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Design of photovoltaic system for public school building

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ABSTRACT

The increase in energy needs to support sustainable development will trigger a large additional power supply. Unfortunately, a current energy source is mostly produced by fossil fuels. This condition can affect the increase of global warming and climate change. Nowadays, many countries including Indonesia are aware of the effect of the use of fossil fuels on environmental devastation. Therefore, the use of clean energy gets more attention from many countries since its energy source is unlimited and harvested from nature. One of the clean energy sources that are widely utilized over the world is photovoltaic (PV). PV is an appropriate clean energy technology to be utilized in Indonesia since this country lies on the equator line and gets solar irradiance over the year. This paper proposed the design of PV systems for a public-school building. These PV schemes proposed in this study are classified into off-grid, on-grid, and hybrid PV systems. From the simulation results, it is shown that the hybrid PV system with energy supplied by PT. PLN (State Electricity Company) results in the highest saving annual cost and provides an environmentally friendly energy source for public-school buildings.

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1. INTRODUCTION

Energy has become the main need of human life since the 19th century. It is used for various types of human needs, such as household, education, and industry. In general, the use of energy used in industry is not sourced from clean energy [1], [2]. The continuous use of unsanitary energy will result in global environmental damage. Due to environmental damage that comes from unsanitary energy, people are aware of switching to using alternative energy such as solar panels [3], [4]. Besides able to reducing environmental damage, the use of solar panels can save electricity costs continuously. The use of solar panels does not require regular maintenance and the resulting energy savings are an added value for utilizing renewable energy easily [5], [6].

The use of solar panel modules can be applied as a source of power generation called solar power generation (SPG) [7], [8]. The SPG application is distributed. It can be used directly on any electrical system in a building. One of the potential savings that can be generated from the implementation of the SPG system is in school buildings [9], [10]. School operational activities generally range from early morning to late afternoon. The school's operational time, which ranges from morning to evening, is the time for sunshine every day. Meanwhile, at night, the school building only requires energy for lighting the building. The characteristics of the school building's electrical load, which are mostly used as long as the sun is shining, have great potential for the use of the SPG system on the school building's electricity.

The application of the SPG system in school buildings can be implemented easily and can be installed in places that have direct sunlight areas. Solar energy absorbed by solar panels does not have harmful emissions, so it does not have an impact on climate change [11], [12]. The durability of the solar panel system can last up to 25 years. Hence, the State Electricity Company (PLN) electricity costs can be saved. In order for the SPG system to operate for 25 years, a feasibility analysis of that system needs to be conducted so that each component used can last up to the maximum usage limit. By keeping each component operating optimally, component replacement costs can be kept to a minimum so that the system produces more economical operating costs. The economy of the SPG system will be compared to the cost of electricity expenditure when only using the PLN electricity network.

This paper proposed an idea for developing solar power generation as the electricity source of school buildings. The school building will be designed as a smart building that can provide electricity without using electricity from the grid. INTIS School Balikpapan Elementary School building is used as the test system for implementing the idea. The rest of the paper is constructed as follows: section 2 describes the procedure specifically designed for the SPG in a school building. The method for designing SPG in a school building is presented in section 3. Detailed results and discussion are described in section 4. Section 5 is highlighted the conclusions and the contribution of the paper.

2. PROCEDURE SPECIFICALLY DESIGNED

2.1. Battery

The battery is an energy storage medium in a photovoltaic (PV) mini-grid system. In SPG applications, the type of battery that is commonly used as an energy storage medium is lead-acid. Lead-acid batteries are divided into two categories: starting batteries and deep cycle batteries. Lead-acid batteries in the starting battery category are generally used in the automotive world because they can provide large currents in a short time. Lead-acid batteries with the deep cycle category have the advantage that they can be used up to 80% of the total capacity and provide a stable electric current for a long time. Lead-acid deep cycle batteries have resistance to repeated charge and discharge cycles which are making them suitable for use in PV mini-grid applications [13], [14]. Where Batt.Cap is Battery capacity (kWh), DOD is depth of discharge (%), and Ereq is the energy required (kWh) respectively. The battery used in the SPG system must be able to supply the load when there is no energy generated from solar panels or PLN [15]. The battery capacity used in the SPG system is determined by the required energy capacity and the depth of discharge (DOD) value of a battery which can be formulated in (1) [16].

$$\text{Batt.Cap} = \frac{1}{\text{DOD}} Ereq \quad (1)$$

2.2. Solar panel

The main component in a PV mini-grid system is solar panels. Solar panels are several series and parallel circuits of a solar cell module. The solar cell module is composed of two layers of semiconductors with different charges. The top layer of the solar cell is negatively charged, and the bottom layer is positively charged. The power generated in one solar panel is determined by the number of solar cells in one panel [17]. Based on [18] the determination of the capacity of solar panels in a PV mini-grid system, it can be formulated according to (2) and (3). Where PSH, Drad, ISTC are sun peak time (h), daily solar radiation (kWh/m2/day) and solar peak irradiation standard (1000 W/m2) respectively. While PVcap and Ereq are solar panel capacity (kW) and energy required (kWh).

$$\text{PSH} = \frac{D_{rad}}{I_{STC}} \quad (2)$$

$$\text{PV}_{\text{cap}} = \frac{\text{E}_{\text{req}}}{\text{PSH}} \quad (3)$$

The power generated by solar panels is highly dependent on the intensity of the sun. The determination of the location and position of solar panels is different for each region. This is caused by the astronomical position of the solar panels to the position of the sun. Due to the different astronomical locations of each region, the output power of solar panels depends on the angle of the sun. The angle that affects the output power of the solar panel is the angle of inclination and azimuth [19]. The tilt angle is the angle of the solar panel to the horizontal axis. Meanwhile, the azimuth angle is the angle of rotation from north to south with a reference angle of 0º, which indicates the direction to the north. The angle of inclination of solar panels in Indonesia generally ranges from 1o in the rainy season to 24º degrees in the dry [20].

As for the azimuth angle of the solar panel, it depends on the position of the hemisphere. The areas with the northern part of the earth optimally have a solar panel azimuth angle of 180º or facing south. For the position of the southern part of the earth, the azimuth angle of the solar panel has an optimal value of 0º which means it faces north. In addition to being influenced by the tilt of the sun's angle, the output power of solar panels is greatly influenced by the intensity of the sun. The output power of the solar panel will depend on the intensity of the sun obtained. The solar panel power will be directly proportional to the intensity of the sun, as shown in Figure 1. Kaplanis *et al.* [21], the change in the output power of the solar panel to the intensity of the sun has a slope graph close to 1. Therefore, the output power of the solar panel is very dependent on the intensity of the sun received as depicted in Figure 2.

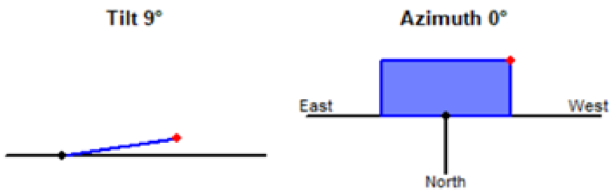

Figure 1. The depiction of the tit angle and azimuth of solar panels

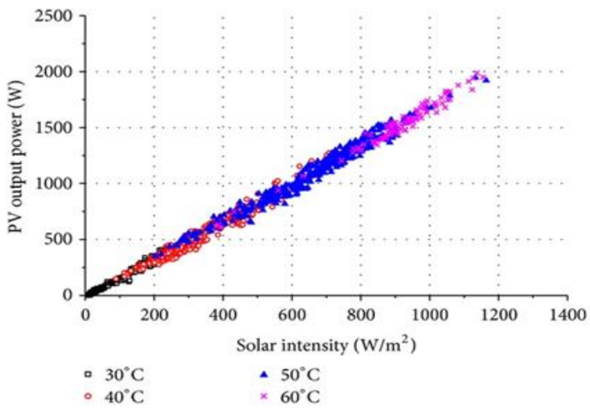

Figure 2. The effect of solar intensity on solar panel output power [15]

2.3. Solar charge controller (SCC)

SCC is a component that is used to regulate the process of charging energy in batteries from solar panels. SCC generally has two types of features, namely pulse width modulation (PWM) and maximum power point tracking (MPPT). SCC, which has MPPT features, can absorb more power than the PWM type. The efficiency of the MPPT type SCC has a higher value than the PWM type. The ability to absorb greater power and higher efficiency makes MPPT type SCCs have a higher price compared to PWM types [22].

SCC type PWM and MPPT, although they have different efficiency, but have the same configuration of use. Both types of SCC can receive power generated from solar panels at a certain voltage level and then lower to the voltage level of the battery system or inverter. With the decrease in the solar panel voltage level to the battery, which tends to be constant, the SCC capacity used is determined by the current capacity that can be flowed. The current capacity of the SCC in the SPG system is determined by the maximum power capacity of the solar panels and the voltage level of the battery system, as well as the inverter input, which can be formulated in (4) and (5) [23]. Where ISCC is SCC Capacity (A), PVcap is Solar panel capacity (W), Vbatt is Battery system voltage (V) and SCCunit is Number of SCC (unit) respectively.

$$I_{SCC}=\frac{PV_{cap}}{V_{batt}} \tag{4}$$

$$SCC_{unit}=\frac{I_{SCC}}{I_{SCC(unit)}} \tag{5}$$

2.4. Net present cost and annualized cost

Net present cost (NPC) is the total value of the investment cost of the system during its service life. NPC calculations can use the HOMER software, which calculates the net cost of each component and the system as a whole. The calculation of the NPC value can be calculated using (6) [24]. Where, Capital cost is component capital cost (IDR), Replacement costs is component replacement costs (IDR), O&M is cost operational and maintenance costs (IDR), resource is energy source cost (IDR) and Salvage is the price of the remaining components (IDR).

$$\text{NPC} = \sum \textit{Capital Cost} + \sum \textit{Replacement costs} + \sum \textit{O\&M costs} + \sum \textit{Resource} - \sum \textit{salvage} \quad (6)$$

Annualized cost is the total cost incurred by the system within one year [25]. The value of the annualized cost depends on the inflation rate and the reference interest rate of each country. The calculation of the annualized cost can be calculated using (7) to (9). Where i, i', f, CRF, N, NPC, $C_{ann,tot}$ are real discount rate, interest rate value, inflation rate, capital recovery factor, system operating period (year), net present cost, system annual fee (IDR) respectively.

$$i = \frac{i' - f}{1 + f} \quad (7)$$

$$CRF = \frac{i(1+1)^N}{(1+i)^N - 1} \quad (8)$$

$$C_{ann,tot} = CRF \times NPC \quad (9)$$

2.5. Renewable fraction and cost of energy

Renewable fraction is a percentage value that shows the volume of energy received by the load from renewable energy sources. The percentage of the renewable fraction is very dependent on the amount of non-renewable energy production on the energy consumed. The percentage of a renewable fraction can be calculated using (10). Where f_{ren} is Percentage of renewable energy absorption (%), E_{nonren} is Total non-renewable energy production (kWh), E_{served} is Total energy consumption (kWh) respectively.

$$f_{ren} = \left(1 - \frac{E_{nonren}}{E_{served}}\right) * 100\ \% \quad (10)$$

Cost of energy (COE) is the value of the costs incurred to produce energy per kWh from the system. By looking at the COE value, the system owner can calculate the cost of each energy income generated by the system. The cost value per kWh generated by the system can be used as a reference for selling the energy produced or reducing electricity costs before the installation of a new electrical system. Calculation of COE value can be calculated using (11). Where cost of energy is cost per kWh (IDR), annual cost is System annual fee (IDR), $E_{Total\ Consumption}$ is total energy consumption in one year (kWh) respectively.

$$\text{COE} = \frac{\text{Annual Cost}}{E_{\text{Total Consumption}}} \quad (11)$$

3. METHOD

3.1. Design procedure

The beginning of the design of the PV mini-grid system requires the completeness of sufficient initial data. The initial data needed include solar radiation at the coordinates of the school building, the characteristics of the electrical load, the ambient temperature around the school building, and the shape of the school building. The coordinates of the school building function to see the value of solar radiation and temperature obtained from NASA, which is accessed using the HOMER software. In addition to the building coordinates, the characteristics of the electrical load indicated by the load power data are needed to determine the components of the PV mini-grid system to be used. The components of the PV mini-grid system are determined through equations on a theoretical basis to calculate the capacity of each PV mini-grid component that will be used. After the component capacity data has been analyzed, the results of the analysis will be input for component variables in the PVsyst software. The variables required in the PVsyst software include the tilt angle and azimuth of the solar panel, solar panel capacity, SCC, inverter, and battery. PVsyst software will play a role in verifying the results of theoretical calculations that have been determined at the time of design. The verification includes the input-output voltage and current of each component used so as not to exceed the maximum limit that has been determined.

After completing the technical design, the economic value of the PV mini-grid system will be calculated using the HOMER software. After getting the optimal SPG system design, a reliability test was carried out to see how reliable the SPG system was to supply electrical power to the school building. The specified reliability of the SPG system must be able to supply 50% or more of renewable energy and be able to operate when there is a disturbance on the grid. After the technical analysis is complete, an economic analysis is carried out to see how much it will cost to implement the system that has been made on the HOMER software. The results of the analysis, which includes technical and economic aspects, are formulated in conclusions to answer the objectives of this research.

3.2. Design Considerations

The SPG system that will be designed has considerations and references for determining system components in accordance with the centralized solar power plant feasibility study guide issued by the Ministry of Energy and Mineral Resources together with USAID in 2018 and the Minister of Energy and Mineral Resources Regulation Number 49 of 2018. The following is the reference for determining each SPG component at the INTIS School Balikpapan Elementary School building:
- In off-grid systems, the minimum inverter capacity is 125% of peak power.
- In systems that export and import energy, the inverter capacity is limited to a maximum of 100% of the connected power of PLN consumers.
- The capacity of solar panels can supply daily energy needs in STC conditions.
- The minimum capacity of SCC can convert 100% of energy from the total solar panel modules.
- Battery capacity can supply the energy needs needed every day.

4. RESULTS AND DISCUSSION

4.1. SPG system technical needs analysis off-grid

The off-grid SPG system at the INTIS School Balikpapan Elementary School is an electrical system that is not connected to the PLN network as Figure 3. The SPG system without being connected to the PLN net will consist of several components with capacities and prices, according to Table 1. Electrical power in the SPG system off-grid will be supplied using an inverter with a total power of 4,000 W. The inverter capacity of 4,000 W in the off-grid system has exceeded the specifications determined by the Ministry of Energy and Mineral Resources of 125% of the peak load power. The energy generated by the inverter comes from solar panels with a capacity of 15,840 Wp. The solar panel capacity of 15,840 Wp in the off-grid system is needed to supply the load and recharge the battery energy when the sunlight intensity is below the standard test condition (STC) value.

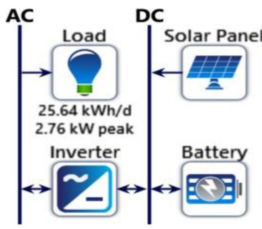

Figure 3. Off-grid system circuit diagram

Table 1. List of capacity and component prices of Off-Grid SPG system

Component	Total capacity	Total number	Unit price (IDR)	Total price (IDR)
Inverter	4,000 W	1	9,692,397	9,692,397
Battery	48,000 Wh	20	4,250,000	85,000,000
Solar panel	15,840 Wp ($78.17\ m^2$)	36	2,500,000	90,000,000
Solar charge controller	12,000 W	3	9,500,000	28,500,000

Based on Figure 4, the battery capacity on January 1 and January 5 was below the 60% level. The battery capacity decreases to below 60% due to the very small intensity of the sun, which causes the load to absorb the energy stored in the battery. On January 2 and January 6, where the sun can shine optimally, the battery capacity will be recharged due to the intensity of the sun, which is approaching the STC value of 1 kW/m2. Charging the battery is supported by the SCC component of 12,000 W. With the SCC charging capacity of 12,000 W, it can absorb solar energy of 11,880 Wp for direct charging of the battery. In addition to solar panels connected to the SCC, as many as 9 units with a peak power of 3,960 Wp connected to the inverter are prioritized to supply the load directly. Based on the capacity of the components in Table 1 that already meet the design reference standards, the off-grid SPG system design in the INTIS School Balikpapan Elementary School building is technically feasible.

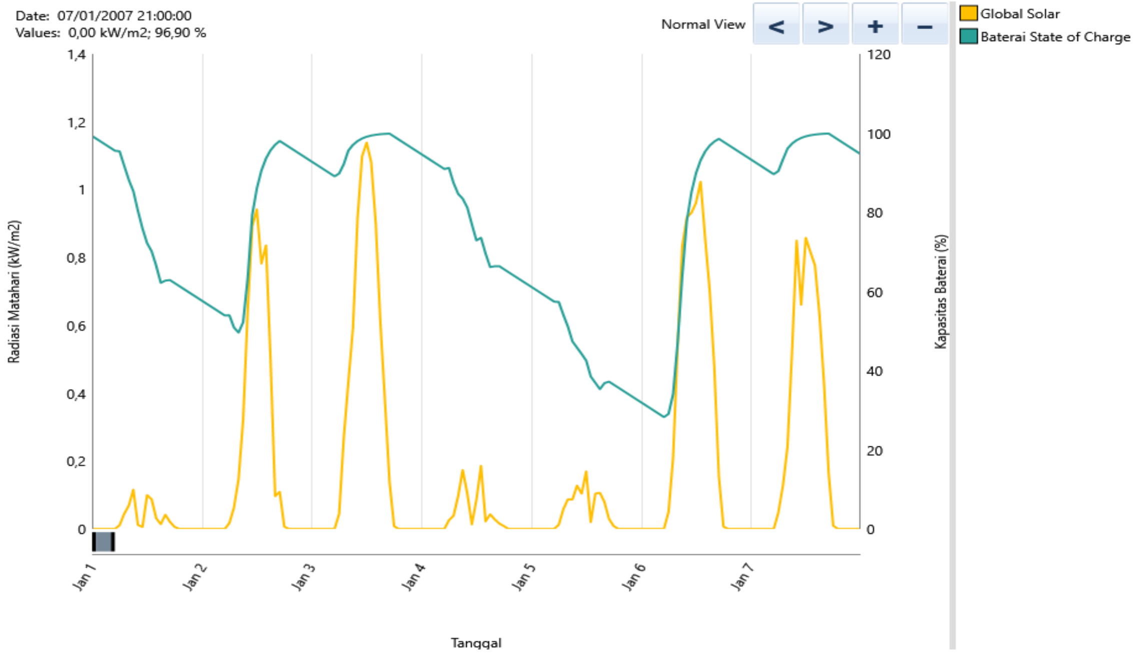

Figure 4. Graph of battery capacity against the solar intensity

4.2. SPG system technical needs analysis on-grid

The on-grid SPG system at the INTIS School Balikpapan Elementary School is an electrical system that is connected to the PLN network as shown in Figure 5. The SPG system connected to the PLN net will consist of several components with the capacity and price as shown in Table 2. Electrical power in the on-grid SPG system will be supplied using an inverter with a capacity of 3,000 W. The inverter capacity in the on-grid PV mini-grid system in the INTIS School Balikpapan Elementary School does not exceed the PLN installed power capacity of 3,500 VA, assuming the power factor is 1. Energy the inverter generated is sourced from solar panels with a capacity of 3,520 Wp, as shown in Figure 6. The solar panel used is 3,520 Wp, which is the maximum input power limit for the inverter specifications used. The limitation of inverter capacity in the on-grid system is due to the regulation of the Minister of Energy and Mineral Resources No. 49 of 2018 that the inverter capacity must not exceed the installed power capacity of consumers to PLN. With the use of an on-grid system that allows the export of energy to the PLN grid, excess power generated by solar panels can be sold to the grid at a price of 65% of the purchase price.

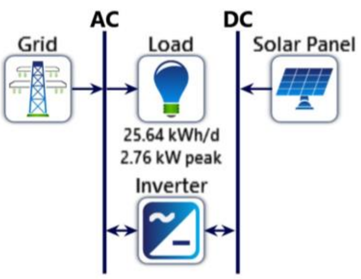

Figure 5. On-grid system circuit diagram

Table 2. List of capacity and component prices of on-grid SPG system

Component	Total capacity	Total number	Unit price (IDR)	Total Price (IDR)
Inverter	3,000 W	1	8,600,000	8,600,000
Solar panel	3,520 Wp (17,37 m^2)	8	2,500,000	20,000,000

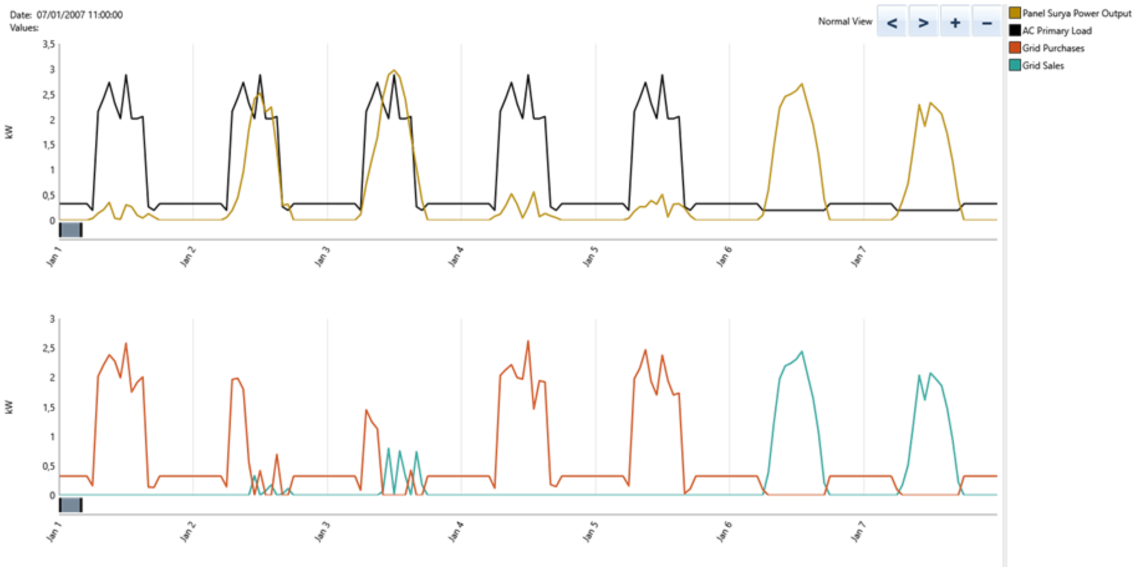

Figure 6. Graph of load power against solar panel output (above) and energy export-import power graph (bottom)

4.3. Hybrid SPG system technical needs analysis

The hybrid SPG system at the INTIS School Balikpapan Elementary School is an electrical system that is connected to the PLN network with an additional battery as an energy storage system as shown in Figure 7. The battery used will function as backup energy when there is no energy supply from solar panels or the PLN network. The capacity and price of components in the PV mini-grid can be seen in Table 3.

Electric power in the SPG system in a Hybrid way will be supplied from solar panels and the PLN network. The solar panels used in the hybrid system at primary school INTIS School Balikpapan are 5,720 Wp. The solar panels used for 5,720 Wp are able to supply energy needs for one full day in STC conditions. From the solar panel of 5,720 Wp, it will directly flow to the MPPT on the inverter of 3,080 Wp and SCC of 2,640 Wp, as shown in Figure 7. The inverter used has a power capacity of 3 kW which can transmit energy simultaneously to the load and to the PLN net. The inverter capacity used is already above the peak power load and below the maximum power capacity installed at PLN. With an inverter capacity that meets the standard for installing rooftop solar panels, the excess energy produced can be sold directly to the PLN network. In addition to the excess energy capacity being sold to the PLN net, the excess energy will also be stored in the battery as a backup energy source. The battery capacity of 38,400 Wh is determined based on the energy needs during the operational hours of school activities. With the battery, school operational activities will still be able to run smoothly for one day when there is a disturbance to the PLN net or solar panels. In Figure 6, it can be seen that there are conditions where the energy in the battery is used for load requirements. When the load receives energy from the battery, the consumption of energy from PLN can be reduced. On January 8, the battery's energy capacity was reduced when the power from the solar panels was insufficient to supply the load. Meanwhile, on January 12, where the solar panel power could not meet the load demand for one full day, the majority of the energy for the load needs was supplied from the PLN net. When there is a condition where the solar panel power is higher than the power required by the load, such as on January 13, the energy produced by the solar panels can be sold directly to the PLN electricity grid. With the export-import of energy and batteries that can be used in conditions where there is not enough sunlight, a hybrid SPG system can potentially get savings and overcome energy supply disruptions when there are disturbances in solar panels or PLN nets.

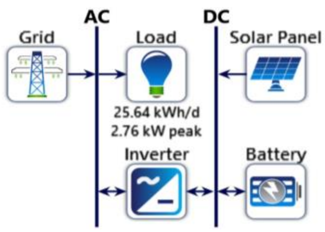

Figure 7. Hybrid system circuit diagram

Table 3. List of SPG hybrid system components capacity and prices

Component	Total capacity	Total number	Unit price (IDR)	Total price (IDR)
Inverter	3,000 W	1	12,808.874	12,808,874
Battery	38,400 Wh	16	4,250,000	68,000,000
Solar panel	5,720 Wp (28,23 m^2)	13	2,500,000	32,500,000
Solar charge controller	3,200 W	1	7,500,000	7,500,000

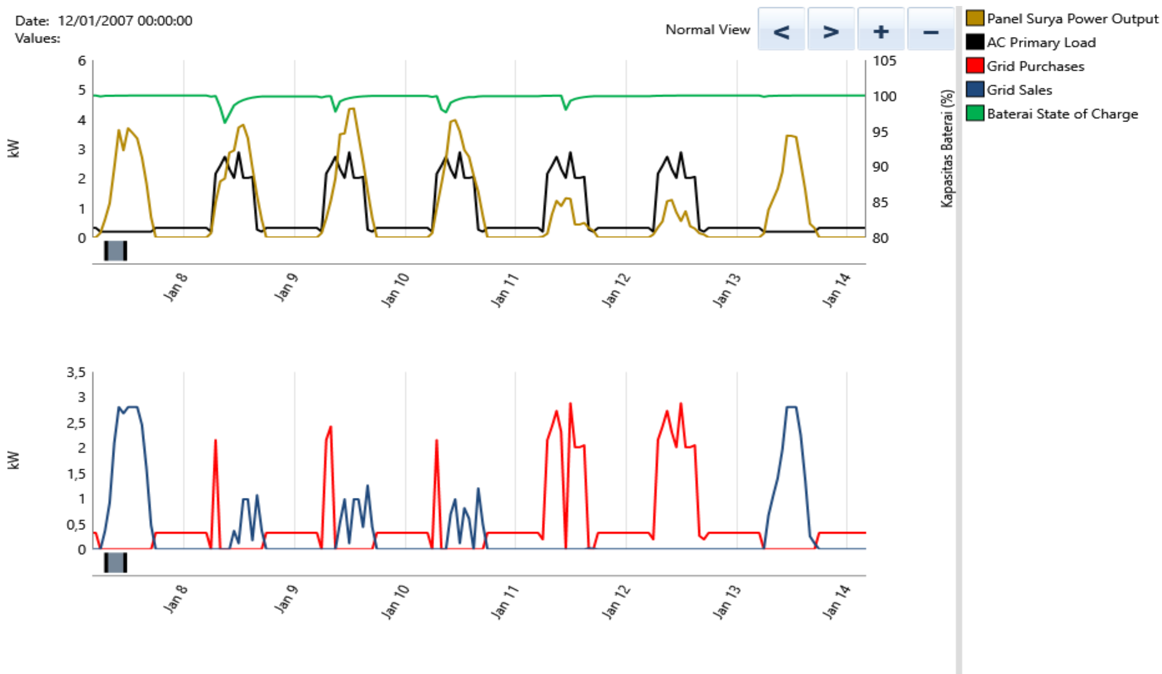

Figure 7. Graph of load power against solar panel output and battery (above) and energy export-import power graph (bottom)

4.4. Economic comparison

After theoretical calculations and testing using PVsyst and HOMER software, a comparison of the economics of the SPG system is obtained, which can be seen in Table 4. In Table 4, the comparison of NPC values, annualized cost, renewable fraction, cost of energy, payback period, and total savings are obtained. In the off-grid system, the total investment and annual cost of the system are the highest compared to other PV mini-grid systems. This is due to the capacity of solar panels and batteries that are used more than other SPG systems to keep the electrical load supplied with energy at all times. Although the total investment cost for the off-grid system is the largest, the energy consumed is already 100% sourced from renewable energy. With the most expensive total investment, the off-grid SPG system also cannot save electricity consumption because the present cost value before the 25th year does not reach IDR 0. In the on-grid system, the total investment and annual cost of the system are the lowest among other PV mini-grid systems. With the lowest investment cost, SPG with an on-grid system can produce the cheapest energy price of IDR 498/kWh. In the on-grid SPG system, the majority of the energy used annually comes from 54.44% of renewable energy. With the cheapest system compared to other PV mini-grid systems, the on-grid system can save energy of IDR 46,993,761 and get a return on investment in the 16th year.

In a hybrid system, the total investment and annual cost of the system are in the middle of the off-grid and on-grid systems. Although the SPG hybrid system requires an investment cost of 3.16 times greater than the on-grid system, the role of renewable energy in supplying the load can reach 69.65%. The hybrid system has a battery as an energy storage medium that can supply loads without a PLN source and solar panels for one full day. With the availability of batteries in the hybrid system, energy will be able to continue to be supplied for a full day if the solar panels or PLN cannot produce energy. Although it has reliability in overcoming energy supply disruptions, the SPG hybrid system has not been able to save the cost of electricity needs when compared to using only PLN. In the application of the SPG system on the electricity network of primary school INTIS School Balikpapan, the on-grid SPG system is the most feasible system to apply. This is because the on-grid SPG system is the only system that has the cheapest energy prices and can generate savings.

Table 4. Economic comparison of PV mini-grid systems

	Off-grid	On-grid	Hybrid
NPC	IDR 390,539,134	IDR 91,471,718	IDR 281,294,307
Annualized cost	IDR 18,309,991	IDR 4,288,549	IDR 13,188,169
Renewable fraction	100 %	54,44%	69,65%
Cost of energy	IDR 2,539/kWh	IDR 498/kWh	IDR 1,341/kWh
Payback period	-	16 Years	-
Total savings	-	IDR 46,993,761	-

5. CONCLUSION

This paper proposed an application of SPG as the electricity sources of the school building to reduce the total electricity cost. From the calculation it is found that, in the off-grid system, the operational cost is IDR 2,539/kWh, which is 2.8 times more expensive than the PLN price. In the on-grid system, the operational cost of the system is IDR 498/kWh, which is 44.7% cheaper than the PLN price. Meanwhile, for the hybrid system, the operational cost of the system is IDR 1,341/kWh, which is 1.5 times more expensive than PLN's electricity price. The savings obtained only occur in the on-grid SPG system of IDR 46,993,761. Savings in electricity consumption, when compared to PLN, occurs after the 16th year, where the present cost value is IDR 0.

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