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Assessing the utilization of palm oil mill effluent in photovoltaic and biogas hybrid energy system for off-grid village

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ABSTRACT

The increasing demand for electricity, high prices, and lack of fossil fuels are forcing local community to look for renewable energy sources. Villages in palm oil mills have large volumes of biomass waste, especially palm oil mill effluent (POME), which causes environmental and health issues. This study proposed a hybrid renewable energy system consisting of solar photovoltaic (PV) and biogas to provide sustainable electrification for an off-grid village. To minimize the environmental impact and availability of the applied technology, the PV panels were incorporated with a biogas-fueled generator. Simulation experiments were carried out using the HOMER software for an average daily demand of about 159.65 kWh/day and a peak load of 20 kW. The investigation was emphasized to find the optimal PV/biogas system to serve the village community considering electrical, economical, and environmental aspects. Subsequently, a standalone biogas system was used as the base case. The proposed configuration consisted of a biodigester, a biogas-fueled generator, PV panels, an inverter, and batteries with 8.5 hours of autonomy to produce electricity of around 67,216 kWh/year. The results demonstrated the technical and economic feasibility, as well as the environmental benefits of a PV/biogas system for generating electricity for the off-grid village community.

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1. INTRODUCTION

Oil palm (*Elaeis guineensis*) is a tropical tree crop that has higher productivity than other oil-producing vegetation [1]. Oil palm trees are cultivated crops in Southeast Asia, Africa, America, and Oceania [2], [3]. Oil palm plantations are widely grown in Indonesia covering an area of more than 15 million hectares, especially in Sumatra, Kalimantan, Sulawesi, and Papua (as seen in Figure 1), and they are still growing rapidly.

In Indonesia, the sources of oil palm fresh fruit bunches (FFB) usually come from nucleus estates and smallholder plantations (NES) [4]. Palm oil mills extract crude palm oil (CPO) from the FFB. Processing FFB into CPO produces large amounts of solid and liquid waste, which is rich in organic substrates and it can be reprocessed into biomass fuel products, such as bioethanol, biodiesel, and biogas [5]. Solid biomass waste mainly comes from oil palm shells, mesocarp fibers, and empty fruit bunches, while abundant liquid biomass waste is generated by palm oil mill effluent (POME). Palm oil biomass waste, both solid and liquid, has great potential as a valuable energy provider and, at the same time, reduces the environmental impact caused by waste disposal [6].

Figure 1. Oil palm plantation in Indonesia (Source: APCASI Indonesia)

The development of small-scale biomass power generation has very good prospects, especially for remote areas, by utilizing the potential of existing biomass resources in the local area. Another advantage of biomass is that it is easy to store and much less sensitive to climatic conditions compared to other renewable sources, such as wind and solar energy [7]. The obstacles faced in operating a sustainable biomass power plant are the availability of supply and competitive prices of biomass. However, oil palm biomass sources are generally available and concentrated in several places, such as in oil palm mill areas and oil palm plantation sites, so that the sustainability of biomass energy will not be hampered by the availability of raw materials. In terms of oil palm biomass, the price of oil palm shells continues to increase every year due to the high demand in the global market. Likewise, oil palm mesocarp fibers and empty fruit bunches (in the form of fibers and pellets) have been used commercially as biomass fuels for steam boilers in biomass power plants. POME is a source of oil palm biomass with the most negligible economic value compared to palm oil solid waste. POME is produced from the sterilization and clarification process of CPO from FFB, and it is an abundant and sustainable source of palm oil biomass energy. Increasing CPO production from palm oil mills will definitely increase the amount of POME biomass. The liquid waste becomes a source of serious environmental problems produced by the palm oil industry due to the high concentration of oxidizable organic matter [8]. Nevertheless, POME can be converted into biogas fuel through the gasification process, purified, and then used as a renewable gaseous fuel for biogas engines to generate electricity [9]. From several POME processing technologies, the biodigester through an anaerobic process is an effective effluent method to produce biogas [10]. Anaerobic biogas contains about 45%-75% methane, with the remainder being carbon dioxide and small amounts of other gases. According to reports [11], [12], one cubic meter of biogas can produce about 2.5-3.0 kWh of electrical energy.

Hybrid renewable energy systems are more flexible and economical than single renewable energy systems for remote areas far from the power grid [13]. Moreover, hybrid systems are usually designed to ensure sustainable power generation to serve electricity needs by integrating several complementary single power plants. Therefore, to meet the need for sustainable and economical electrical energy, biomass can be integrated with wind or solar energy sources. Solar energy technologies are associated with high investment costs and renewable intermittency, while biomass power generations require a large supply of fuel which must be available at all times. However, the combination of solar and biomass energy will be a reliable energy investment and it is projected to be able to reduce global greenhouse gas emissions due to its availability in most parts of the world [14].

There are two common hybrid scenarios for combining solar and biomass to generate electricity, i.e., concentrated solar power (CSP)-biomass combustion and photovoltaic (PV)-biomass gasification. In the CSP-biomass combustion scenario, the CSP collects heat from solar energy, while biomass is burned to produce heat. The heat is then used to rise high-temperature steam and drive a turbine through a thermodynamic process in an external combustion system to produce electricity. The hybrid CSP-biomass combustion can be arranged to generate steam [15], [16] or use an integrated gasification combined cycle (IGCC) [17], [18] for electricity generation. The biomass sources that are burned as the primary fuel generally come from solid wastes, such as rice husk [19], wood chips [20], food waste [21], sugarcane bagasse [22], animal manure [23], oil palm kernel shell, mesocarp fiber, and empty fruit bunches. In the PV-biomass gasification scenario, the PV panels directly convert solar energy into electricity, while biogas from biomass gasification is used for a biogas-fueled generator or a micro gas turbine generator [24] to generate electricity through an internal combustion system.

Furthermore, gasification-based biomass for electricity generation typically results in significantly lower pollutant emissions compared to the external combustion of biomass. The gas engine will contribute to carbon dioxide reduction by high-efficiency operation using biogas. Ruiz *et al*. [25] recommended using gasification techniques for installed electric power of less than 2 MWe, whereas external combustion systems were considered to be more reliable for applications between 2 and 10 MWe. According to economic viability, Pantaleo *et al*. [15] found low economic profitability of hybrid CSP-biomass combustion compared to biomass power generations due to the high investment costs of the large CSP size. On the other hand, a hybrid system from PV and biomass gasification showed very feasibly if the renewable energy gave 50% of the electricity contribution [26]. Higher electricity contribution required more biomass supply which increased the cost of electricity. The cost of electricity from biomass became expensive due to the price of biomass, especially when using commercial biomass sources. Al-Ghussain *et al*. [27] determined the optimal size of a PV/wind/biomass hybrid system with integrated energy storage to meet almost 99% of the electricity demand. Another study on hybrid PV-biomass gasification [28] reported that the hybrid renewable system was the most economical and reliable for rural areas when the biomass supply was free and always available. The hybrid PV-biomass gasification would become an attractive option as the costs of photovoltaic fell and free biomass waste was available in abundance. Another consideration for using PV technology was that PV was much cheaper than CSP in implementation.

The aforementioned works showed a limited focus on resource assessment and modeling for energy and exergy analysis on solar and biomass for hybridization. In this study, a hybrid renewable energy system that combines PV and biomass gasification for a small-scale power plant was modeled and optimized to generate electricity and serve load demands continuously. The main contribution of this study was to propose an optimal PV/biogas hybrid system to serve the village community in a palm oil mill according to electrical, economic, and environmental aspects. Biogas from the digestion of POME was used as fuel in a biogas-fueled generator. The biogas-fueled generator was chosen because it had a relatively low implementation cost and high electrical efficiency compared to gas turbines and micro-turbines [29].

2. RESEARCH METHOD

2.1. PV/biogas hybrid system

In order to study the PV/biogas hybrid system, the configuration as shown in Figure 2 is constructed using HOMER software. Hybrid optimization of multiple energy resources (HOMER) is a hybrid power optimization software for designing and optimizing village power, island utilities, and grid-connected systems. It is mainly used for the design and analysis of microgrid and hybrid power systems in order to achieve technically optimal and maximum cost-effective configurations.

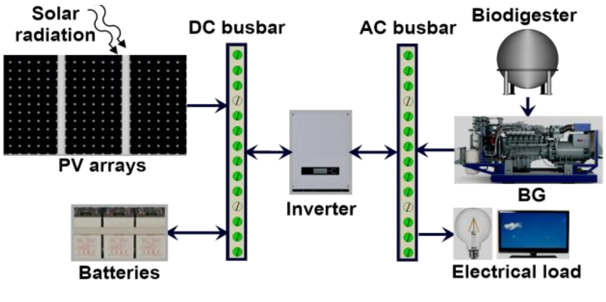

Figure 2. Designed configuration of PV/biogas hybrid system

The load profile of a palm oil mill village is presented in Figure 3. The most common electricity-consuming devices used by villagers in palm oil mills are lights, televisions, fans, electric irons, and water pumps. The load profile has a peak load of 20 kW with an average energy consumption of 159.65 kWh/day. The average demand load is about 6.65 kW with a load factor of 0.33. Rural communities are generally characterized by a low load factor [30] due to a more varied demand load. There are periods of high demand load and low electricity utilization leading to a low load factor.

2.2. Main components

The proposed PV/biogas system consists of five components to be designed, i.e., a biodigester, a biogas-fueled generator, PV panels, an inverter, and batteries. This hybrid system requires energy sources from solar radiation and biogas. Solar energy is free and available from the sun. The biogas fuel is produced from POME. The biodigester is a structure to convert POME into valuable biogas through an anaerobic digestion process. The biogas is then purified and used as fuel in an internal combustion engine and generates electricity.

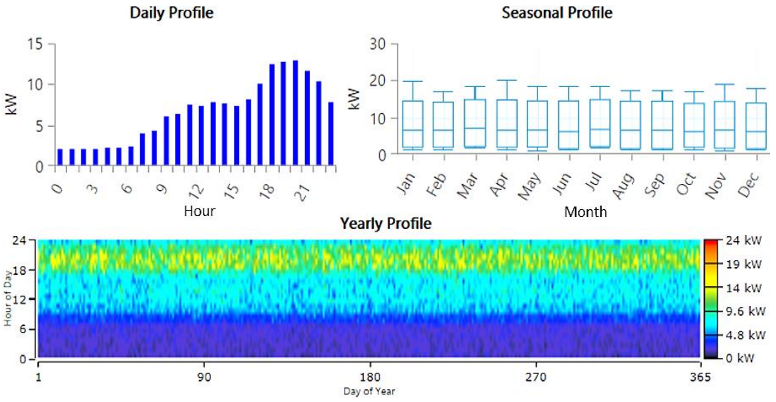

Figure 3. Load profile of the village

In this study, POME as the biomass feedstock is produced by a palm oil mill with a processing capacity of 30 tonnes/hour, and the palm oil mill can create 400 m^3 of POME on daily basis. The price of POME is assumed to be zero because the waste biomass is freely available around the palm oil mill. POME contains about 96% water, a small amount of oil, and suspended solids from fruit debris [31]. Since POME is a carbon-neutral energy source that produces biogas through an anaerobic digester technology, the net carbon content of POME is typically near zero. Although the combustion of biogas produces carbon dioxide and returns that carbon to the atmosphere, the carbon in POME is initially absorbed from the atmosphere.

The biogas fuel is produced from POME biomass utilizing sequential processes to upgrade and purify it from moisture (H_2O), carbon dioxide (CO_2), oxygen (O_2), hydrogen sulfide (H_2S), and other contaminants, such as siloxane and volatile organic compound (VOC) [32], [33] as seen in Figure 4. According to the previous study in [34], one tonne of POME can produce approximately 29 m^3 of biogas with a gasification ratio of 0.03, and typically the price for POME-based biogas production is \$0.2 per m^3. The biogas fuel used in this study has a density of 1.18 kg/m^3 and a lower heating value (LHV) of 22 MJ/kg [35].

Figure 4. Biogas processing from POME

The capital cost of a biodigester generally depends on the volume of the digester to accommodate the total amount of POME and its retention time. The digester volume (in m^3) for small-scale biogas production can be calculated as (1).

$$D_V = F_T . R_T \tag{1}$$

Where F_T is the flow rate of POME (in m^3/day), and R_T is the retention time of POME (in day). The retention time is the amount of time required by POME to stay in the anaerobic digester. The retention time for processing POME into commercial biogas is about 20 days, while using an open ponding system takes 40-65 days [36]. The capital cost for the biodigester, including installation, processing, and piping, is approximately \$300/m^3 [37], and the O&M cost is assumed to be 1% of the capital cost, as presented in Table 1. The capital cost of the biodigester in HOMER is included as the system fixed capital cost.

A biogas-fueled generator is the combination of a biogas engine with an electric generator to generate electricity. The electrical power output (in kW) of a biogas-fueled generator is defined as (2) [29].

$$P_{BG} = \frac{LHV.Q_{BR}.\eta_{BG}}{\gamma_i.CF} \tag{2}$$

Where LHV is the lower heating value of biogas (in MJ/m^3), Q_{BR} is the biogas consumed by BG (in m^3/h), and η_{BG} is the BG efficiency, γ_i is the conversion factor (3.5714 MJ/kWh), and CF is the capacity factor. The BG is applied to run in a particular time step. The BG fuel intercept coefficient and slope are taken from its performance data and fuel consumption curve (as seen in Figure 5), which give a fuel intercept coefficient of 0.0475 kg/h/kW rated and a fuel slope of 0.5025 kg/h/kW output. In the simulation, a 20 kW BG is applied to meet the peak load. The BG is set to operate at a minimum load of 25% and has 15000 hours of operation lifetime. The capital and replacement costs for the BG are \$500/kW and \$450/kW, respectively. This investment includes preparation, labor, installation, and other regulatory costs. The operation and maintenance (O&M) cost per operation hour is set at \$0.03/kW [38], as summarized in Table 1.

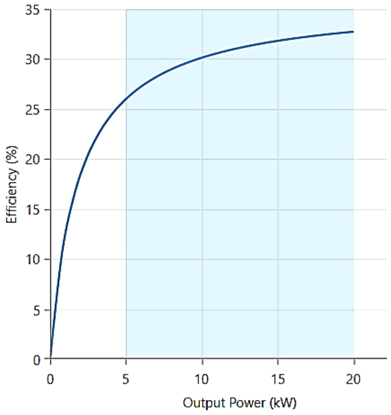

Figure 5. Efficiency curve of a biogas-fueled generator

A PV array functions as a converter of solar radiation into electricity. The data collected from solar radiation and ambient temperature, along with the orientation angle, are then used to compute the electricity output of the PV array. The electrical power output (in kW) of a PV array is defined as (3):

$$P_{PV} = f_{PV}.f_{T}.\frac{G_T}{G_{T,STC}}.P_{PV,STC} \tag{3}$$

where f_{PV} is the derating factor that reduces the output of a PV array due to dirt, dust, shading, aging, wiring, and others, while f_T, G_T, $G_{T,\,STC}$, and $P_{PV,\,STC}$ are the derating factor due to increasing PV cell temperature, the total solar radiation incidents on a tilted surface of the PV array (in kW/m^2), the solar radiation at a standard test condition in kW/m^2), and the rated capacity of the PV array (in kW), respectively. The standard test condition (STC) is the solar PV panel output testing condition used by most manufacturers and defined as the testing under a cell temperature of 25 °C and solar radiation of 1 kW/m^2 with an air mass of 1.5.

The hybrid system is designed to use mono-crystalline PV panels with a nominal operating cell temperature of 25 °C and a temperature coefficient of power of -0.43%/°C. The temperature effect is also taken into account as the annual average temperature is 26.19°C at the site and it is higher than the nominal operating cell temperature. The PV panel power output will decrease by about 0.43% with the increase in cell temperature per °C from the nominal operating cell temperature. The PV mounting system is installed to an optimal tilt angle of 1.69° facing due north to maximize the solar radiation harvesting in Pontianak [39]. The cost of PV panels is based on the market price in Indonesia. The price of a PV panel has fallen since 2013 [40] to about half of its price by 2022. The capital cost for the PV arrays is \$550/kW, including preparation, labor, installation, and other regulatory costs, as provided in Table 1. The replacement cost is assumed to drop 60% after 25 years. The annual O&M cost is for dirt cleaning and PV arrays adjustment.

The inverter commonly used in a PV/battery system is a hybrid converter, which combines PV inverter and battery inverter in a single unit. The hybrid inverter converts alternating current (AC) and direct current (DC) interchangeably. In the hybrid system, there are two different types of electrical current, AC from BG and DC from PV arrays and batteries, but the output from the inverter to supply the electrical loads is AC. The inverter capacity is often equal to or less than the installed PV capacity to minimize costs. The other reason is that PV arrays do not always operate at full power. The inverter price is \$250/kW at scale, and the replacement cost is taken to be \$225/kW. The lifetime of the inverter is 15 years with zero maintenance cost and an efficiency of 96%. A brief summary of the inverter costs is presented in Table 1.

A battery is a device used to store electrical energy for later use in order to reduce the mismatch between electricity generation and demand. The power output (in kW) of a battery can be calculated as (4) [41].

$$P_{Batt} = \frac{T}{DOD.\eta_{Batt}.\eta_{DC-AC}}.P_{Load} \tag{4}$$

Where P_{Load} is the AC electrical load (in kW), while T, DOD, η_{Batt}, and $\eta_{DC\text{-}AC}$ are the battery backup time, depth of discharge, battery efficiency, and DC-to-AC conversion efficiency, respectively. The most widely available battery technology in the Indonesian market is the valve-regulated lead-acid (VRLA) battery [42]. The VRLA battery needs less maintenance as no electrolyte is added during the battery life. The maintenance is carried out for routine functional testing and cleaning to prevent premature failure and extend the battery lifespan. In this study, the battery chosen is a 200 Ah, 12-V VRLA battery. This type of battery can be operated up to a DOD of 80% without shortening the working life of the battery. Operating at a DOD of 70% with a roundtrip efficiency of 80%, the battery life cycle can achieve 2000 cycles with an energy throughput of 1120 kWh. The battery price is \$130/kWh based on the local market in Indonesia, and the replacement cost is assumed to be equal to the capital cost with the O&M cost of \$0.01/kWh/yr. The battery costs is provided in Table 1.

Table 1. Components and costs

Main component	Capital cost	Replacement cost	O&M cost	Lifetime
Biodigester	\$300/m^3	\$300/m^3	\$3/m^3/y	25 y
BG	\$500/kW	\$450/kW	\$0.03/kW/h	15,000 h
PV	\$550/kW	\$220/kW	\$5.5/kW/y	25 y
Inverter	\$250/kW	\$225/kW	\$0	15 y
Battery	\$130/kWh	\$130/kWh	\$0.01/kWh/y	10 y

3. RESULTS AND DISCUSSION

3.1. Electricity production

A palm oil mill with an FFB processing capacity of 30 tonnes/hour has a capability to produce about 350 tonnes or 400 m^3 of POME on daily basis. In this study, 1% of the daily POME production is used to generate biogas for fueling a 20-kW BG. To maintain an average POME flow rate of 3.5 tonnes/day or 4 m^3/day (as seen in Figure 6) with a retention time of 20 days, a biodigester with a capacity of 80 m^3 is needed. Therefore, the fixed capital cost of the biodigester is estimated to be \$24.000, and the O&M cost is 1% of the capital cost.

The annual average solar radiation and ambient temperature at the site are 5.05 kWh/m^2/day (as seen in Figure 7) and 26.19 °C, respectively. The PV arrays used in the hybrid system have nominal operating cell temperature, temperature effects on power, and efficiency at STC of 25 °C, -0.430%/°C, and 17.00%, respectively. The simulation is conducted based on 25 years project lifetime, 8% discount rate and 2% inflation rate. Optimization results for the proposed PV/biogas system is presented in Table 2. The optimal PV/biogas system comprises of biodigester (80 m^3), BG (20 kW), PV (21.7 kW), inverter (11.5 kW), and battery (80 kWh) to produce electricity of about 67,216 kWh/year. The hybrid system meets all community electrical loads with this optimal configuration, and there are no unmet loads. From a technical perspective, the optimal hybrid system should not only provide the lowest cost of all potential competing systems, but it must also meet the demand loads with the minimum unmet electricity and capacity shortage. The monthly electricity generation shared between the BG and PV is shown in Figure 8. The BG and PV contribute 53.3% and 46.7% of annual electricity, respectively, to serve a demand load of 58,272 kWh/year with 5.5% of excess electricity to be stored in batteries. Solar PV energy is limited to a maximum share of 50%. Therefore, the BG can be operated continuously at full load conditions at night time and part loads conditions in day time [43].

The PV has a capacity factor of 16.5% with an average electrical output of 3.58 kW, while the BG has a capacity factor of 20.4% with an average electrical output of 16.1 kW, as shown in Table 3. The capacity factor of BG is higher than that of PV. As a consequence, the BG produces more electricity than the PV to serve the total demand loads. The capacity factor indicates that the average power output of BG is higher than the output from PV. This is because the PV only generates electricity during the day when solar radiation is sufficient. Batteries, as energy storage, capture excess electricity generated by the PV. When the electricity from the PV output is low, the batteries and BG complement it. The batteries and BG become very useful to serve the demand loads on cloudy, rainy, or foggy days as well as at night. In the optimized PV/biogas system, the battery bank with a nominal capacity of 80 kWh captures surplus electricity from PV of approximately 16,693 kWh/year and delivers 13,373 kWh/year for demand loads. The safe operating state of charge (SOC) of batteries is maintained in the range between 30% and 100%, as shown in Figure 9. The annual throughput of the batteries is 14,951 kWh/year, with a battery autonomy of 8.5 hours.

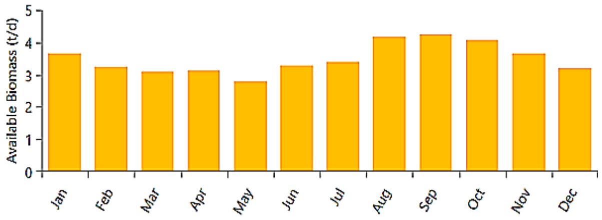

Figure 6. POME biomass data

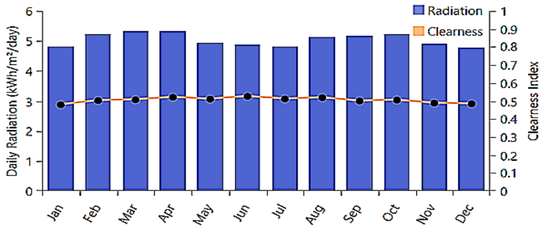

Figure 7. Solar radiation data

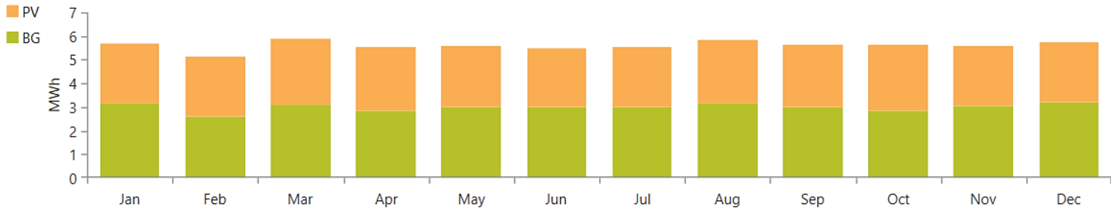

Figure 8. Monthly electricity production of PV and BG

Table 2. Optimal PV/biogas hybrid system

Component	Biodigester (m^3)	BG (kW)	PV (kW)	Inverter (kW)	Battery kWh)
Capacity	80	20	21.7	11.5	80

Table 3. Electricity production

Quantity	PV	BG
Rated capacity	21.7 kW	20 kW
Mean electrical output	3.58 kW	16.1 kW
Capacity factor	16.5%	20.4%
Electricity production	31394 kWh/year	35822 kWh/year

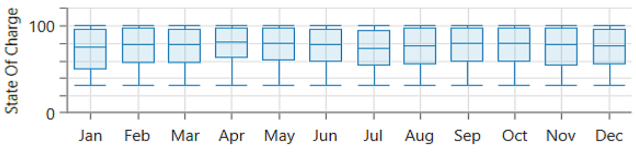

Figure 9. Battery state of charge

3.2. Economic performance

There are two ways to compare economics on HOMER: cost summaries and economic metrics. The cost summaries provide information on total net present cost (NPC), cost of energy (COE), and total annualized cost. Total NPC is the sum of the total discounted cash flows in each year of the project lifetime, while COE is defined as the average price of useful electricity generated by an energy system. Total NPC and

COE are calculated for both PV/biogas and standalone biogas. The standalone biogas system is considered as a base case. Next, comparisons are made in terms of total NPC, COE, and total annualized cost.

The simulation results show that the total NPC and COE of the standalone biogas system are estimated at $169,479.30 and $0.2250, respectively. In contrast, the total NPC of the proposed PV/biogas system is estimated at $111,393.50 with a COE of $0.1479/kWh. The capital cost of the PV/biogas system is estimated at $59,232, and it is higher than above-mentioned standalone biogas system costing $34,000 because there are additional costs for PV and batteries. However, in terms of the total NPC and COE, the standalone biogas system is higher than the aforementioned hybrid system due to the high O&M and replacement costs. In the standalone biogas system, the BG requires 8,760 operating hours annually to meet a demand load of 58,272 kWh/year. On the other hand, the BG in PV/biogas system needs 2,221 operating hours per year. In this case, with a BG lifetime of 15,000 operating hours, the standalone biogas system requires a higher replacement cost than the PV/biogas system over the 25 years project lifetime. The annualized cost of the standalone biogas system is tabulated in Table 4. The total annualized cost of the standalone biogas system is about $13,109.96/year. The total annualized cost of the PV/biogas system is estimated at $8,616.77, and the annualized cost breakdown of each component is presented in Table 5. It is clear that hybridization of the biogas system with another renewable energy resource, such as a PV system, has the beneficiary of reducing the total NPC and COE of the energy generation system.

Table 4. Annualized cost of the biogas system

Component	Capital ($/y)	Replacement ($/y)	O&M ($/y)	Salvage ($/y)	Total ($/y)
Biodigester	1856.51	0	240	0	2,096.51
BG	773.54	5,050.63	5,256.00	-66.71	11,013.46
System	2,630.05	5,050.63	5,496.00	-66.71	13,109.96

Table 5. Annualized cost of the PV/biogas hybrid system

Component	Capital ($/y)	Replacement ($/y)	O&M ($/y)	Salvage ($/y)	Total ($/y)
Biodigester	1,856.51	0	240	0	2,096.51
BG	773.54	1013.58	1,332.6	-49.76	3,069.96
PV	925.26	0	119.61	0	1,044.87
Inverter	222.04	84.79	0	-15.96	290.87
Battery	804.49	1468.92	0.8	-159.65	2,114.56
System	4,581.84	2,567.29	1,693.01	-225.37	8,616.77

Compared to an electricity tariff, the COE of the PV/biogas system is 35.77% higher than the Indonesian electricity tariff for households of $0.095/kWh in 2022. This low electricity tariff is cross-subsidized based on the cost of electricity production by various regions in Indonesia, which ranges between $0.0625/kWh and $0.1925/kWh. The highest electricity production costs occur in islands, mountains, and other small sub-system power plants in Indonesia. However, the COE of the PV/biogas system is still 30.16% lower than the highest cost of electricity production in Indonesia. The high investment cost of the PV/biogas system is influenced by the high cost of the biogas system. The installation costs for the biodigester that are necessary to obtain biogas from POME biomass are relatively expensive. In this case, the NPC of PV/biogas is dominated by a biogas system (59.96%) which comprises of biodigester and BG costs, as shown in Figure 10. Nevertheless, observations on the COE of PV/biogas systems in different countries show that the PV/biogas system using POME is very competitive with the PV/biogas system using solid biomass, as reported in [44]. It indicates that PV/biogas using POME has a good prospect for electrifying the village communities in palm oil mills with no electricity connecting to the national grid.

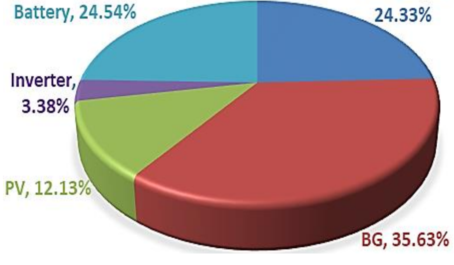

Figure 10. PV/biogas hybrid costs

HOMER uses simple payback, internal rate of return (IRR), and return on investment (ROI) as economic metrics. Simple payback is the length of time when money saved after the renovation will cover the investment [45]. To show how the hybrid energy system saves money over the project lifetime, HOMER uses the simple payback to determine the number of years it would take to recover the difference in investment costs between two energy systems. One energy system has a low capital cost and a high O&M cost, whereas another energy system has a high capital cost and a low O&M cost. In this case, the standalone biogas system has a low investment cost and a high O&M cost. On the other hand, the PV/biogas system has a high investment cost but a low O&M cost. Therefore, the simple payback occurs at the time when the cumulative cash flow of the difference between the two energy systems shifts from negative to positive, as seen in Figure 11. Figure 11 shows that the PV/biogas system and the standalone biogas system are referred as the lowest-cost system and the base case, respectively. As a result, the payback period is 3.4 years.

The IRR is calculated by determining the discount rate at which the standalone biogas system and the PV/biogas system have the same net present cost. Furthermore, the ROI is obtainable after dividing the average yearly difference in nominal cash flows over the project lifetime by the difference in capital cost. By comparing the PV/biogas system with the standalone biogas system, the IRR and the ROI are 26% and 21%, respectively.

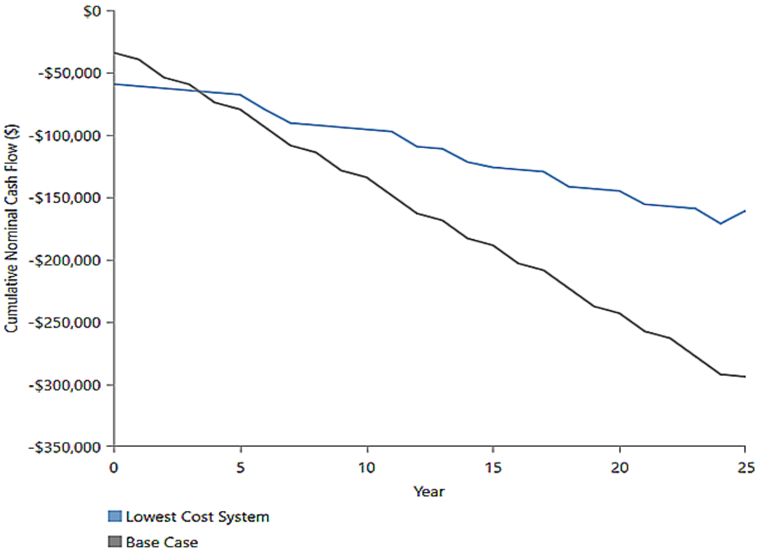

Figure 11. Simple payback over the project lifetime

3.3. Environmental performance

POME, as a waste product after FFB processing, has a detrimental impact on the environment because it releases gases containing high methane (CH_4) and carbon dioxide (CO_2). Methane and CO_2 emissions are major sources of environmental impact, and they play an essential role in increasing global warming. Conversion of POME to biogas for electricity generation has the benefit of minimizing the impact of CH_4 and CO_2 on the environment. According to Jolliet *et al.* [46], biogas fueling in internal combustion systems has no impact on global warming because it emits almost no exhaust gas emissions of CH_4 and CO_2. Biogas produced from the anaerobic digestion process of POME has clean combustion properties. It does not give impact on global warming when used as fuel in a BG to generate electricity through the internal combustion process. However, there are other toxic emissions to the environment caused by the use of biogas in internal combustion, such as nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbon (HC), and particulate matter (PM) that must be considered. According to the damage assessment in [47], large amounts of these toxic emissions have negative effects on human health. In this study, the annual 67,216 kWh electrical load (as seen in Figure 3) is required to be served. Both PV/biogas and standalone biogas systems have 100% renewable fraction. This means that 100% of the energy supplied to the electrical load comes from renewable energy sources. Simulation demonstrates that using the standalone biogas system to meet the demand load results in CO, HC, PM, and NO_x emissions of 19.9 kg/year, 0.875 kg/year, 0.119 kg/year, and 18.7 kg/year, respectively. These results can be compared with the PV/biogas system, as presented in Table 6. The main finding is a reduction of 51.76%, 51.66%, 51.60%, and 51.71% of CO, HC, PM, and NO_x emissions, respectively, when the electricity generated by PV/biogas system compared to standalone biogas system due to

PV penetrations. Table 6 also shows that the emissions are dominated by CO and NO_x. However, the use of biogas allows exhaust CO and NO_x emissions to be reduced significantly compared to gasoline and natural gas [48]. In addition, integrating PV into the biogas system also helps decrease CO, HC, PM, and NO_x emissions to the environment that are harmful to human health. Consequently, the PV/biogas hybrid system contributes a great environmental benefit in generating clean electricity [49].

Table 6. Components of emissions

Quantity	Standalone biogas	PV/biogas
CO	19.9 kg/y	9.6 kg/y
HC	0.875 kg/y	0.423 kg/y
PM	0.119 kg/y	0.0576 kg/y
NO_x	18.7 kg/y	9.03 kg/y

4. CONCLUSION

In this study, an optimal PV/biogas hybrid system was proposed for village electrification. The use of POME to produce biogas as a renewable gaseous fuel for the hybrid PV/biogas system showed that it could change the negative value of POME into a positive externality, both for the community and environmental sustainability. The technical analysis showed that the hybrid system met demand loads without electricity shortages. However, utilizing biogas for electricity was still expensive due to high capital and O&M costs. The energy cost was significantly reduced when integrating a biogas system with other renewable resources, such as solar energy. In the biogas system, the levelized cost of energy was about $0.2250 and dropped to $0.1479/kWh when hybridized with a PV system. The results have indicated the low economic profitability of the biogas power plant in comparison to the PV/biogas hybrid system. From an environmental perspective, the hybrid PV/biogas system using POME could not only produce sustainable renewable energy but it also minimized methane and CO_2, as well as reduce emissions of other harmful gases, such as CO, HC, PM, and $So_{x.}$

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REFERENCES

[1] E. Barcelos, S. Rios, R. N. Cunha, R. Lopes, S. Y. Motoike, E. Babiychuk, A. Skirycz, and S. Kushnir, "Oil palm natural diversity and the potential for yield improvement," *Frontiers in plant science*, vol. 6, p. 190, 2015, doi: 10.3389/fpls.2015.00190.

[2] V. Vijay, S. L. Pimm, C. N. Jenkins, and S. J. Smith, "The impacts of oil palm on recent deforestation and biodiversity loss," *PLOS ONE*, vol. 11, no. 7, p. e0159668, 2016, doi: 10.1371/journal.pone.0159668.

[3] C. Lesage, J. Cifuentes-Espinosa, and L. Feintrenie, "Oil palm cultivation in the Americas: review of the social, economic and environmental conditions of its expansion," *Cahiers Agricultures*, vol. 30 p. 27, 2021, doi: 10.1051/cagri/2021015.

[4] I. Jelsma, M. Slingerland, K. E. Giller, and J. Bijman, "Collective action in a smallholder oil palm production system in Indonesia: The key to sustainable and inclusive smallholder palm oil?" *Journal of Rural Studies*, vol. 54, pp. 198-210, 2017, doi: 10.1016/j.jrurstud.2017.06.005.

[5] L. A. J. Letti, *et al.*,"Chapter 9 - Valorization of solid and liquid wastes from palm oil industry," *Waste Biorefinery, Elsevier*, pp. 235-265, 2021, doi: 10.1016/B978-0-12-821879-2.00009-0.

[6] S. Kaniapan, S. Hassan, H. Ya, K. P. Nesan, and M. Azeem, "The utilisation of palm oil and oil palm residues and the related challenges as a sustainable alternative in biofuel, bioenergy, and transportation sector: a review, *Sustainability*, vol. 13, no. 6, p. 3110, 2021, doi: 10.3390/su13063110.

[7] C. Moliner, E. Arato, and F. Marchelli, "Current status of energy production from solid biomass in Southern Italy," *Energies*, vol. 14, no. 9, p. 2576, 2021, doi: 10.3390/en14092576.

[8] S. Mohammad, S. Baidurah, T. Kobayashi, N. Ismail, and C. P. Leh, "Palm oil mill effluent treatment processes-a review," Processes, vol. 9, no. 5, p. 739, 2021, doi: 10.3390/pr9050739.

[9] N. Firdaus, B. T. Prasetyo, Y. Sofyan, and F. Siregar, "Part I of II: palm oil mill effluent (POME): biogas power plant," Distributed Generation & Alternative Energy Journal, vol. 32, no. 2, pp. 73-79, 2017, doi: 10.1080/21563306.2017.11869110.

[10] S. S. Raman, Z. Z. Noor, S. S. Syed Narolhisa, C. S. Chong, and L. C. Stringer, "Energy generation from palm oil mill effluent (POME): the environmental impact perspective," *Chemical Engineering Transactions*, vol. 72, pp. 25-30, 2019, doi: 10.3303/CET1972005.

[11] W. Uddin *et al.*, "Biogas potential for electric power generation in Pakistan: a survey," *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 25-33, 2016, doi: 10.1016/j.rser.2015.09.083.

[12] M. Caliskan and N. F. T. Ozdil, "Potential of biogas and electricity production from animal waste in Turkey," *BioEnergy Research*, vol. 14, pp. 860-869, 2021, doi: 10.1007/s12155-020-10193-w.

[13] W. S. Ho, H. Hashim, M. H. Hassim, Z. A. Muis, and N. L. M. Shamsuddin, "Design of distributed energy system through electric system cascade analysis (ESCA)," *Applied Energy*, vol. 99, pp. 309-315, 2012, doi: 10.1016/j.apenergy.2012.04.016.

[14] M. R. Mohaghegh, M. Heidari, S. Tasnim, A. Dutta, and S. Mahmud, "Latest advances on hybrid solar–biomass power plants," Energy Sources, Part A: Recovery, *Utilization, and Environmental Effects*, 2021, doi: 10.1080/15567036.2021.1887974.

[15] A. M. Pantaleo, S. M. Camporeale, A. Miliozzi, V. Russo, N. Shah, and C. N. Markides, "Novel hybrid CSP-biomass CHP for flexible generation: thermo-economic analysis and profitability assessment," *Applied Energy*, vol. 204, pp. 994-1006, 2017, doi: 10.1016/j.apenergy.2017.05.019.

[16] J. Soares, A. C. Oliveira, S. Dieckmann, D. Krüger, F. Orioli, "Evaluation of the performance of hybrid CSP/biomass power plants," *International Journal of Low-Carbon Technologies*, vol. 13, no. 4, pp. 380-387, 2018, doi: 10.1093/ijlct/cty046.

[17] Y. Tanaka, S. Mesfun, K. Umeki, A. Toffolo, Y. Tamaura, and K. Yoshikawa, "Thermodynamic performance of a hybrid power generation system using biomass gasification and concentrated solar thermal processes," *Applied Energy*, vol. 160, pp. 664-672, 2015, doi: 10.1016/j.apenergy.2015.05.084.

[18] C. Xu, T. Xin, X. Li, S. Li, Y. Sun, W. Liu, and Y. Yang, "A thermodynamic analysis of a solar hybrid coal-based direct-fired supercritical carbon dioxide power cycle," *Energy Conversion and Management*, vol. 196, pp. 77-91, 2019, doi: 10.1016/j.enconman.2019.06.002.

[19] U. Sahoo, R. Kumar, P. C. Pant, and R. Chaudhary, "Resource assessment for hybrid solar-biomass power plant and its thermodynamic evaluation in India," *Solar Energy*, vol. 139, pp. 47-57, 2016, doi: 10.1016/j.solener.2016.09.025.

[20] R. Soria, J. Portugal-Pereira, A. Szklo, R. Milani, and R. Schaeffer, "Hybrid concentrated solar power (CSP)–biomass plants in a semiarid region: a strategy for CSP deployment in Brazil," *Energy Policy*, vol. 86, pp. 57-72, 2015, doi: 10.1016/j.enpol.2015.06.028.

[21] J. Soares and A. C. Oliveira, "Numerical simulation of a hybrid concentrated solar power/biomass mini power plant," *Applied Thermal Engineering*, vol. 111, pp. 1378-1386, 2017, doi: 10.1016/j.applthermaleng.2016.06.180.

[22] E. K. Burin, L. Buranello, P. L. Giudice, T. Vogel, K. Görner, and E. Bazzo, "Boosting power output of a sugarcane bagasse cogeneration plant using parabolic trough collectors in a feedwater heating scheme," *Applied Energy*, vol. 154, pp. 232-241, 2015, doi: 10.1016/j.apenergy.2015.04.100.

[23] C. C. Ebeya *et al*., "A novel approach for sizing and optimization of hybrid solar-PV, biogas-generator, and batteries system for rural electrification: case study," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 2, pp. 1070-1084, 2023, doi: 10.11591/ijpeds.v14.i2.pp1070-1084.

[24] S. Othman, M. R. Ab. Ghani, Z. Jano, and T. Sutikno, "Modelling of solar micro gas turbine for parabolic dish based controller application," *Telkomnika*, vol. 18, no. 6, pp. 3184-3190, 2020, doi: 10.12928/TELKOMNIKA.v18i6.16676.

[25] J. A. Ruiz, M. C. Juárez, M. P. Morales, L. M. López-Ochoa, and J. Doménech, "Biomass gasification or combustion for generating electricity in Spain: review of its current situation according to the opinion of specialists in the field," *Journal of Renewable and Sustainable Energy*, vol. 5, p. 012801, 2013, doi: 10.1063/1.4792605.

[26] D. Alfonso-Solar, C. Vargas-Salgado, C. Sánchez-Díaz, and E. Hurtado-Pérez, "Small-scale hybrid photovoltaic-biomass systems feasibility analysis for higher education buildings," *Sustainability*, vol. 12, no. 21, p. 9300, 2020, doi: 10.3390/su12219300.

[27] L. Al-Ghussain, A. D. Ahmad, A. M. Abubaker, and M. A. Mohamed, "An integrated photovoltaic/wind/biomass and hybrid energy storage systems towards 100% renewable energy microgrids in university campuses," *Sustainable Energy Technologies and Assessments*, vol. 46, p. 101273, 2021, doi: 10.1016/j.seta.2021.101273.

[28] N. Chowdhury, C. A. Hossain, M. Longo, and W. Yaïci, "Feasibility and cost analysis of photovoltaic-biomass hybrid energy system in off-grid areas of Bangladesh," *Sustainability*, vol. 12, no. 4, p. 1568, 2020, doi: 10.3390/su12041568.

[29] A. Barragán-Escandón, J. M. O. Ruiz, J. D. C. Tigre, and E. F. Zalamea-León, "Assessment of power generation using biogas from landfills in an equatorial tropical context," *Sustainability*, vol. 12, no. 7, p. 2669, 2020, doi: 10.3390/su12072669.

[30] Y. Rajbhandari, A. Marahatta, A. Shrestha, A. Gachhadar, A. Thapa, F. Gonzalez-Longatt, and J. M. Guerre, "Load prioritization technique to guarantee the continuous electric supply for essential loads in rural microgrids," *International Journal of Electrical Power & Energy Systems*, vol. 134, p. 107398, 2022, doi: 10.1016/j.ijepes.2021.107398.

[31] P. L. Tang, W. L. Hong, C. S. Yue, and S. Harun, "Palm oil mill effluent as the pretreatment solvent of oil palm empty fruit bunch fiber for fermentable sugars production," *Bioresource Technology*, vol. 314, p. 123723, 2020, doi: 10.1016/j.biortech.2020.123723.

[32] O. W. Awe, Y. Zhao, A. Nzihou, D. P. Minh, and N. Lyczko, "A review of biogas utilisation, purification and upgrading technologies," *Waste and Biomass Valorization*, vol. 8, pp. 267-283, 2017, doi: 10.1007/s12649-016-9826-4.

[33] G. Wang, Z. Zhang, and Z. Hao, "Recent advances in technologies for the removal of volatile methylsiloxanes: a case in biogas purification process," *Critical Reviews in Environmental Science and Technology*, vol. 49, no. 4, pp. 2257-2313, 2019, doi: 10.1080/10643389.2019.1607443.

[34] X. Lok, Y. J. Chan, and D. C. Y. Foo, "Simulation and optimisation of full-scale palm oil mill effluent (POME) treatment plant with biogas production," *Journal of Water Process Engineering*, vol. 38, p. 101558, 2020, doi: 10.1016/j.jwpe.2020.101558.

[35] S. O. Masebinu, E. T. Akinlabi, E. Muzenda, A. O. Aboyade, and C. Mbohwa, "Experimental and feasibility assessment of biogas production by anaerobic digestion of fruit and vegetable waste from Joburg Market," *Waste Management*, vol. 75, pp. 236-250, 2018, doi: 10.1016/j.wasman.2018.02.011.

[36] A. Hazmi, R. Desmiarti, E. P. Waldi, and P. Emeraldi, "Preliminary study on treatment of palm oil mill effluent (POME) by sand filtration-DBD plasma system," *Journal of Engineering and Technological Sciences*, vol. 48, no. 1, pp. 21-30, 2016, doi: 10.5614/j.eng.technol.sci.2016.48.1.3.

[37] M. Mohammed, I. S. Egyir, A. K. Donkor, P. Amoah, S. Nyarko, K. K. Boateng, and C. Ziwu, "Feasibility study for biogas integration into waste treatment plants in Ghana," *Egyptian Journal of Petroleum*, vol. 26, no. 3, pp. 695-703, 2017, doi: 10.1016/j.ejpe.2016.10.004.

[38] C. Ghenai and I. Janajreh, "Design of solar-biomass hybrid microgrid system in Sharjah," *Energy Procedia*, vol. 103, pp. 357-362, 2016, doi: 10.1016/j.egypro.2016.11.299.

[39] R. Kurnianto, A. Hiendro, and M. I. Yusuf, "Optimum orientation angles for photovoltaic arrays to maximize energy gain at near equator location in Indonesia," *International Review of Automatic Control*, vol. 10, no. 1, pp. 86-91, 2017, doi: 10.15866/ireaco.v10i1.11017.

[40] A. Hiendro, R. Kurnianto, M. Rajagukguk, Y. M. Simanjuntak, and Junaidi, "Techno-economic analysis of photovoltaic/wind hybrid system for onshore/remote area in Indonesia," *Energy*, vol. 59, pp. 652-657, 2013, doi: 10.1016/j.energy.2013.06.005.

[41] H. Al-Najjar, H. J. El-Khozondar, C. Pfeifer, and F. Al Afif, "Hybrid grid-tie electrification analysis of bio-shared renewable energy systems for domestic application," *Sustainable Cities and Society*, vol. 77, p. 103538, 2022, doi: 10.1016/j.scs.2021.103538.

[42] I. P. G. I. Dwipayana, I. N. S. Kumara, and I. N. Setiawan, "Status of battery in Indonesia to support application of solar PV with energy storage," *Journal of Electrical, Electronics and Informatics*, vol. 5, no. 1, pp. 29-40, 2021, doi: 10.24843/JEEI.2021.v05.i01.p06.

[43] T. Srinivasa, and B. V. Reddy, “Hybrid solar-biomass power plant without energy storage,” *Case Studies in Thermal Engineering*, vol. 2, pp. 75-81, 2014, doi: 10.1016/j.csite.2013.12.004

[44] S. O. Sanni, M. Ibrahim, I. Mahmud, T. O. Oyewole , and K. O. Olusuyi, “Potential of off-grid solar PV/biogas power generation system: Case study of Ado Ekiti slaughterhouse,” *International Journal of Renewable Energy Research*, vol. 9, no. 3, pp. 1309-1318, 2019, doi: 10.20508/ijrer.v9i3.9559.g7711.

[45] N. Lepkova, D. Zubka, and R. L. Jensen, “Chapter 10 - Financial investments for zero energy houses: the case of near-zero energy buildings,” *Global Sustainable Communities Handbook*, pp. 217-253, 2014, doi: 10.1016/B978-0-12-397914-8.00010-2.

[46] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, and R. Rosenbaum, “IMPACT 2002+: a new life cycle impact assessment methodology,” *The International Journal of Life Cycle Assessment*, vol. 8, pp. 324-330, 2003, doi: 10.1007/BF02978505.

[47] A. Macor and A. Benato, “Regulated emissions of biogas engines—on site experimental measurements and damage assessment on human health,” *Energies*, vol. 13, no. 5, p. 1044, 2020, doi: 10.3390/en13051044.

[48] S. K. Hotta, N. Sahoo, and K. Mohanty, “Comparative assessment of a spark ignition engine fueled with gasoline and raw biogas,” *Renewable Energy*, vol. 134, pp. 1307-1319, 2019, doi: 10.1016/j.renene.2018.09.049.

[49] A. Sakhrieh, J. A. Asfar, and N. A. Shuaib, “An optimized off-grid hybrid system for power generation in rural areas,” *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 2, pp. 865-872, 2022, doi: 10.11591/ijpeds.v13.i2.pp865-872.

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