications and configuration of all system components. It is added with the metering from the DC and AC sides. Wiring on the DC side control panel uses the NYAF type with a size of 5 mm square. Meanwhile, the AC side uses the NYH type with a square size of 1.5 mm square. The cable type shown in Figure 4 follows the standard of use. In comparison, the size is adjusted to the voltage and electric current that passes.

Figure 4 shows a 300 Wp mini SHS installation on site. Another important thing is the PV panel array installation and controller panel placement by considering the topology above the house. The elevation angle of the PV panels is 10-15 degrees, which faces the equator. Therfore, if the location is south of the equator, the PV panels must face north and vice versa. In addition, there should be no objects from the east, west, and north that have a height higher than the PV panel installation. This can cause shadows on the surface of the PV panel array.

Afterward, the panel distance between the array to the controller and the battery panels should not be more than 50 meters. This will cause huge losses on the DC side. In this study, the distance from the solar panel array to the controller panel is 13.5 meters. Moreover, the mini SHS installation at the site already meets the standards mentioned.

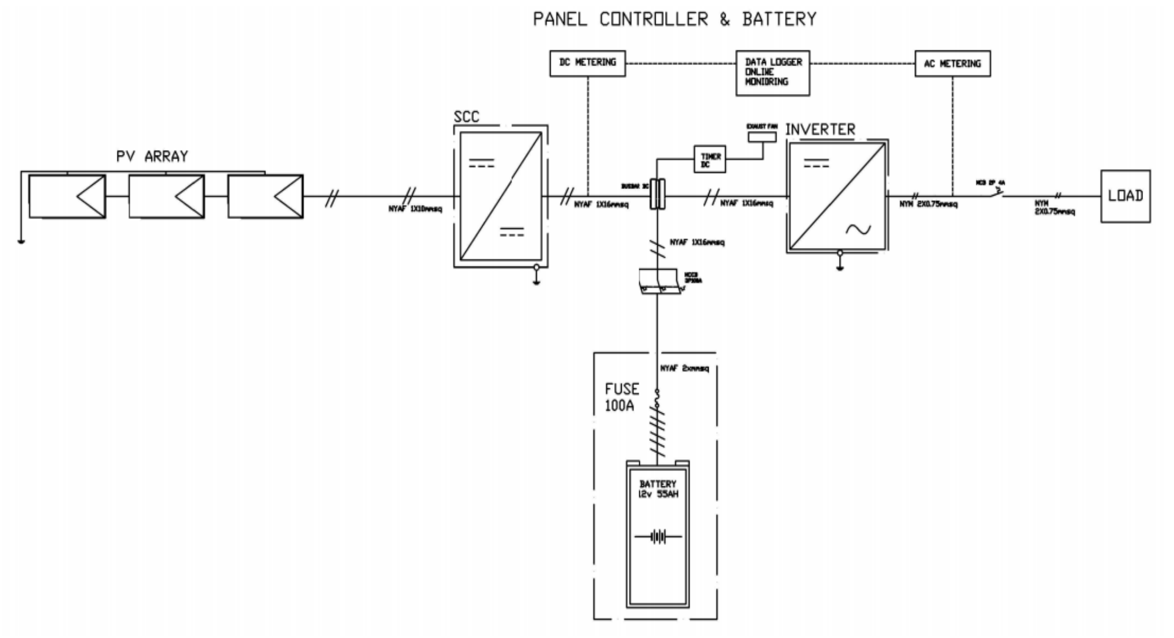


Figure 3. Single line diagram of mini SHS

(a) (b)

Figure 4. 300 Wp mini SHS installation in the rooftop (a) PV panel array and (b) controller and battery panel box

4.2. SHS performance analysis

The performance analysis of the mini SHS that has been built is conducted to determine the level of system reliability. This test aims to determine that the mini SHS system can harvest enough solar energy and supply electricity for several electronic devices in the household. The data collection was conducted on July 15, 2021, for 24 hours, especially for solar insolation data, which was only from 05.00 to 18.00. It follows the daily cycle of the sun.

Figure 5 shows that the solar energy available for 13 hours of irradiation on July 15, 2021, is 14.8 kWh. Meanwhile, the electrical energy produced is 4.2 kWh. Thus, the energy harvested into electrical energy is an average of about 28%. The energy stored by the battery is 4.1 kWh. There is a difference between the energy generated and stored in the battery. This is because there is energy loss in the SCC. In this observation, SCC has an average efficiency of 99%.

Figure 6 shows the voltage and current performance from the DC side, which is from the solar panel generation and battery storage. The solar panel voltage and current (PV) follow the solar insolation graph, with the average value during PSH (09.45 to 14.15) is 51.5 V, and the current is 2.8 A. This is because the solar panels are connected in series 3. Under 24-hour loading, the battery is always in a state of charge at least about 93%. This can be seen from the achieved minimum battery voltage, which is 12.2 V. Meanwhile, the battery in full condition is 12.9 V. This means that the battery has excess capacity compared to the use of an electric load for 24 hours. On the other hand, the charging current to the battery also follows the contours of the solar insolation graph, with the average value during PSH is 10.2 A. It refers to the weather data accessed on the

Accuweather page (source: https://www.accuweather.com/id/id/medokan-ayu/1685675/july-weather/1685675) on 15 July 2021. It was showing clear cloudy weather with an ambient temperature of 34 °C. From the AC side, the inverter showed good performance during the test with an average voltage of 226 V and never less than 225 V. The inverter used is a modified sine wave type with a capacity of 500 W. With variations in input loading of 5.5 W and 34 W, the inverter does not show a decrease in performance. The loading of 5.5 W was conducted for 12 hours from 18:00 to 06.00, whereas the loading of 34 W was conducted for 12 hours from 06.00 to 18.00. The energy produced is used an average of 411 kWh per day.

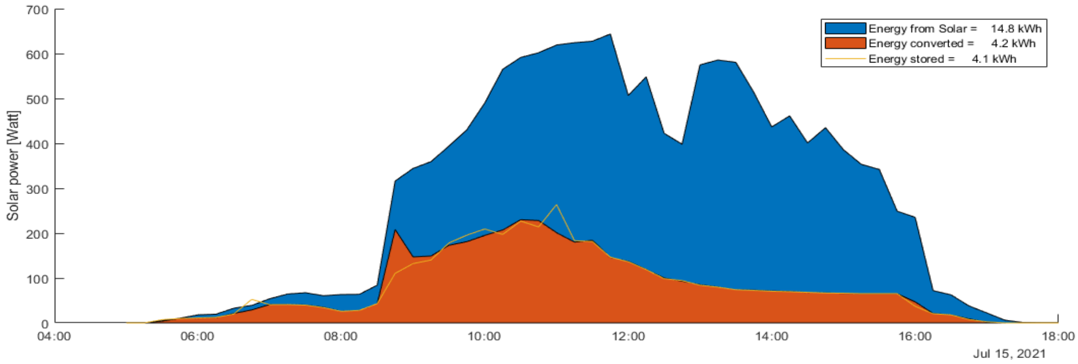


Figure 5. Solar power compared to PV module output occurred in the location

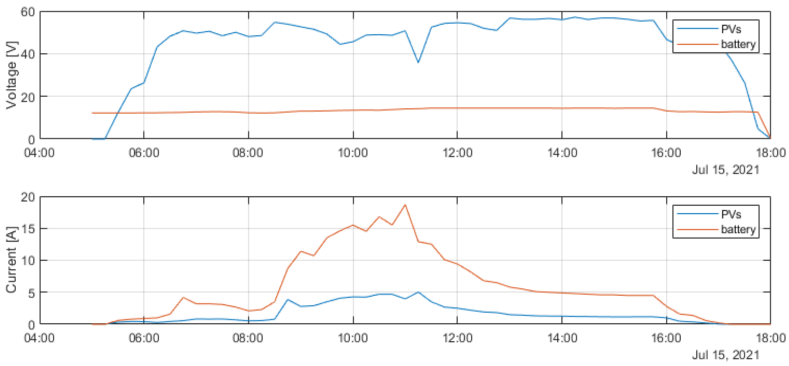


Figure 6. PVs and battery electricity measurement occurred in the location

5. CONCLUSION

The SHS design proposed in this study can be applied to housing with various electrical device loads. The calculation of the potential of solar energy can be done using primary data, which is by measuring the solar power directly in the field. It can also be done using the secondary data obtained from RETScreen. The calculation of electricity demand per day can be done based on the capacity of the electrical load and the electrical power. The correct calculation of potential and electricity demand, it will produce an SHS design that is feasible to be applied in real conditions. Performance analysis also determines the reliability of SHS in the housing sector. The design and construction of the SHS in this study show good performance in terms of energy harvesting and energy use. The battery is never empty, even though the weather conditions are cloudy or even rainy. Electrical energy harvested form the SHS is always available in good quality for 24 hours everyday.

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