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ECONOMIC ANALYSIS OF ROOFTOP BASED ON-GRID AND OFF-GRID PHOTOVOLTAIC SYSTEMS IN EQUATORIAL AREA

Ali Basrah Pulungan[1*], Adam Rasyid Sidiqi[2], Hamdani[3], Ichwan Yelfianhar[4], Habibullah[5], Wawan Purwanto[6], Kristine Mae Paboreal Dunque[7]
Department of Electrical Engineering, Universitas Negeri Padang, Indonesia[1,2,3,4,5]
Department of Automotive Engineering, Universitas Negeri Padang, Indonesia[6]
Department Electrical Engineering, University of Science and Technology of Southern Philippines Cagayan de Oro City, Philippines[7]
alibp@ft.unp.ac.id

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Corresponding Author

ABSTRACT
Through a thorough analysis using Net Present Cost (NPC) over a 20-year period, this research presents a comprehensive and economically optimized solar panel design methodology. The study examines two different PV system configurations: On-Grid PV and Off-Grid PV, using sophisticated simulation and analytical techniques with the aid of HOMER Pro software. The simulation results offer compelling new information about these systems' economic viability. The simulation results in an NPC value of IDR 31,386,360,- for the Off-Grid PV configuration. The On-Grid PV system, in contrast, exhibits a significantly lower NPC value of IDR 8,903,329,- emphasizing its superior economic performance. This On-Grid PV system boasts a significant energy generation capacity of 5,012 kWh/year in addition to favorable cost efficiency. Notably, this is greater than the National Power Company's 1,186 kWh/year energy output. These results highlight the financial benefits of the On-Grid PV system and demonstrate its capability to provide affordable and sustainable energy solutions over a long period. The thorough analysis carried out in this study aids in the optimization of solar panel designs, offers insightful information for future sustainable energy projects, and emphasizes the crucial part that economic factors play in influencing the adoption of renewable energy technologies.
Keywords: *Economic Study, On-Grid PV System, Off-Grid PV System, NPC Value*

1. Introduction

Energy conservation has evolved into a paramount global concern, assuming a pivotal role in national strategies worldwide. The United Nations' adoption of the 2030 Sustainable Development Goals (SDGs) in 2015 underscored the imperative of affordable and clean energy, positioning it at the forefront of the international agenda (Tsalis et al., 2020).

A prevailing surge in the global demand for clean and sustainable energy solutions has propelled photovoltaic (PV) systems into the limelight. As a promising avenue for meeting burgeoning energy demands while addressing environmental apprehensions, PV systems have garnered widespread adoption (Mondejar et al., 2021). The remarkable solar potential of equatorial regions, characterized by consistent and intense sunlight year-round (de Lima Montenegro Duarte et al., 2021), amplifies their significance in the journey toward renewable energy proliferation. Photovoltaic systems as a sustainable solution for electrifying the pivotal role of national energy policies and strategic planning in advocating for and implementing clean energy initiatives (Kuno et al., 2023).

Indonesia, straddling the equatorial line with its stable tropical climate, boasts an exceptional solar energy potential, with thermal radiation reaching up to 4.8 kWh/m2 per day (Syafii et al., 2020),the realized solar energy capacity in Indonesia remained at a modest 195.4 MW by 2021 (Kementerian ESDM, 2022). The nation grapples with the task of harnessing its abundant renewable sources to address growing energy needs while navigating economic and infrastructural constraint. Padang, a city in Indonesia, stands as a beneficiary of its abundant solar resources(Pulungan et al., 2019), with high levels of solar radiation throughout the year. This solar abundance not only promises efficient PV system operation but also positions equatorial regions such as Padang as ideal locales for consistent and predictable solar energy generation, unlike areas farther from the equator prone to seasonal variations and erratic weather patterns (Caeiro et al., 2020). The unwavering and potent equatorial sunlight ensures a reliable and uninterrupted energy output from PV systems, optimizing their performance and efficacy (Ab. Rahman et al., 2019).

The unique geography of Padang enhances its suitability for investigating and implementing rooftop PV installations, particularly within university campuses. Rapid urbanization in the city has resulted in the construction of numerous buildings, including universities, endowed with untapped rooftop spaces ripe for solar PV systems. Various studies have extensively examined the potential for utilizing these spaces in urban areas. For example, a study on city-wide rooftop solar PV deployment in Bandung, Indonesia, provides insights into the multi-criteria assessment for identifying suitable rooftops for solar PV deployment (Sakti et al., 2022). Additionally, research on planning a smart energy city using rooftop solar PV in Bandung, Indonesia, offers a geospatial assessment for prioritizing solar PV rooftop construction in urban areas (Ihsan et al., 2021). Integrating PV systems within the academic fabric of equatorial regions like Padang unveils a singular opportunity to showcase the viability and advantages of renewable energy adoption in educational institutions (Abdelhafez et al., 2021). This endeavor not only inspires students, faculty, and the broader community to embrace sustainability but also bolsters renewable energy education (Wang et al., 2023).

This research employs a holistic approach encompassing technical modeling, system simulation, and economic analysis. Leveraging advanced software tools and algorithms, the study delves into the performance of diverse PV system configurations, accommodating variables such as building orientation, shading impacts, and the unique geographical attributes of Padang's university campus. Complementing this analysis is an economic evaluation, which gauges the financial viability, payback period, and return on investment (ROI) of the proposed PV installation system within the operational framework of the university (Bazionis et al., 2023)(Hamdani et al., 2021).

Extending the foundations laid by prior studies on PV system design and techno-economic analysis, particularly within university contexts and equatorial regions, this research pioneers optimal grid-connected rooftop PV systems for universities (Mokhtara et al., 2021). Building upon optimal sizing insights (Khairi et al., 2022) and financial viability revelations (Shabbir et al., 2022), this study amalgamates the knowledge gleaned from Padang's equatorial characteristics. In doing so, the research endeavors to offer a comprehensive comprehension of the prime design and techno-economic facets of rooftop PV installations in the distinct equatorial milieu of a university campus.

The scope encompasses a comprehensive analysis of rooftop PV installations, with a focus on the university campus in Padang. Parameters such as building orientation, shading impacts, and unique geographical attributes will be considered (Chepp & Krenzinger, 2021). The research employs advanced software tools and algorithms to conduct technical modeling, system simulation, and economic analysis. Leveraging the expertise of previous studies, the research pioneers optimal grid-connected rooftop PV systems for universities, considering the equatorial characteristics of Padang.

Through an exhaustive techno-economic exploration of a rooftop PV installation system in Padang, this research aspires to illuminate design considerations, system sizing, financial feasibility, and prospective environmental gains of solar PV systems within a university campus in an equatorial region. The findings are poised to contribute significantly to the existing repository of knowledge on solar PV system optimization in equatorial zones (Pachauri et al., 2020). By doing so, the research stands to empower university administrators, sustainability managers, and decision-makers with the insights needed to steer effective and sustainable renewable energy initiatives (Phap & Nga, 2018). The research culminates in the formulation of On-Grid PV System models for the Department of Electrical Engineering at Universitas Negeri Padang, Kota Padang. The employment of HOMER Pro Software to ascertain the initial investment for designing the On-Grid PV System over a 25-year utilization period underscores the aim of achieving optimal usability and feasibility of the designed system (Park et al., 2019).

2. Literature Review

The utilization of solar energy as electric power generation is achieved through two types of implementations which are photovoltaic (PV) and photothermal (Zhang et al., 2023). PV technology directly converts solar radiation into electricity by using semiconductor devices called solar cells. This technology can be used in Solar Panels Power Generation (PLTS) in the form of a centralized PV System, stand-alone PV System (Ghivari & Revankar, 2016), and On-Grid PV System(Bahramara et al., 2016). In an On-Grid PV System, the solar panels are interconnected with other power generation from utilities. Therefore, this system is also known as On-Grid PV System(Panhwar et al., 2017).

The installation of a PV System requires a great amount of investment which is sometimes probably not feasible for long time period(Pradhan et al., 2017). Therefore, accurate calculation and economic study is really important to determine the initial fund required for investment and avoid future losses of the investment (Song et al., 2022). Not only solar panels, PV System also required supporting components, therefore the design of the PV System sophisticatedly can be achieved by using HOMER Pro Software (Aprillia et al., 2019). There has been plenty of economic studies in PV System design, such as economic analyses of PV System design to supply domestic network of 900 VA (Hidayat et al., 2019). Additionally, HOMER Pro software also has capability to simulate, optimize models and determine the most feasible configuration with lowest NPC value by using the most sensitive parameters for accurate results(Bachtiar & Syafik, 2016).

The global landscape of solar energy adoption is witnessing a transformative shift, with an increasing focus on PV systems as pivotal contributors to achieving renewable energy goals (Haegel et al., 2019). Notable developments include advancements in PV technology, improved efficiency, and scaled-up manufacturing, contributing to the widespread integration of solar solutions in diverse sectors (Fu et al., 2022). There have been many research studying the techno-economic aspect of PV System, whether it is off-grid system or grid-connected system. In general, the application of grid-connected (On-Grid) System provides more advantages, due to an opening opportunity to sell excess power from the solar panels to the power companies (Ahmad et al., 2022). In regions like Padang, where economic considerations play a crucial role in decision-making, the significance of economic analysis in the context of PV system installations cannot be overstated. Accurate economic assessments are paramount to determining the feasibility and sustainability of PV projects (Datta et al., 2020). This analysis guides stakeholders in making informed decisions, mitigating financial risks, and optimizing the economic viability of PV installations, aligning them with broader sustainability goals (Duman & Güler, 2020).

Budes et al., (2020) has evaluated the economic studies of On-Grid Wind Solar Power Generation in Colombia. The sector with high demand of electric supply, required thermo-electric power generation to fulfil the power demand. HOMER Pro Software is used in this study to perform hybrid optimization of power systems with various energy sources (Bismark et al., 2023). This process will help to reduce the impact of power system installation on the environment and reduce the production cost of the power system network. Based on the simulation result, it was concluded that Rancho Grande was the most appropriate city from three other optional cities to be installed with On-Grid Solar Panels – Wind Turbine Power System.

Rousis et al., (2018) conducted a case study of an islanding house without any power supply from grid. The design consists of a combination of PV and diesel generator, AC load and energy storage devices in battery forms. The HOMER Pro, is used to identify the lowest cost design with high sensitivity to obtain the most optimal design criteria. In this research, it can be concluded that the hybrid system is the cheapest and most environment-friendly solution compared to autonomous diesel generators.

Hidayat et al., (2019) in his research analyse economically the design of PV power generation (PLTS) at Faculty of Engineering, Universitas Diponegoro Indonesia. The PV System designed was installed at the roof top of parking area in Electrical Department by using 390 panels of PV. The design was simulated with HOMER Pro and PV System software. It was summarized in the research that the PV System design considered feasible if the energy selling price of the PV system was increased.

Additionally, Riayatsyah et al., (2022) performed techno-economic analyses and optimization on On-Grid PV-Wind Turbine Power System with Battery as Power Storage at

Univeritas Syah Kuala, Aceh. This design is performed by using average load, solar radiation and wind index and daily temperatures at the location as the data input. Based on the analyses, the designed On-Grid PV-Wind Turbine is capable of supplying up to 82 % of the power demand.

Techno-economic study of On-Grid PV System was also performed by Anugrah (Anugrah & Pratama, 2022) at a mosque Masjid Tablighiyah Garegeh in Bukittingi which was built with capacity up to 1.400 peoples. This study was conducted by using HOMER Pro to judge the most optimum configuration of the design for On-Grid PV System. There were four options considered in this study, PV-Grid, PV-Battery-Grid, Battery-Grid, and Grid Only System. The simulation shown that the most optimum configuration was On-Grid PV without battery system.

In the unique equatorial context of Padang, Indonesia, the solar potential, stable tropical climate, and urban development trends present a conducive environment for PV system installations. The choice of PV system configurations is influenced by these factors, emphasizing the need for tailored solutions that harness abundant solar resources efficiently within the urban landscape (Formolli et al., 2022). Despite the wealth of research in PV system design and economic analysis, there remains a gap in understanding the specific challenges and opportunities in implementing optimal grid-connected rooftop PV systems within university campuses in equatorial regions like Padang (Yap et al., 2022). This research aims to address this gap by providing a comprehensive exploration of design considerations, system sizing, and economic feasibility, contributing to the knowledge base on renewable energy adoption in equatorial zones.

3. Research Methods

In this research, HOMER Pro software is used as a tool for optimization and sensitivity analyses to determine the investment cost to install On-Grid PV System (Manlapaz et al., 2023). The calculation and simulation are performed based on the collection of data obtained from the design such as location, load demand and power system components being used. After the data has been collected, it will be input into the software. This software then will optimize and analyse every possible configuration and then determine which configuration is the most feasible based on the simulation. The most feasible configuration based on the simulation result is then being used as the reference model for the installation. Figure 1 shows the simulation flowchart that was carried out.

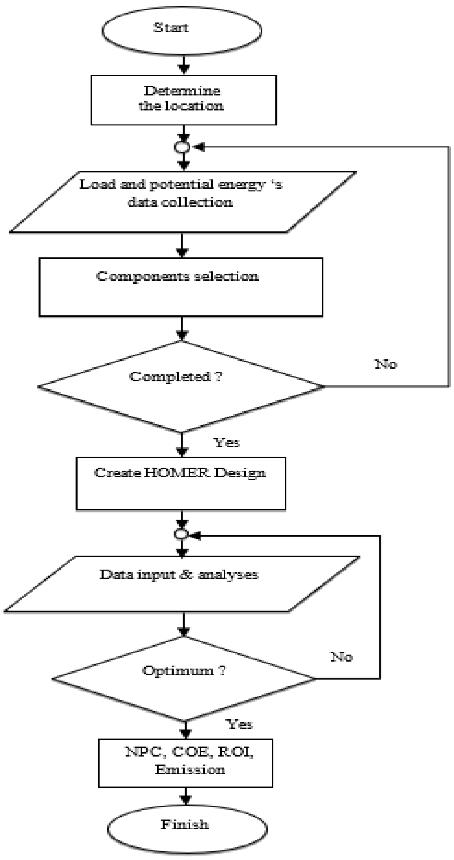

Fig. 1. Simulation flowchart

3.1. Meteorology Data

Solar radiation, temperature and wind speed affect the amount of energy produced by the solar panel. The data for solar radiation, wind speed and temperature in this research was downloaded from Nasa Surface Meteorology and Solar Energy Database on June 23rd, 2022. It is obtained by entering the coordinate of the research location (West Sumatera, Padang City, Universitas Negeri Padang, Engineering Faculty Building, Electrical Engineering Department) as shown in figure 2 0°53.9'S, 100°21.0'E to HOMER Pro software.

Fig. 2. Research Location Coordinate

3.2. Solar Radiation

Solar radiation ranges between 4.53 kWh/m2/day to 5.23 kWh/m2/day, with average radiation in a year 4.91 kWh/m2/day as illustrated in figure 3. The highest solar radiation occurs in February and the lowest radiation occurs in November.

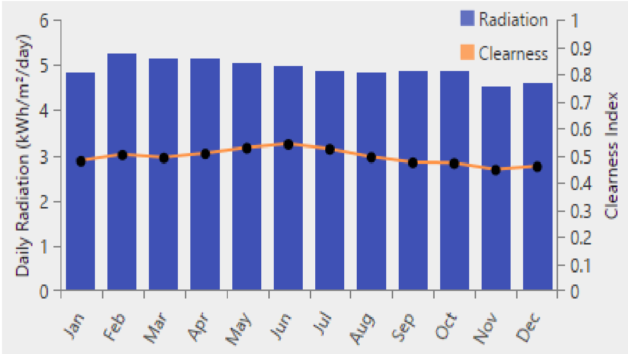

Fig. 3. Daily Solar Radiation Curve

3.3. Temperatures

The temperature of Padang is shown in figure 4, with highest point on Mei at 25.79°C and the lowest point in November and December at 24.85°C. Average yearly temperature is at 25 to 22°C. These temperatures data will be considered to determine the power efficiency of the PV as the HOMER software can determine the power output of PV panels configuration based on the temperature data.

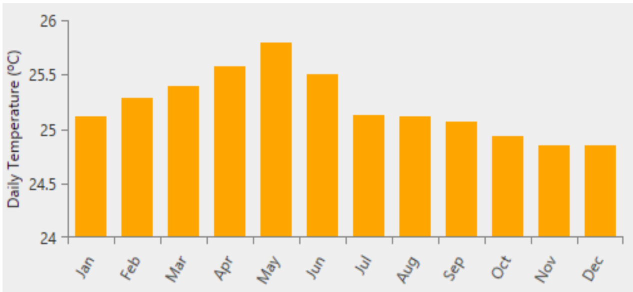

Fig. 4. Daily Temperatures Data in a Year

3.4. Load Profile

The load profile is very important to design optimum power system accurately, where the load demand at particular time can be supplied accordingly and the excess cost of over design can be avoided. The daily load profile is provided in figure 5 based on the load demand hourly. The daily load is obtained from the electrical loads used in the Electrical Engineering Department, Universitas Negeri Padang. Operation and service times of the departement are assumed to be from 06.00 AM – 06.00 PM, 10 % of day-to-day variability and 15 % of time step variability are used based on the value obtained from the data. Hourly load consumption varying around 500 Watt to 600 Watt as shown in figure 6.

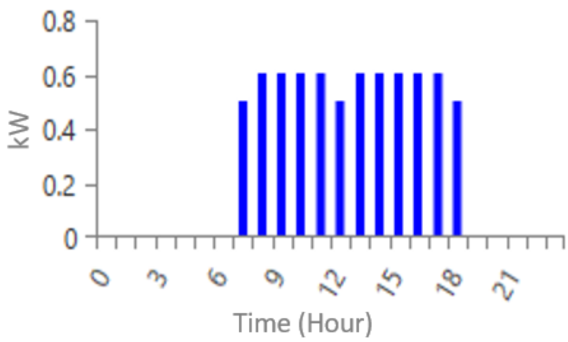

Fig. 5. Daily Load Profile Curve

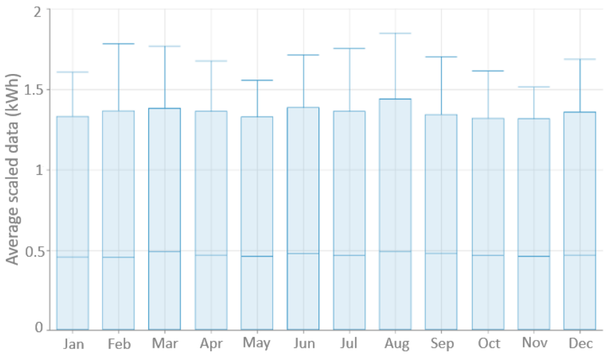

Fig. 6. Load Consumption Histogram

3.5. Energy Sources

There are several input components being used in this research, namely: PV, Battery, and converter. The values of these components are shown in table 1.

Table 1 - Energy Source Components

Components	Power (kW)	Usage Periods	Capacity
Generic flat plate PV	1	20 yrs.	0-5 kW
Generic 1kWh lead acid	-	10 yrs.	0-4 unit
Converter	1	15 yrs.	0-5 kW

3.6. Grid and Renewable Energy Tariff

The utilization of the energy source from PV System only operates in day light time. PV System is the main energy source during the daylight time even though the grid is connected with the power company. If the power production of the PV system is greater than the load demands, then the excess power will be sold to the power company through the grid connection. On the other hand, if the PV System produces less power, then the rest of the unsupplied load demands would be supplied by the power company. The official 2020 electricity tariff from the Ministry of Energy and Mineral Resources for the P2/TR is IDR 1,114.47/kWh(Syafii et al., 2020).

3.7. Net Present Cost

Net Present Cost (NPC) is the main economic output of a PV System parameter. The summation of all components and operational cost in the project are calculated by using the following equation:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})}$$

On the other hand, the Capital Recovery Factor (CRF) is obtained by using the following formula:

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

3.8. Cost of Energy

Cost of Energy (COE) is the current value of all installment cost and the operational cost of the components during the period of operation. Average cost per kWh of the electricity consumption by the system is also considered. In COE calculation, the cost of energy production per year is separated into the amount of used energy production.

$$COE = \frac{C_{ann,tot}}{E_{tot,served}}$$

3.9. Total Energy Production

Total energy production is the summation of energy being produced in the period of system operation. Total energy production is obtained by using the following equation:

$$E_{tot.prod} = E_{photovoltaic} + E_{grid}$$

3.10. Initial Capital Cost

Initial Capital Cost is the total investment cost of the initially installed components in the project. There are three main components: solar panel, battery, and converter. HOMER calculate this value by using the following equation:

C = PV Cost + Battery Cost + Converter Cost

3.11. Internal Rate of Return

Internal Rate of Return (IRR) is a method to analyze the financial cost of investment. IRR is usually used to calculate the interest rate of an investment. IRR is obtained from the following equation:

$$IRR = i_1 + \frac{NPV1}{(NPV1-NPV2)}(i_2 - i_1)$$

3.12. PV System Modelling

In this research, the system is modelled into two system models namely Off-Grid System and On-Grid System. Both models will be used to determine which system optimally operates with the lowest cost and impact on the environment. Figure 7 shows an Off-Grid PV system. The power production of the solar panel will be stored into the battery for later use if the solar radiation decreases.

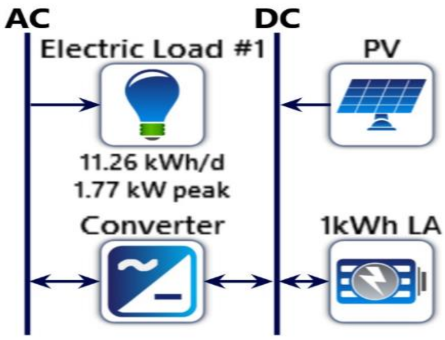

Fig. 7. Off-Grid PV System Model

Figure 8 illustrates an On-Grid PV System model. If the power production excess the load demand, then the excess power can be sold to the power company.

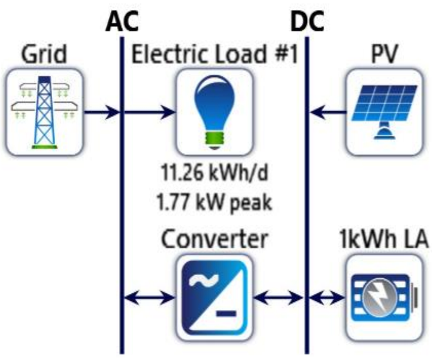

Fig. 8. On-Grid PV System Model

4. Results and Discussions

The PV System simulation was conducted by using 2 models design, namely Off-Grid PV System and On-Grid PV System (Grid-Connected PV System). Both models would have compared each other to determine which one is the most appropriate and feasible design to be implemented. The most appropriate and feasible model design criteria were the one with the lowest cost of investment and lowest impact to the environment damage.

4.1 . Optimize Results of Off-Grid PV System

In figure 9, the total monthly power production of a PV's only power system network is illustrated. The highest power production is marked in March and the lowest one in November. This variation is due to the difference in the amount of solar radiation available each month.

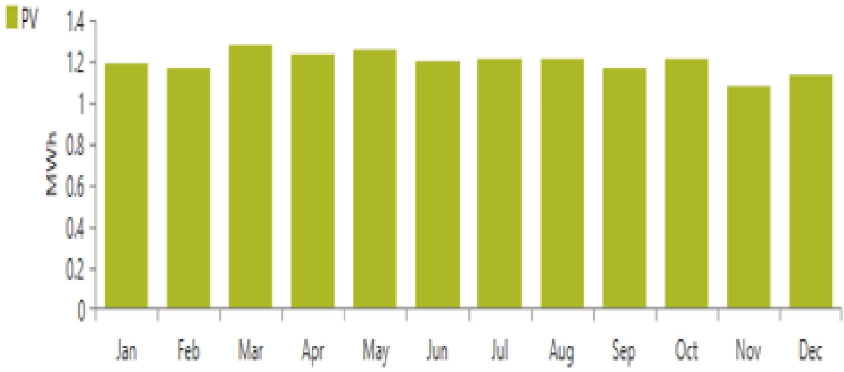

Fig. 9. Monthly Power Production of Off-Grid PV System

The NPC value of Off-Grid PV System reaches up to IDR. 31,368,630.00 with battery storage cost at IDR. 12,483,377.00 The solar panels cost would be IDR. 15,913,186.00 Lastly, the converter system would cost at IDR. 2,990,065.00 All these component's cost is illustrated in figure 10.

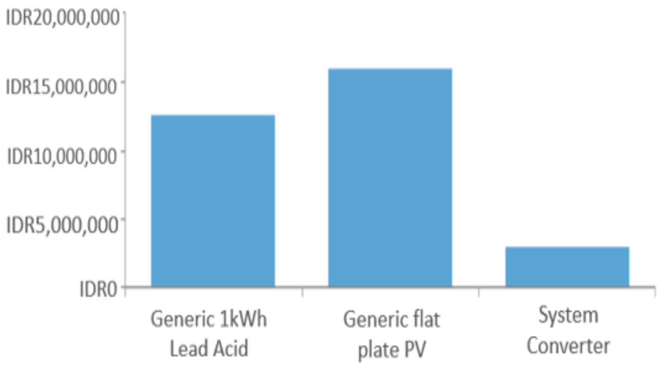

Fig. 9. NPC Value of Off-Grid PV System

4.2 Optimize Results of On-Grid PV System

The monthly total power production of the Grid-Connected PV System is shown in figure 11. The peak of power production occurs in March and the valley occurs in November. Again, this variation is caused by the variation of solar radiation each month.

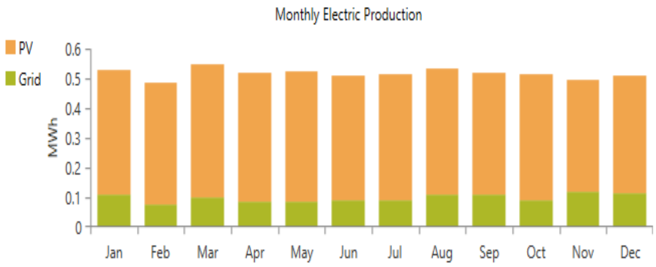

Fig. 10. Monthly Diagram of On-Grid PV System's Power Production

The NPC value of On-Grid PV System reaches up to IDR. 8,903,329.00 with solar panel cost at IDR. 5,565,000.00 The cost of power supply from the power company is at IDR. 120,742.00 The cost for the converter system is IDR. 3,217,586.00 All these cost components are shown in figure 12. This result proved that the total cost of investment in an Off-Grid PV System is higher than the total cost of an On-Grid PV System.

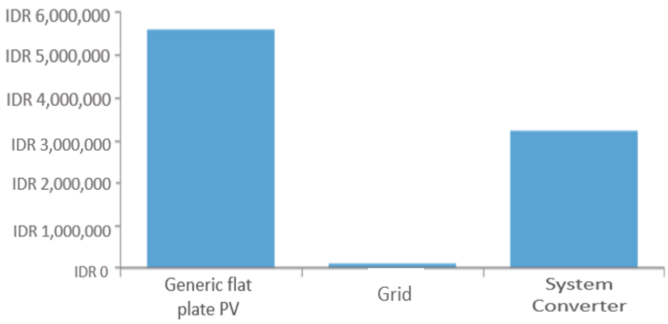

Fig. 11. NPC Value Result of On-Grid PV System

In table 2. The payment cost for power supplied from the grid is provided. The payment for November is IDR. 7,249.00 The total energy purchased from the power company in one year is 1.186 kWh, while the energy sold to the power company is 1.471 kWh.

Table 2 - Grid Power Production Simulation Results

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)
January	110	124	-14.4	1.25
February	77.1	120	-42.7	1.11
March	100	123	-22.3	1.26
April	87.5	133	-45.3	1.29
May	86.4	135	-48.8	1.16
June	91.3	126	-35.2	1.24
July	91.0	124	-33.3	1.32
August	111	116	-5.17	1.32
September	108	118	-9.82	1.33
October	92.0	125	-32.5	1.23
November	117	112	5.02	1.39
December	114	115	-0.429	1.16
Annual	1.186	1.471	-285	1.39

Based on the simulation result of the HOMER Pro Software, the On-Grid PV System is more feasible and more profitable than the Off-Grid PV System. The cost of investment to provide electrical energy supply from PV only is very high at IDR. 31,386,630.00 while the cost of investment to provide power supply from On-Grid PV is lower at only IDR. 8,903,329.00 This On-Grid PV System would be more optimum if it is designed without battery storage as illustrated in figure 13. This is due to direct supply from the grid will be connected to the load if the supply from the PV System is not enough to supply the demand.

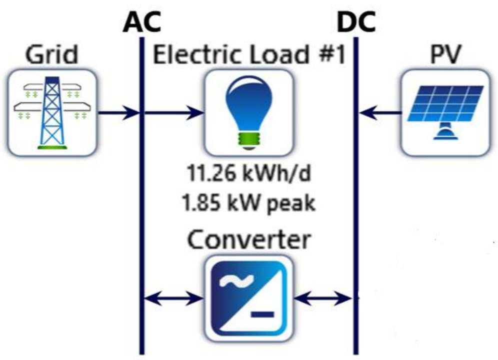

Fig. 12. Optimum Model Design

In the On-Grid PV System, the reduction of carbon dioxide emission also significantly improved. The time for return value of investment would be achieved after 1.36 year with IRR value at 73.7 %.

Table 3 - Time for return value

Metric	Value
Present Worth (IDR)	8,903,329,-
Return on Investment (%)	68.2

Internal rate of return (%)	73.7
Simple Payback (yr)	1.36
Discounted payback (yr)	1.39

4.3 Economic Comparison of On-Grid and Off-Grid PV System

The choice between on-grid and off-grid photovoltaic (PV) systems becomes crucial when thinking about the adoption of solar energy systems, and it is influenced by a number of economic considerations. In order to assess these two separate solar installations' viability, long-term cost-effectiveness, and applicability for various situations, an economic comparison is essential. In-depth examination of the original investment, ongoing costs, upkeep, possible returns on investment, and wider financial ramifications are all included in this research of the economic elements of both off-grid and on-grid PV systems.

Table 4 below shows the economic comparison between On-Grid and Off-Grid PV System

Table 4 - Economic Comparison

Metric	On-Grid	Off-Grid
Present Worth (IDR)	8,903,329.00	31,368,630.00
Levelized Cost of Energy (IDR)	858.00	1,465.00
Operating Cost (IDR/yr)	1,960,000.00	955,880.00
Return on Investment (%)	68.2	-
Internal rate of return (%)	73.7	-
Simple Payback (yr)	1.36	-
Discounted payback (yr)	1.39	-

The table's comparative economic analysis clearly favors the On-Grid PV system's viability over its Off-Grid version, particularly because the latter includes batteries as an essential component. In spite of this benefit, it's important to note that the On-Grid system's yearly operating expenses are marginally higher than the Off-Grid system's. This discrepancy in operating costs brings up interesting questions and points to the necessity of a more thorough analysis than simple cost comparisons. Even though the On-Grid system might have greater yearly operating costs, when compared to the Off-Grid system, its total economic viability which takes into account things like initial investment, upkeep, and prospective returns remains very strong. Determining the overall economic environment of both systems requires an understanding of these subtleties, which enables stakeholders to make better decisions that are in line with their unique energy needs and budgetary goals.

5. Conclusion

Based on the simulation performed on the Off-Grid PV System and On-Grid PV System at Electrical Engineering Department of Faculty of Engineering Universitas Negeri Padang, the total energy production is up to 6.199 kWh per year. The On-Grid PV System is more recommended than the PV only System. This is due to the result of simulation which shows that the NPC value for Off-Grid PV System at IDR. 31,368,630,00 while NPC value for On-Grid PV System at IDR. 8,903,329.00 The energy production for the On-Grid PV System is supplied from solar panels energy at 5.012 kWh per year and supplied from grid at 1.186 kWh per year. This On-Grid PV System would require 1.36 years to gain return of investment. The recommended On-Grid PV System for the best value is the one without battery storage instalment to reduce the initial cost of investment and avoid additional maintenance cost in the future. The supply from the grid will directly supply the load demand in the case when the PV System cannot supply the load demand. This is due to the load demand supplied from the PV System mostly during daylight time, while the grid supplies the load demand during the night.

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