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Profitability on Solar Power Plant Systems for Households Electricity in Indonesia

HENDRA SETIAWAN[1], ALI PARKHAN[2]

[1]Electrical Engineering Department, Universitas Islam Indonesia, Indonesia
[2]Industrial Engineering Department, Universitas Islam Indonesia, Indonesia
Email: hendra.setiawan@uii.ac.id

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ABSTRAK

Paper ini menganalisis secara teknis dan ekonomi PLTS (pembangkit listrik tenaga surya) hibrid off-grid untuk rumahtangga di Yogyakarta, Indonesia. Sistem PLTS terdiri dari delapan panel surya polikristalin dengan daya 410Wp masing-masing, inverter 3kW, dan baterai LiFePO4 (lithium ferrophosphate) 48V 300Ah. PLTS telah dioperasikan sejak awal 2021, dan energi yang terkumpul dari panel surya dimulai November 2021 hingga akhir Agustus 2022, menunjukkan variasi nilai dari 3,2kWh hingga 17,4kWh. Dengan mempertimbangkan efisiensi perangkat 85%, hasil total energi diperkirakan 3.740,7 kWh per tahun. Penelitian ini mendapatkan nilai hasil rata-rata tahunan sebesar 1.140,5 kWh/kWp dan rasio kinerja 63,4%. NPV (net present value) digunakan sebagai indikator kelayakan investasi, dengan hasil masa investasi 24 tahun, tingkat diskonto 7%, laju degradasi PV (fotovoltaik) sebesar 0,8%, dan penurunan baterai sebesar 1,5% per tahun. Studi ini menyoroti potensi keuntungan investasi PLTS dengan kondisi tertentu dan mendorong intervensi regulasi pemerintah untuk meningkatkan aplikasi PLTS.

***Kata kunci**: PLTS, off-grid, NPV, panel surya, rasio kinerja*

ABSTRACT

This paper presents technical and economic analysis of hybrid off-grid SPP (Solar Power Plant) for a home in Yogyakarta City, Indonesia. The system consists of eight polycrystalline photovoltaic with 410Wp each, 3kW inverter and a 48V 300Ah LiFePO4 (lithium ferrophosphate) battery. The harvested energy was recorded starting from November 2021 to the end of August 2022. The recorded data shows the variation of values from 3.2kWh to 17.4kWh. The annual energy is 3,740.7 kWh by considering 85% devices efficiency. Furthermore, an annual average final yield is 1,140.5 kWh/kWp and performance ratio is 63.4%. NPV (net present value) was used as an indicator of feasibility investments by considering device lifespan, 7% discount rate, 0.8% of PV (photovoltaic) degradation rate and 1.5% battery fade per year. This study highlights the potential benefits of investing in hybrid off-grid SPP under specific conditions and advocates for government intervention through regulations to enhance the SPP applications.

***Keywords**: Solar Power Plant, off-grid, NPV, photovoltaic, performance ratio*

1. INTRODUCTION

Based on solar resource maps **(Solargis, 2018)**, Indonesia has a significant potential for sunlight, estimated at around 3.6 – 6 kWh/m^2/day, with energy harvesting of 1,170 – 1,530 kWh/kWp per year. According to Nayak *et al.* **(Nayak et al., 2019)** this potential should be taken into account and explored as an alternative source of electrical energy. Unfortunately, the solar capacity utilization in Indonesia is only 2% of total renewable capacity by 2021 **(International Renewable Energy Agency, 2021)**.

The capacity of solar energy as an alternative source has witnessed significant growth in the past decade. According to data presented in **(International Renewable Energy Agency, 2023)**, the total installed capacity of solar power plants (SPP) worldwide reached 1.05 TW by the end of 2022. Although the SPP capacity falls slightly behind hydropower, which reached 1.25 TW by the same period, it surpasses wind power (0.89 TW), bioenergy (148.9 GW), and geothermal (14.8 GW) capacities **(International Renewable Energy Agency, 2023)**. However, in terms of capacity expansion, solar power plants have emerged as the leading renewable energy source.

To expedite the adoption of renewable energy (RE) in Indonesia, the government established the Dewan Energi Nasional (National Energy Council) in 2007. Additionally, the government issued Government Regulation No. 79 of 2014 **(Indonesia, Pemerintah Pusat, 2014)** concerning national energy policies. That regulation and policy declare the target for RE capacity reach 23% in 2025 and 31% in 2050.

At the operational level, the government has issued Presidential Decree No. 22 of 2017 **(Indonesia, Pemerintah Pusat, 2017)**, which outlines the national energy public plan. This decree highlights the technical potential of solar power plants (SPP) and sets expectations for each province in Indonesia. According to the decree, the SPP potential is projected to reach 6.5 GW by 2025, as illustrated in Figure 1.

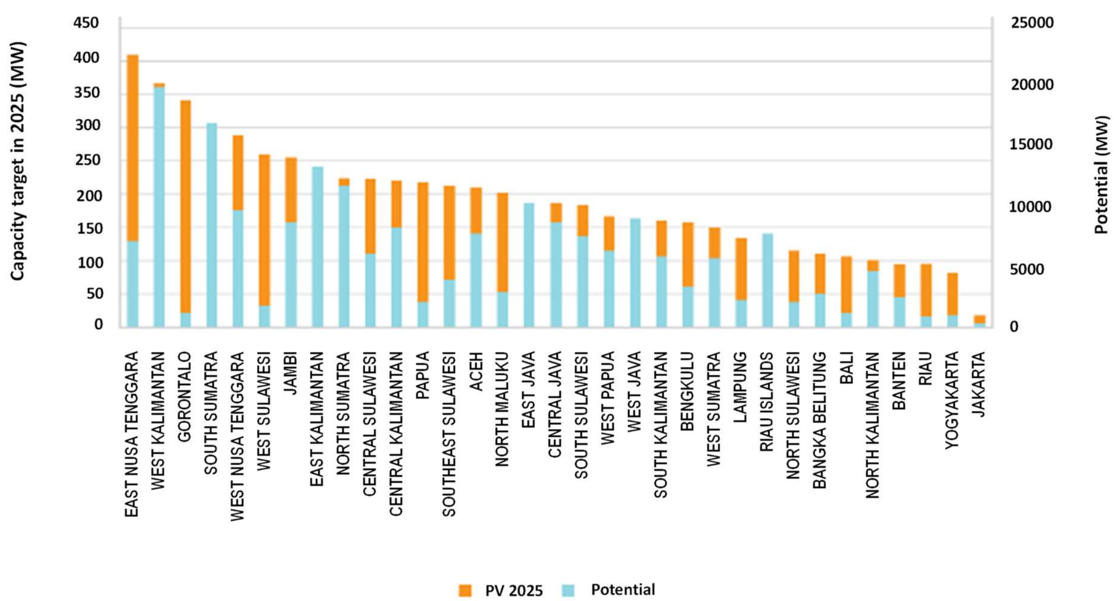

Figure 1. PV Potential and Capacity Targets in 2025 are Based on the Location of Each Province in Indonesia (Indonesia, Pemerintah Pusat, 2017)

The Ministry of Energy and Mineral Resources targets a rooftop solar photovoltaic (PV) total capacity of 3.6 GW in 2025 which is 450 MWp in 2022, 900 MWp in 2023, 1,800 MWp in 2024 and 3,600 MWp in 2025 **(Humas EBTKE, 2022)**. However, until the end of January 2022, the total capacity of rooftop solar PV was 51.19 MWp or around 11.4% of the 450 MWp target.

Numerous articles regarding the implementation of solar power plants (SPP) in Indonesia have been published. Off-grid SPP systems were presented in studies by Hasanah *et al*. **(Hasanah et al., 2018)**, Syafii *et al.* **(Syafii et al., 2019)**, Naim **(Naim, 2020)**, Syawil dan Kadir **(Syahwil & Kadir, 2021)**, and Alwani *et al*. **(Alwani et al., 2022)**. Additionally, on-grid systems were discussed in works by Naim and Wardoyo **(Naim & Wardoyo, 2017)**, Nurosyid *et al*. **(Nurosyid et al., 2019)**, and Hutajulu *et al.* **(Hutajulu et al., 2020)**. Studies comparing off-grid and on-grid SPP systems, such as the one conducted by Jalaluddin and Safarudin **(Jalaluddin & Safarudin, 2020)**, explored the design and technical aspects of SPP and provided data generated by SPP over short time durations. However, to obtain a more accurate representation of reality, it is essential to have long-term electrical data records (at least 6 months) from SPP systems.

The availability of valid data over a sufficient period is crucial for further studies and serves as strong evidence of the benefits of solar power plants (SPP). Furthermore, most articles predominantly focus on the technical aspects of SPP rather than the economic aspects. Therefore, in this article, we aim to contribute a comprehensive perspective on SPP, covering both technical and economic aspects by providing real data obtained from an SPP system. The data was collected over a 10-month period (November 2021 to August 2022) following the installation of the SPP in Yogyakarta, Indonesia. Based on this data, we conducted an analysis of the SPP to address the question, "Is the implementation of SPP in Indonesia profitable?" We hope that the results of this study will be beneficial for individuals and organizations considering the implementation of SPP systems in Indonesia, as well as for the government in expediting the development of SPP across the country.

The aim of this research is to assess the feasibility of off-grid solar power generation systems for household applications in Indonesia. The research comprises four stages: (1) designing and installing off-grid solar power generation systems, (2) gathering energy harvesting data, (3) analyzing system performance, and (4) conducting an economic feasibility analysis.

2. METHOD

In this research, the method consists of designing an SPP system, implementing it, observing the resulting data, and conducting an analysis of that data. The design process was carried out based on the actual load profile conditions of a house in the Yogyakarta area. Based on this load profile, calculations were made for the required capacities of the solar panel, inverter, and battery. The details of our design are presented below.

2.1 Location

The SPP system is situated in the Special Region of Yogyakarta, with Google Maps coordinates -7.806754, 110.426279, and an elevation of 100 meters above sea level.

According to the data provided by Solargis **(Solargis, 2022)**, the SPP location exhibits a photovoltaic power output of 4.09 kWh/kWp per day or 1493.4 kWh/kWp per year. This value aligns with the average photovoltaic power potential for the Indonesian region, as reported by Solargis in 2018 **(Solargis, 2018)**. Consequently, the findings from this SPP system can be extrapolated to other typical SPP systems throughout Indonesia, regardless of the specific components involved.

2.2 Load Profile

The SPP system is utilized to provide electricity for the household, replacing the previous reliance on the Perusahaan Listrik Negara (PLN), the State Electricity Company. The household was previously a customer of PLN with a maximum power capacity of 1,300VA. The loads to be powered by the SPP system include common household appliances such as lamps, television, air conditioning, and refrigerator. The complete load profile for the household is provided in Table 1

Table 1. Load Profile of A Solar Power Plant for A Particular Household

Appliances	Qty	Power (W)	Utilization (hours)	Appliances	Qty	Power (W)	Utilization (hours)
Refrigerator	1	120	24	Bread mixer	1	400	0-1
Water pump#1	2	125	1-2	Vacuum Cleaner	1	450	0-1
Water pump#2	1	175	1-3	Rice cooker	1	350	0.5-4
Washing machine	1	400	2-3	Lamp#1	1	20	24
Television	1	60	1-5	Lamp#2	3	20	8-10
Air conditioning#1	1	480	4-8	Lamp#3	1	15	10-15
Air conditioning#2	2	450	0-6	Lamp#4	3	10	10-12
Computer desktop	1	120	2-6	Lamp#5	2	7	1-2
Standing fan	1	30	20-24	Lamp#6	1	7	24
Treadmill	1	600	0-2	Lamp#7	3	9	6-12
Iron	1	300	0-3	Lamp#8	1	40	10-12
Deck oven	1	100	0-3				

2.3 Solar Power Plant Specification

The total energy consumption is estimated to range from 10.53 kWh to 22.37 kWh per day. The peak load, which occurs when all appliances are turned on simultaneously, is 4,288 W. The design of the SPP system takes into account the following constraints: (a) maximizing the duration of electricity and minimizing blackouts, (b) maximizing the utilization of solar energy while utilizing backup energy from PLN, and (c) minimizing the budget. Based on these constraints, the SPP system is designed with the following specifications.

2.3.1 Photovoltaic (PV)

Indonesia has a potential sunlight availability of around 3.6 – 6 kWh/m^2/day **(Solargis, 2018)**. Assuming a solar power potential of 1 kW/m^2, this translates to an irradiation duration of approximately 3.6 – 6 hours per day. Let's consider an irradiation duration of 4.5 hours, resulting in a solar panel or PV capacity requirement of 2.34 to 4.97 kWp for a daily energy output of 10.53 to 22.37 kWh.

Table 2 displays several PV available in Indonesia, along with their prices, aiming to match the 2.34 to 4.97 kWp capacity range. Please note that the prices listed were obtained from the lowest price offerings on Indonesian online markets, as of early 2021. We have selected the three lowest-priced, i.e. 410 Wp Canadian poly, 330 Wp JA poly, and 200 Wp ICA mono.

Table 2. Various Photovoltaic Quantities and Budgets to Match the 2.34 to 4.97 kWp

Solar Panel	Quantity	Total Price ($\times 10^6$ rupiah)	Price/kWp ($\times 10^3$ rupiah)
250Wp Solana Mono	10 – 20	21.1 – 42.3	8.4
150Wp Solana Mono	16 – 34	21.6 – 45.9	9.0
410Wp Canadian Poly	6 – 13	15.0 – 32.5	6.0
120Wp Maysun Mono	20 – 42	23.2 – 48.7	9.6
200Wp ICA Mono	12 – 25	16.8 – 35.0	7.0
120Wp GH Mono	20 – 42	17.7 – 37.1	7.3
330Wp JA Poly	8 – 16	16.8 – 33.6	6.3
540Wp JA Mono	5 – 10	19.5 – 39.0	7.2

2.3.2 Inverter

The proposed SPP system is a hybrid off-grid system. With a daily energy consumption of 22.37 kWh, the average power per hour amounts to 932 W. However, during peak load when all appliances are turned on, the total power can reach up to 4,290 W. Therefore, the suitable inverters for this system are either 3,000 W or 5,000 W. Considering budget constraints, a 3,000 W hybrid inverter is chosen. The detailed specifications of the inverter are provided in Table 3.

Table 3. Detail of the Inverter Specifications

Parameter	Value
Max. PV input	150VDC
Optimum operating voltage	65 - 120VDC
Max. Charging current	65A
Recommended PV configuration	3,500
Inverter Output power	3000W
Power factor	1
Rated Output Frequency	50Hz / 60Hz ± 1% (inverter mode)
Maximum Efficiency (resistive load)	≥85 %
Battery Voltage	48V

Let's assess the compatibility of the PV candidates with the chosen inverter based on the inverter specifications. The key considerations include ensuring that the total open circuit voltage (Voc) of the PV array matches the optimum operating voltage of the inverter, and that the total power of the PV array aligns closely with the recommended PV configuration for the inverter. Table 4 presents these parameters for evaluation.

Table 4. The Comparison of PV Configurations to Match the Inverter's Voc With A Total PV Power of 2.34 to 4.97 kWp

PV Candidate	Voc (V)	Config.	Total Voc (V)	Total Power (W)
410Wp Canadian	47.60	2S 4P	95.2	3280*
		2S 5P	95.2	4100
200Wp ICA	50.53	2S 6P	101.1	2400
		2S 7P	101.1	2800
		2S 8P	101.1	3200
		2S 9P	101.1	3600*
		2S 10P	101.1	4000
330Wp JA	46.40	2S 4P	92.8	2640
		2S 5P	92.8	3300*
		2S 6P	92.8	3960

Table 4 suggests three recommended PV array configurations: 2S 4P for the 410Wp Canadian panel, 2S 9P for the 200Wp ICA panel, and 2S 5P for the 330Wp JA panel. Considering budget constraints, the 2S 4P configuration for the 410Wp Canadian panel is chosen for the PV array in the SPP system.

2.3.3 Battery

The required battery capacity can be determined based on either the load profile or the PV capacity. Considering the load profile, where the maximum energy consumption per day is 22.37 kWh and assuming equal energy consumption during daylight and night-time, the minimum battery capacity required is 11.2 kWh. For a 48V system with an 80% depth of discharge (DOD), the minimum battery current capacity would be 292Ah, approximately 300Ah.

From the PV capacity perspective, considering the expected energy generation by the PV system for 3.6 - 6 hours of irradiation (11,808 - 19,680Wh), assuming equal energy consumption during daylight and night-time, the minimum battery capacity required during maximum irradiation is 9.84 kWh. For a 48V system with an 80% depth of discharge (DOD), the minimum battery current capacity is calculated to be 256.25 Ah. Hence, a battery capacity of 300 Ah is reasonable.

We have chosen to use $LiFePO_4$ (LFP) batteries as the energy storage for several reasons. Firstly, LFP batteries are widely used and offer benefits such as long lifespan and high safety **(Panchal, et al., 2017)**. Secondly, they are lightweight, require zero maintenance, and exhibit superior charge and discharge characteristics **(Li & Ma, 2019)**. Additionally, Table 5 presents the specifications of the LFP batteries utilized in this project. To optimize the performance of the batteries, we have incorporated a battery management system (BMS) and active balancing.

Table 5. Detail LiFePO4 Battery Specification

Parameters	Value	Parameters	Value
System voltage	48V	Charging voltage	55V
Configuration	16s	Max charging current	60A
Capacity	300Ah	Max discharge current	100A
DOD	80%		

2.4 Data Collecting

The installation of the SPP system commenced in April 2021. However, the collection of energy harvesting data began on November 1^{st}, 2021, and continued until August 31^{st}, 2022. The energy harvesting data was measured and displayed by the inverter, representing the total energy produced by the PV system during daylight hours. The data collection typically took place in the evening, between 6:00 PM and 7:00 PM.

Based on the collected data, we conducted an analysis from technical aspects, including efficiency calculations and statistical figures. Additionally, we assessed the economic value of the SPP system using Net Present Value (NPV). The detailed discussions regarding these aspects are provided below.

3. RESULT AND DISCUSSION

3.1 Technical Aspects

The initial value recorded on October 31st, 2021, was 1,847.1 kWh, while the final value recorded on August 31st, 2022, was 5,396.8 kWh. There is a linear trend with a total energy harvest of 3,549.7 kWh over the course of 10 months. This translates to an average energy harvest of 354.97 kWh per month. However, the daily energy harvest exhibits significant variation, ranging from 3.2 kWh to 17.4 kWh, as shown in Figure 2. Assuming 100% PV and SCC efficiencies, this indicates that the duration of irradiance varies from 1.0 hour to 5.3 hours per day.

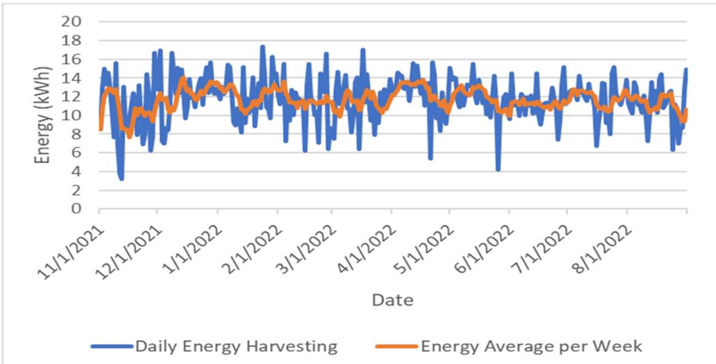

Figure 2. Daily and Weekly Variation of Energy Harvested from PV During November 1st, 2021, to August 31st, 2022

The annual average final yield and performance ratio (PR) serve as crucial performance indicators for any PV system. The PR represents the relationship between the actual power generation of the photovoltaic system and the reference power generation (Y_{ref}) as defined by the International Electrotechnical Commission **(International Electrotechnical Commission, 2021)**. The annual average final yield (Y_f) is a measure of the energy produced by the PV system (E_p) divided by the installed power (P_{nom})

$$PR = \frac{Y_f}{Y_{ref}} = \frac{E_p/P_{nom}}{Y_{ref}} \quad (1)$$

To forecast the annual energy production, we utilize the PVGIS data presented by European Commission website **(European Communities, 2023)**, where the energy yield from November 2021 to August 2022 represents approximately 80.66% of the total annual energy production. Based on an energy harvest of 3,549.7 kWh during this period, the estimated annual energy production amounts to 4,400.8 kWh. Taking into account the inverter efficiency of 85% as stated in Table 3, the total energy required to supply the load is calculated as 3,740.7 kWh. Consequently, the annual average final yield is determined to be 1,140.5 kWh/kWp. This performance is 10.2% lower than the findings of Lindig *et al*. **(Lindig et al., 2021)**, which reported an annual average final yield of 1,270 kWh/kWp for global horizontal irradiance (GHI) in the range of 1,600-1,800 kWh/m^2/year.

According to Solargis **(Solargis, 2018)**, the global horizontal irradiance (GHI) in Indonesia ranges from approximately 1,170 to 2,190 kWh/m^2/year. However, at the specific location where the photovoltaic system is installed, the GHI is approximately 1,800 kWh/m^2/year. With an annual average final yield (Y_f) of 1,140.5 kWh/kWp, we can calculate the performance ratio (PR) based on (1), which amounts to 63.4%. This value is 5.4% lower than the average PR reported for GHI in the range of 1,600-1,800 kWh/m^2/year, which is 67% **(Lindig et al., 2021)**.

3.2 Economical Aspects

To set up the SPP system, a total initial investment of 4,492 USD is required, as detailed in Table 6. Please note that the prices of the solar devices are provided in Indonesian Rupiah (IDR) and have been converted to US dollars using an exchange rate of IDR 15,000 per 1 US dollar. Consequently, the project's initial cost amounts to 1.37 USD/Wp, which is lower than the initial investment for Concentrated Solar Power in China, where the range was between 3.05 and 5.77 USD/Wp **(Yang et al., 2018)**.

Table 6. Initial Capital Consisting of PV, Battery, Inverter, and Initial Installation

Components	Price (USD)	Expected life (Year)
Solar Panel (PV)	1,067	25
Battery	2,775	12
Inverter (include SCC)	500	15
Initial installation	150	-
Total cost	4492	

The anticipated lifespan of a device refers to the duration it is expected to remain operational after being utilized. The user manual states that the expected lifespan for PV is 25 years, while SCC is anticipated to last 15 years. However, the lifespan of a battery is dependent on usage and its environment. Research indicates that the lifespan of a battery ranges from 8 to 12 years **(Beltran et al., 2020)**. In this case, we will consider a battery lifespan of 12 years due to an 80% depth of discharge (DOD). According to Kennedy **(Kennedy, 2021)**, the lifespan of a centralized residential string inverter is approximately 10 to 15 years, and we will take the middle value of 13 years. Consequently, during the 24 years of operation, it will be necessary to replace the SCC, inverter, and battery at least once.

The total amount of energy produced annually is approximately 3,740.7 kWh. PLN, the state electricity company, has created 37 different tariff groups to set electricity tariffs. The tariff adjustment at the end of 2022 has been set at IDR 1,444.70 for non-subsidized residential customers with a power limit of 2,200 VA and commercial groups with a power limit ranging from 6,600 VA to 200 kVA **(PLN, 2022)**. As a result, implementing SPP will yield a total savings of IDR 5,404,189 or USD 360.3 per year.

According to Darghouth *et al*. **(Darghouth et al., 2020)**, the yearly expense for the operation and maintenance (O&M) of SPP systems in Indonesia stands at 350,000.00 IDR/kWp or 23.33 USD/kWp of the installed solar panel capacity. Consequently, the annual O&M cost would amount to IDR 1,148,000 or USD 76.5. Based on this, the net income for a year would be USD 283.8, which is derived by subtracting USD 76.5 from USD 360.3.

To determine the economic value of an SPP investment, a net present value (NPV) calculation is performed. NPV represents the current worth of an investment over its lifetime, taking into account the time value of money. The NPV formula is expressed as follows:

$$NPV = \sum_{t=0}^{24} \frac{R_t}{(1+i)^t} \quad (2)$$

where R_t is net cash inflow – outflows during a single period t, i is the discount rate or rate of return on capital, and t is the number of times periods.

According to the IRENA **(International Renewable Energy Agency, 2020)**, the discount rate specified for Organization for Economic Cooperation and Development (OECD) countries and China is 7.5%, while for other countries, it is 10%. However, IEA **(International Energy Agency, 2020)** assumes a discount rate of 7% specifically for developing countries.

For the NPV calculation (2), we will use a discount rate (*i*) of 7% since it is appropriate for developing countries. The analysis period for the NPV calculation is 24 years, which aligns with the previous information provided. Additionally, we will consider a PV system performance loss or degradation rate (DR) of -0.8% based on the research by Lindig *et al*. **(Lindig et al., 2021)**.

According to Naumann *et al*. **(Naumann et al., 2020)**, for a battery with 80% depth of discharge (DOD) and 1C in charge and discharge, the battery's discharge capacity will degrade to 70% after approximately 9,000 full equivalent cycles (FEC). Assuming one FEC per day, 9,000 FECs is equivalent to 25 years. This degradation rate corresponds to a 1.5% reduction in battery capacity per year. Since the battery stores half of the total energy obtained in one day, the total energy yield will decrease by 0.75% per year. In further, we call it battery fade (BF). Additionally, it is assumed that there is no residual value for any of the devices involved in this system.

Based on the parameters provided and assuming flat electricity tariffs over 24 years, the NPV profile is depicted in Figure 3. The investment value at the end of the 24-year period is USD -3,139.99. This negative value indicates that the investment is not profitable.

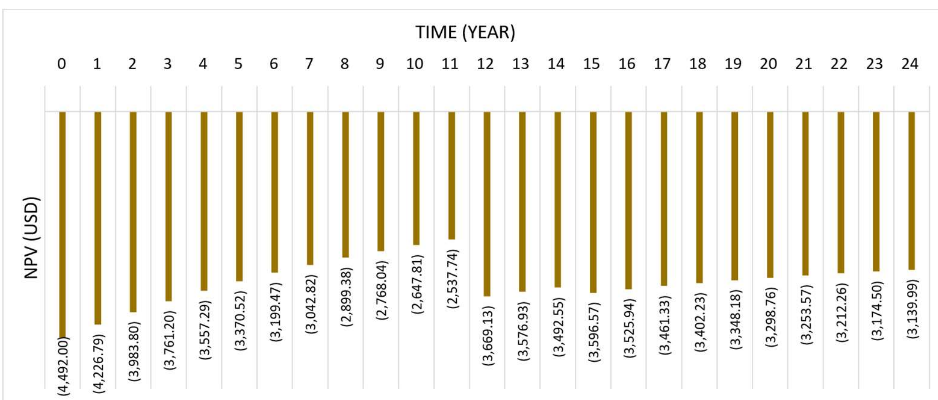

Figure 3. NPV Profile for Discount Rate (i) of 7%, PV Degradation Rate (DR) of 0.8%, Battery Fade (BF) of 0.75%, and A Constant Electricity Tariff

Let's consider various scenarios to explore possibilities for making the SPP system profitable within 24 years. Firstly, we can reduce the discount rate to 6%, 4%, 2%, and 0%, while keeping the other parameters unchanged. Figure 4 illustrates the NPV profile for this scenario, and it indicates that changing the discount rate alone does not make the SPP system profitable. The internal rate of return (IRR) is a discount rate at which the net present value (NPV) of all cash flows becomes zero. In this scenario, we have determined that the IRR is -5.37%. This indicates that it is not possible to make the SPP system profitable using this particular scenario.

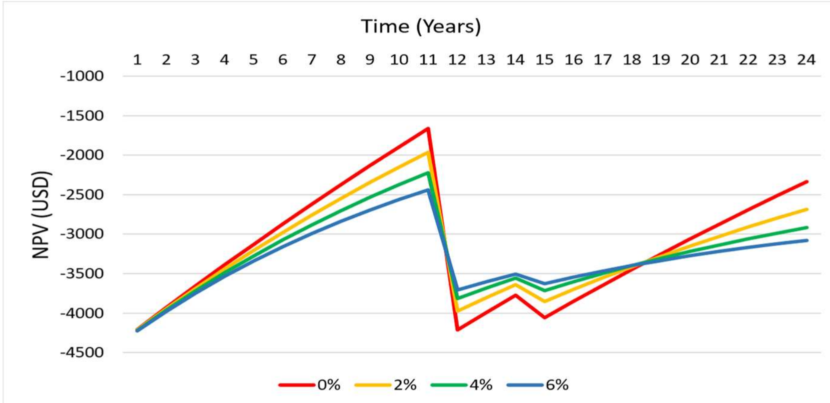

Figure 4. The Investment Remains Unprofitable for Various Discount Rates (i) and A Constant Electricity Tariff

In the second scenario, we consider reducing the PV degradation rate (DR), reducing battery fade (BF), and increasing the efficiency (DE) of the devices, including the SCC and inverter. Despite making these changes that approach an ideal condition, the SPP investment still does not generate a profit within the 24-year timeframe. It is observed that the impact of these parameter adjustments is relatively less significant compared to the effect of the discount rate. This suggests that the discount rate plays a more significant role in determining the profitability of the SPP investment than the individual changes made to the PV degradation rate, battery fade, and device efficiency.

In the third scenario, we consider using the battery for the full 24-year duration without replacement. This means there is no expense in the 12th year for battery replacement. However, the PV degradation rate, battery fade, and device efficiency remain the same as in the first scenario. Despite this change, as depicted in Figure 5, the SPP investment still does not become profitable within the given timeframe.

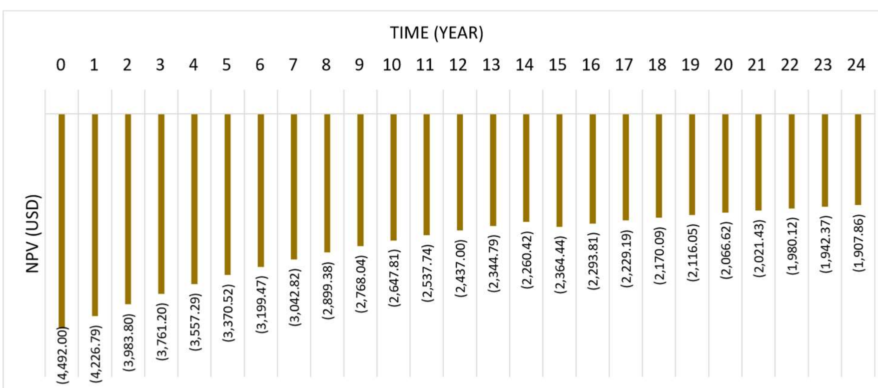

Figure 5. NPV Profile Indicates that Even by Extending the Battery's Lifespan to Its Maximum Without Replacement

In the fourth scenario, we combine the elements of the previous scenarios, including the discount rate (*i*), PV degradation rate (DR), battery fade (BF), devices efficiency (DE), and the absence of battery replacement cost. Figure 6 displays the NPV profile for this combined scenario. Based on the results, the SPP investment will become profitable after 24 years if the discount rate (*i*) is 3%, PV degradation rate (DR) is 0.3%, battery fade (BF) is 0.5%, and devices efficiency (DE) is 95%.

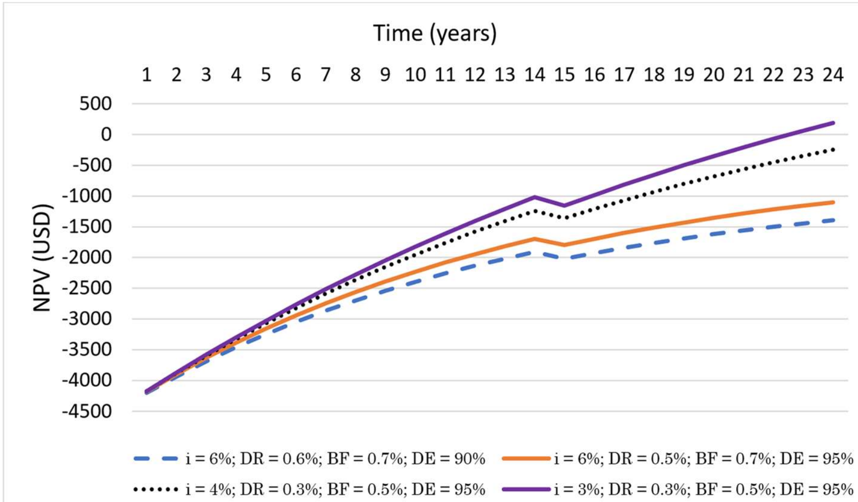

Figure 6. Optimizing Multiple Parameters Simultaneously

As mentioned before, the SPP investment can profit with certain parameters. However, this condition is difficult to meet in the real implementation. Thus, we need to find another alternative solution to make SPP investment profit. We propose two alternative solutions that involve government regulations. First, installation subsidy by government such that SPP system is profit within a certain period. How much subsidy should be provided? Recall third scenario with initial cost reduction, we found that the maximal initial cost of USD 2,584 instead of 4,492 (for 3,280Wp of PV capacity) to get NPV USD 0.00 at 24th year. Thus, the subsidy equal to USD 581.7/kWp. For 900MWp target of rooftop solar PV in 2023, as reported by Dirjen EBTKE **(Humas EBTKE, 2020)**, 0.5 billion US dollar should be provided by the government.

Another aspect involving government regulation is the potential increase in electricity tariffs. Figure 7 presents the NPV profile of the third scenario with different increments in electricity tariffs. It is observed that a 5% annual increase in electricity tariffs can lead to profitability in SPP investments after 24 years. Additionally, the analysis reveals that a minimum increment of 4.9% in electricity tariffs per year is necessary to achieve an NPV of 0 at the end of the 24-year.

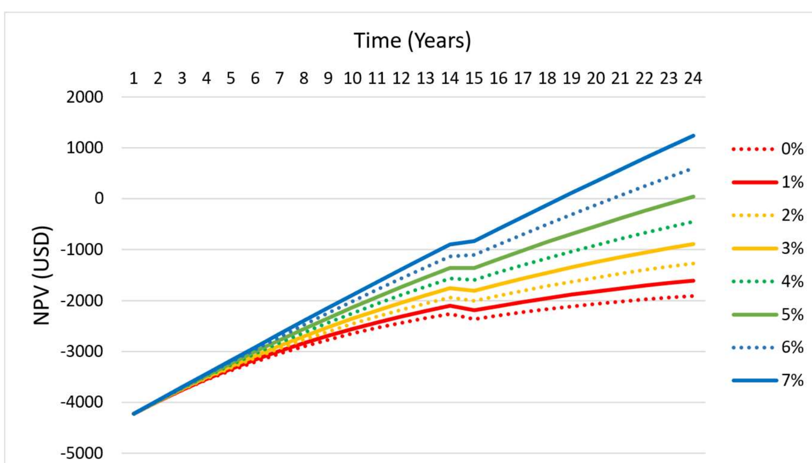

Figure 7. The Investment in SPP Appears to be Profitable When the Electricity Tariff Increases by 5% or More Per Year

The historical data shows that the residential electricity tariff price increased from IDR 563.05 per kWh in 2005 to IDR 1,444.7 per kWh in 2022. This represents a 156% increase over a span of 17 years, averaging about 5.7% annual growth. If this upward trend continues in the coming years, it indicates a favorable environment for investments in off-grid solar power plants to be profitable.

4. CONCLUSION

We have designed an off-grid solar power plant with a capacity of 3.28 kilowatts peak (kWp) to serve as the main source of electricity for households. The system comprises of 8×410Wp PV polycrystalline, 3000W hybrid off-grid inverter, and 48V 300Ah $LiFePO_4$ battery system. The daily energy harvested from the PV panels varies between 3.2 kilowatt-hours (kWh) and 17.4 kWh, depending on the amount of sunlight received. This corresponds to an irradiance duration of 1.0 to 5.3 hours per day. The estimated annual energy generation of the off-grid solar power plant is 3,740.7 kilowatt-hours (kWh), considering an inverter efficiency of 85%. This estimate aligns closely with the prediction data provided by PVGIS, which is released by the European Communities. Furthermore, the annual average final yield of the system is calculated to be 1,140.5 kWh per kilowatt-peak (kWp), with an average annual performance ratio of 63.4%. Although these results may be lower than those reported in previous studies conducted in Europe, it is important to note that they can be improved by utilizing higher efficiency PV panels and inverters. Overall, based on the estimated energy generation and performance metrics, we can conclude that the system is well installed and functioning correctly. Moreover, in the economic analysis of the SPP investment, we estimate that increasing the electricity tariff by 4.9% per year would make SPP investments for households in Indonesia more attractive.

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REFERENCES

Alwani, H., Fadhilah, F., & Setiawan, J. (2022). Aplikasi plts off-grid di Desa skonjing kabupaten ogan ilir. *Jurnal Pengabdian Community, 4*(3), 101-105.

Beltran, H., Ayuso, P., & Pérez, E. (2020). Lifetime expectancy of Li-ion batteries used for residential solar storage. *Energies, 13*(3), 568. doi:https://doi.org/10.3390/en13030568

Burck, J. (2019). *Brown to Green Report 2019: The G20 Transition towards a Net-Zero Emissions Economy.* Germanwatch. Dipetik March 10, 2023, dari https://www.germanwatch.org/en/17200

Darghouth, N., McCall, J., Keyser, D., Aznar, A., & Gokhale-Welch, C. (2020). *Distributed Photovoltaic Economic Impact Analysis in Indonesia.* Dipetik February 17, 2023, dari National Renewable Energy Lab.(NREL): chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.nrel.gov/docs/fy20osti/75281.pdf

Emissions Database for Global Atmospheric Research Team. (2022). *CO2 emissions of all world countries.* IEA. Dipetik March 10, 2023, dari https://edgar.jrc.ec.europa.eu/report_2022

European Communities. (2023). *Photovoltaic Geographical Information System: Performance of Off-Grid PV System*. Dipetik March 24, 2023, dari EU Science Hub: https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY

Hasanah, A. W., Koerniawan, T., & Yuliansyah. (2018). Kajian Kualitas Daya Listrik PLTS Sistem Off-Grid Di STT-PLN. *Energi & Kelistrikan, 10*(2), 93-101. doi:https://doi.org/10.33322/energi.v10i2.211

Humas EBTKE. (2020, Oktober 22). *Menteri Arifin: Transisi Energi Mutlak Diperlukan*. Dipetik February 8, 2023, dari Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi: https://ebtke.esdm.go.id/post/2020/10/22/2667/

Humas EBTKE. (2022, February 21). *Dorong Stakeholder Lakukan Pemasangan PLTS Atap Secara Masif, Pemerintah Tawarkan Insentif*. (T. d. Direktorat Jenderal Energi Baru, Produser) Dipetik January 7, 2023, dari https://ebtke.esdm.go.id/: https://ebtke.esdm.go.id/post/2022/02/22/3093/dorong.stakeholder.lakukan.pemasangan.plts.atap.secara.masif.pemerintah.tawarkan.insentif?lang=id.

Hutajulu, A. G., Siregar, M. R., & Pambudi, M. P. (2020). Rancang Bangun Pembangkit Listrik Tenaga Surya (Plts) On Grid di Ecopark Ancol. *TESLA: Jurnal Teknik Elektro, 22*(1), 23-33. doi:https://doi.org/10.24912/tesla.v22i1.7333

Indonesia, Pemerintah Pusat. (2014, October 17). Peraturan Pemerintah (PP) Nomor 79 Tahun 2014 tentang Kebijakan Energi Nasional. *Kebijakan Energi Nasional*. Jakarta, Indonesia: Database Peraturan BPK. Dipetik December 23, 2022, dari https://peraturan.bpk.go.id/Home/Details/5523/pp-no-79-tahun-2014

Indonesia, Pemerintah Pusat. (2017). Rencana Umum Energi Nasional. *Peraturan Presiden (PERPRES) Nomor 22 Tahun 2017*. Indonesia: Database Peraturan BPK. Dipetik December 23, 2022, dari https://peraturan.bpk.go.id/Details/68772

International Electrotechnical Commission. (2021, July 1). *Photovoltaic System Performance (2017) Part 1: Monitoring, IEC - 61724-1.* Diambil kembali dari IEC.

International Energy Agency. (2020). *Projected Costs of Generating Electricity 2020*. Dipetik January 15, 2023, dari IEA: https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

International Renewable Energy Agency. (2020, December). *Renewable Power Generation Costs in 2020.* Dipetik January 15, 2023, dari chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.irena.org//media/Files/IRENA/Agency/Publication/2021/Jun/IRENA_Power_Generation_Costs_2020.pdf

International Renewable Energy Agency. (2021, August 8th). *IRENA.* Dipetik December 23, 2022, dari www.irena.org: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Asia/Indonesia_Asia_RE_SP.pdf?rev=41b045ce3b7240c485610e3f878fc635

International Renewable Energy Agency. (2022). *Renewable capacity statistics 2022*. (A. D. International Renewable Energy Agency (IRENA), Produser) Dipetik September 22, 2022, dari www.irena.org: https://www.irena.org/publications/2022/March/Renewable-Capacity-Statistics-2022

International Renewable Energy Agency. (2023). *Renewable energy statistics 2023.* Dipetik March 25, 2023, dari www.irena.org: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Renewable_energy_statistics_2023.pdf?rev=7b2f44c294b84cad9a27fc24949d2134

Jalaluddin, R., & Safarudin, Y. M. (2020). Perbandingan Biaya Perancangan Plts On-Grid dan Off-Grid pada Laboratorium Listrik PPSDM MIGAS. *Seminar Nasional NCIET. 1*, hal. 162-169. Semarang: Jurusan Teknik Mesin, Politeknik Negeri Semarang. doi:https://doi.org/10.32497/nciet.v1i1.76

Kennedy, R. (2021, September 16). How long do residential solar inverters last? *PV Magazine*. Dipetik October 29, 2022, dari https://www.pv-magazine.com/2021/09/16/how-long-do-residential-solar-inverters-last/

Li, J., & Ma, Z.-F. (2019). Past and present of LiFePO4: from fundamental research to industrial applications. *Chem, 5*(1), 3-6. doi:https://doi.org/10.1016/j.chempr.2018.12.012

Lindig, S., Ascencio Vasquez, J., Leloux, J., Moser, D., & Reinders, A. (2021). Performance analysis and degradation of a large fleet of PV systems. *IEEE journal of photovoltaics, 11*(5), 1312-1318. doi:https://doi.org/10.1109/JPHOTOV.2021.3093049

Naim, M. (2020). Rancangan Sistem Kelistrikan Plts Off Grid 1000 Watt Di Desa Loeha Kecamatan Towuti. *Vertex Elektro, 12*(1), 17-25. doi:https://doi.org/10.26618/jte.v12i1.4013

Naim, M., & Wardoyo, S. (2017). Rancangan Sistem Kelistrikan Plts On Grid 1500 Watt Dengan Back Up Battery Di Desa Timampu Kecamatan Towuti. *DINAMIKA Jurnal Ilmiah Teknik Mesin, 8*(2), 11-17. doi:https://doi.org/10.33772/djitm.v8i2.2379

Naumann, M., Spingler, F. B., & Jossen, A. (2020). Analysis and modeling of cycle aging of a commercial LiFePO4/graphite cell. *Journal of Power Sources, 451*, 1-12. doi:https://doi.org/10.1016/j.jpowsour.2019.227666

Nayak, C. K., Kasturi, K., & Nayak, M. R. (2019). Economical management of microgrid for optimal participation in electricity market. *Journal of Energy Storage, 21*, 657-664. doi:https://doi.org/10.1016/j.est.2018.12.027

Nurosyid, F., Supriyanto, A., Suryana, R., & Iriani, Y. (2019). Aplikasi PLTS On Grid Pada Usaha Pembesaran Lele. *Jurnal Kewirausahaan dan Bisnis, 23*(11), 1-6. doi:https://doi.org/10.20961/jkb.v22i12.26616

Panchal, S., Mcgrory, J., Kong, J., Fraser, R., Fowler, M., Dincer, I., & Agelin-Chaab, M. (2017). Cycling degradation testing and analysis of a LiFePO4 battery at actual conditions. *International Journal of Energy Research, 41*(15), 2565-2575. doi:https://doi.org/10.1002/er.3837

PLN. (2022). *Tariff Adjustment October-December 2022*. Dipetik January 15, 2023, dari PLN: https://web.pln.co.id/statics/uploads/2022/09/TTL-OKT-DES.jpg

Solargis. (2018). *Global Horizontal Irradiation: Indonesia*. Dipetik August 15, 2021, dari solargis.com: https://solargis.com/maps-and-gisdata/download/indonesia

Solargis. (2022). *globalsolaratlas.info*. Dipetik October 29, 2022, dari Global Solar Atlas online application website: https://globalsolaratlas.info/map?c=-%207.741882,110.358971,11%20&s=-7.805154,110.430038&m=site

Syafii, S., Mayura, Y., & Muhardika, M. (2019). Strategi Pembebanan PLTS Off Grid untuk Peningkatan Kontinuitas Suplai Energi Listrik. *Jurnal Rekayasa Elektrika, 15*(3), 157-161. doi:https://doi.org/10.17529/jre.v15i3.14793

Syahwil, M., & Kadir, N. (2021). Rancang Bangun Modul Pembangkit Listrik Tenaga Surya (PLTS) Sistem Off-grid Sebagai Alat Penunjang Praktikum Di Laboratorium. *Jurnal Pengelolaan Laboratorium Pendidikan, 3*(1), 26-35. doi:https://doi.org/10.14710/jplp.3.1.26-35

Yang, S., Zhu, X., & Guo, W. (2018). Cost-benefit analysis for the concentrated solar power in China. *Journal of Electrical and Computer Engineering*, 1-11. doi:https://doi.org/10.1155/2018/4063691