JURNAL INFOTEL
Informatics - Telecommunication - Electronics
Website: http://ejournal.st3telkom.ac.id/index.php/infotel
ISSN: 2085-3688; e-ISSN: 2460-0997

Optimal planning on-grid power system for 2200 VA household sector by considering economic criteria

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Received 5 July 2022, Revised 11 September 2022, Accepted 14 September 2022

Abstract — The main economic factors, which are less attractive in the installation of PV power systems, include incentives that are not attractive to consumers, high investment costs, and land acquisition problems. Therefore, to reduce the cost of capital costs, the installation of solar panels in Indonesia can be installed on the roofs of buildings in urban areas so that it does not require a special area. This study discusses efforts to model solar grid systems by considering economic and regulatory factors in system design. The Hybrid Optimization of Multiple Electric Renewables software is used to evaluate the economic viability of the on-grid PV technology that provides 2200 VA of power in the household sector. Optimal costs are assessed from Net Present Cost (NPC) which is a cost analysis to determine investment feasibility based on interest rates and fees in the coming years and Break Even Point (BEP) which is the point where expenditure and income are balanced. The simulation results show that in the project period of 25 years the installation of a grid PV power system has an NPC that is 20% lower than the PLN network power supply with a BEP value lower than 15 years. The lowest NPC and BEP values were obtained from the installation of 7 PV panels with 300 Wp capacity connected to the PLN network. This system is able to save electricity costs by IDR 23,060,260 compared to the use of 100% electricity from the State Electricity Enterprise grid. This system is worthy of being an economic tool for providing electricity services throughout the year and meeting rising energy demands in the household sector.

Keywords – Economics of PV power system, household sector, on-grid photovoltaics

I. Introduction

Indonesia is an archipelagic country. There are 17,504 islands in Indonesia which consist of 267 million people. This number continues to increase every year. According to the Central Statistics Agency (BPS), increasing population is directly proportional to electricity demand. Based on BPS observations, the electrification ratio in Indonesia in 2020 has reached 99.48%. In which the number of customers rose by 1.18% compared to 2018. The largest number of customers came from the household group with 62,543,434 customers or 91.88% [1], [2]. Furthermore, according to the Ministry of Energy and Mineral Resources (ESDM), the capacity of the state-owned power plant namely the State Electricity Enterprise (PLN) has supplied the needs of electricity users in Indonesia with 67% coming from non-renewable energy sources and 6.2% of energy sources renewable [3].

In Essence, fossil fuels are the main energy source in various countries [4]–[9]. Based on several research studies, the use of fossil fuels raises several problems related to their utilization aspects [10]. These problems are related to environmental impacts, scarcity, supply risks, instability in market prices and the placement of fossil fuels at the center of a low-carbon economic shift [11].

The reduced potential of non-renewables, especially oil and gas, has encouraged the government to make renewable energy a top priority for maintaining energy security and independence [3]. One of the regulations governing the development of new renewable energy is PP No. 79 of 2014 concerning national energy policy. ESDM has implemented several main policies to accelerate the development of new renewable energy. One such policy is the Feed in Tariff (FiT) system. The FiT system is a policy mechanism for implementing the purchase price of electricity from new renewable energy plants by PLN. The amount of rate varies for each type of energy. ESDM also issued a policy related to increasing the portion of biofuels, increasing the electrification ratio of off-grid areas, *etc*. in order to increase the utilization of new renewable energy.

Indonesia is a tropical country with solar radiation distribution reaching 4 kWh / m^2 / day in each region [12]. For this reason, solar radiation energy has a high harvesting potential as a renewable energy source in Indonesia. Solar radiation can be converted into electrical energy using a solar panel system. A solar panel system is a complete set of interconnected components to convert sunlight energy into electrical energy through the photovoltaic effect [13]. The amount of electrical energy conversion from a solar power system depends on the intensity of solar radiation [14].

Solar power can be integrated on-grid or standalone [15]–[17]. If solar panels are connected to a battery as a storage medium or energy bank to meet the needs of the load, the system would be commonly referred to as a standalone solar power system [18]. As for an On-grid solar system, solar panels would be connected to the State Electricity Enterprise (PLN) network. Therefore, the use of energy in an on-grid solar system can be adjusted according to the load requirements [15], [19]. In addition, ESDM has also issued a policy related to the installation of rooftop solar power plants with the aim of saving the cost of PLN customer accounts, which is stated in ESDM Regulation No. 49 of 2018, as amended in ESDM Regulation No. 13 of 2019 (ESDM Ministerial Regulation related to the Use of the Roof PV System by PT PLN Consumers) [20].

The main economic factors, which are less attractive in the installation of PV power systems, include incentives that are not attractive to consumers, high investment costs and land acquisition problems [21], [22]. In particular, to reduce capital costs, solar panel installations in Indonesia can be installed on the roofs of buildings in urban areas so that they do not require a special area [22].

This research will present a case study for the integration of solar grids for 2200 VA household loads in Indonesia by considering technical and economic factors. Analysis related to energy economic factors for small-scale PV power systems (100 Wp to 300 Wp) will be examined and evaluated using Hybrid Optimization of Multiple Electric Renewables software. This research is also expected to be a benchmark for similar residential buildings in locations with similar characteristics.

The composition of this paper consists of three parts. The first part presents statistics on electricity consumption and the high potential of renewable energy in Indonesia. Accompanied by several government policies related to accelerating the development of renewable energy in Indonesia. The second section presents case studies and analyzes related economic factors in the application of government policies for on-grid PV systems at 2200 VA household load. Furthermore, discussing the methodology used in taking a 2200 VA scale household load profile and designing the solar grid. The third part discusses the mathematical modeling that is used related to several parameters that will be the basis of optimal price planning in the design of solar grids. The final section provides an analysis of optimal planning in the integration of solar on-grid systems in terms of the economy along with recommendations on grid solar power system capacity for 2200 VA household loads [3], [4].

II. Research Method

Fig. 1 shows the design scheme to get the optimal price from an on-grid solar energy system. As shown in Fig. 2, taking a 2200VA household load profile is measured directly using a power data logger. Next is the design of solar on-grid systems with PV capacity of 100 Wp (22 pieces), 200 Wp (11 pieces), and 300 Wp (7 pieces) to supply household loads. The simulation was carried out in accordance with existing regulations in Indonesia [1]–[3], [8]. The Electric Power Tariff (TDL) capacity of 2200 VA of IDR 1,467.28 while the selling price of electricity is IDR 953,732 and the installation of on-grid solar panel capacity must not exceed the capacity of the house which means it cannot exceed 2200 Wp [2], [3].

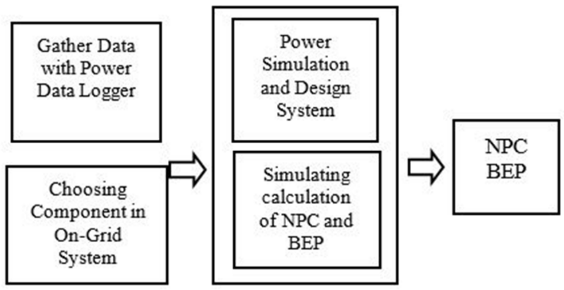

Fig. 1. Schematic for optimal price design with NPC and BEP analysis technique.

Optimal price planning can be done by knowing which kind of system is used. Economic factors in the integration of solar power on-grid were analyzed and evaluated for the project for 25 years. The system installation costs are seen from the present time (also present) evaluation of the length of return on capital or called the Break-Even Point (BEP) which is one of the important parameters for considering investment feasibility can be presented in section three of this paper.

A. Power Data Logger

Fig. 3 shows a power data logger used to obtain a 2200 VA household load profile by measuring the power usage, voltage, and currently used on each

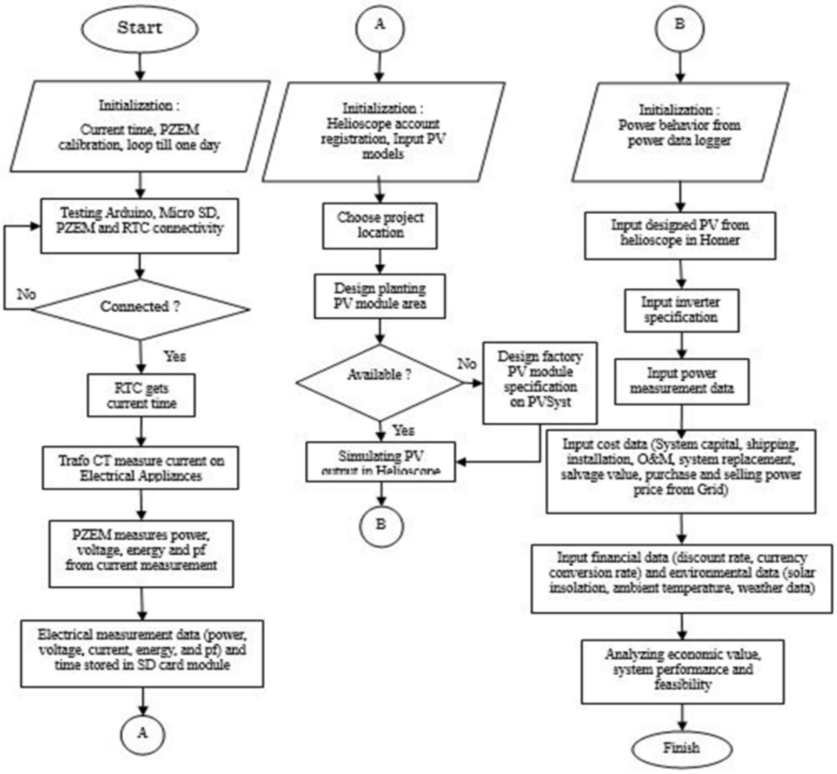

Fig. 2. Flowchart of designing an on-grid PV power system.

electronic device when used by residents of the house. Power data loggers were created using the Arduino Mega microcontroller because it contains a large memory capacity, a PZEM V004-T which is a module for measuring power, voltage, and current simultaneously, a Micro SD card Module, and a Real Time Clock (RTC) as shown in Fig. 3. The power data logger is a combination of two processes, namely monitoring energy consumption and data storage. A Pzem would measure the power, voltage, and current of the electronic appliance through the CT transformer then the measurement results will be processed in the Arduino Mega microcontroller. After processing, the measurement data will be stored on the micro-SD card accompanied by the time when the data is retrieved using a real-time clock for recording the load profile in one day.

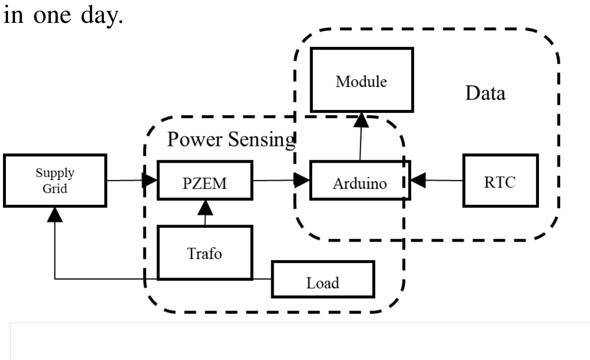

Fig. 3. Power data logger block diagram.

B. On-Grid Solar Power System Design

The Hybrid Optimization of Multiple Electric Renewables software is used to design small-scale on-grid solar power (100 Wp to 300 Wp) as shown in Fig. 4.

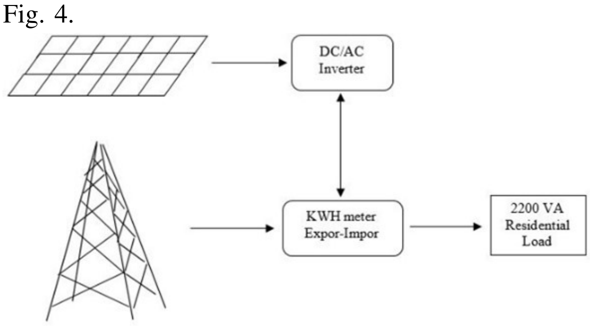

Fig. 4. Conceptual drawing of household-scale on-grid PV power system.

Solar panels convert sunlight radiation into direct current (DC) electricity. Afterward, the direct current is converted to alternating current (AC) using an inverter. Next, the electricity that has been converted into Alternating Current (AC) is then used for electrical consumption inside the consumer's household. Finally, if the electricity produced by solar panels would be in excess, then the excess electricity will be exported to PLN as a deposit using the Export-Import kWh meter (ExIm) and at the time of payment, the bill will be deducted from exports to PLN with the export of electricity to PLN valued at 65% of the price of the Electric Power Tariff (TDL) [2], [3]. In the analysis of economic factors, several methods are used in the Hybrid Optimization of Multiple Electric Renewables Software to determine the cost-effective, Break-even Point (BEP), Net Present Cost (NPC), and COE based on the present value and the power sold or purchased to PLN (Grid).

C. PV Module Modeling

Modeling a PV module using the Shockley diode model can be shown in(1) with Photocurrent (I_{ph}), Inverse saturation current (I_o) and Shunt resistance (R_{sh}) which can be found by (2), (3), and (4), respectively.

$$I = I_{ph} - I_0 \left(e^{\frac{q}{kT}\frac{1}{\gamma N_{CS}}} - 1 \right) - \frac{V + IR_s}{R_{Sh}} \quad (1)$$

$$I_{ph}\left(G.T_c\right) = \left(\frac{G}{G_{ref}}\right) . \left(I_{Ph\ ref} + \mu_{ISc}\left(T_c - T_{Cref}\right)\right) \quad (2)$$

$$I_0(T_C) = I_{0ref}\left(\frac{T_C}{T_{Cref}}\right)^3 . e^{\left(\left(\frac{q.E_{gap}}{\gamma - k}\right)\left(\frac{1}{T_{Cref}} - \frac{1}{T_C}\right)\right)} \quad (3)$$

$$R_{SH}(G) = R_{SH}\left(G_{ref}\right) + \left(R_{SH}(0) - R_{SH}\left(G_{ref}\right)\right) . e^{\left(-\beta\frac{G}{G_{ref}}\right)} \quad (4)$$

The symbols G, G_{ref}, R_s, T_C, T_{Cref}, κ, N_{CS}, γ respectively denote Effective irradiance, Reference irradiance, Series resistance, Module (cell) temperature, Reference temperature, Boltzman constant, Number of cells in series the module and Module quality factor. Meanwhile, the other symbols have been described in equations (1) to (4).

The performance of the inverter ($\eta_{v,p}$) is analyzed using the linear extrapolation method as such in (5). The symbols p, p_1, and p_2 respectively describe power, the nearest power point below target power, and the nearest power point above target power.

$$\eta_{v,p} = \eta_{v,p_1} + (p - p_1)\left(\frac{\eta_{v,p_2} - \eta_{v,p_1}}{p_2 - p_1}\right) \quad (5)$$

III. Numerical Studies

This section discusses the profile of 2200 VA household load, the Net Presnt Cost (NPC), the Present Value (PC), Break Event Point (BEP), levelized Cost of Eneregy (COE), initial capital, operating and maintaining cost, and solar panel electricity production.

A. 2200 VA Household Load Profile

The following load profile is measured directly using power data logger in. Fig. 5 shows the profile of power usage in a house obtained by measuring the power, voltage, and current of electronic appliances that can be summarized as the daily behavior of a 2200 VA household with the list of electronic devices in the following Table 1.

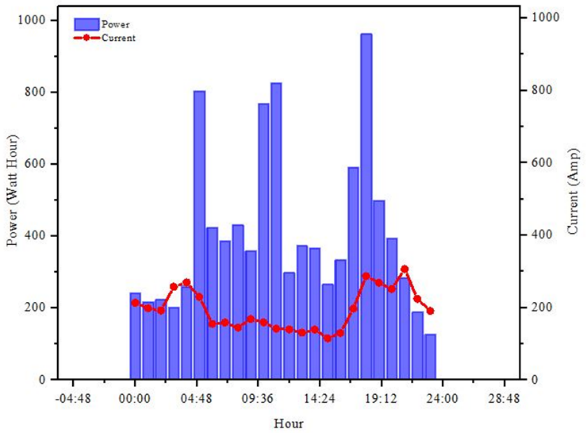

Fig. 5. 2200 VA household load profile.

Table 1. Type of Electrical Load Measured by Power Data Logger

Parameter	Amount	Time Used (hr) in a day
Philip's Iron	1	3
Powerbank Charger	1	3
Laptop Charger	1	5
Samsung Charger	1	6
Outside Lamp 10 W	1	14
Rice cooker	1	24
Sharp TV	1	6
LG Fridge	1	24
Sharp Fridge	1	24
Sanyo Pump	1	6
Room A Lamp 8W	2	6
Room B Lamp 8 W	7	13
Room C Lamp 8W	1	24
Lamp 10W	2	13

B. Net Present Cost (NPC)

Net present cost is one of the determining factors for investors to invest, the smaller the NPC, the better it is to invest. The total NPC can be calculated using the following equation:

$$NPC_{Sistem} = A + B + C + D - E \quad (6)$$

Table 2 follows the results of the analysis of the calculation of the number of electricity bills before and after the installation of solar panels on a 2200 VA house using (6) and (7) over a 25-year period.

Fig. 6 presents an analysis of the correlation of a decrease in the capacity of a power system to an impairment in NPC.

Table 2. NPC of Full Grid and On-grid System in 25 Years Project Lifetime

NPC (IDR)				
Fully Supplied by Grid	**On-Grid 100 Wp**	**On-Grid 200 Wp**	**On-Grid 300 Wp**	**Saving**
72,000,000	39,145,040	39,030,610	38,430,890	45.63% - 46.62%

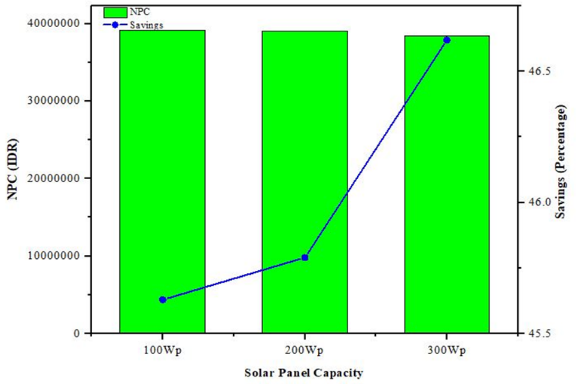

Fig. 6. NPC for solar panels 100Wp, 200Wp and 300Wp.

C. Present Value (PV)

The amount of NPC is obtained from finding the present value of the PV module installed during the project (n). NPC value is influenced by interest rates, and the number of years as shown in (7).

$$PV = \frac{1}{(1+i)^n} \quad (7)$$

D. Break Even Point (BEP)

Long term investment has consequences and risks in the future. Break even calculation, also referred as sensitivity analysis to determine the return of money that has been invested and used in the project (profit) through the calculation of the turning point of capital is shown in (8). While (9) shows the value of BEP which is influenced by annual cumulative interest rates with cash flow.

$$BEP_{simple} = a + \frac{b}{c} \quad (8)$$

$$BEP_{Discounted} = PV * CF \quad (9)$$

a, b, c, PV, and CF represent last year number with a negative cumulative cash flow, Absolute value of cumulative net cash flow at the end of the year a, Total cash inflow during the period following period a, present value, and cash flow respectively.

The BEP value in Table 3 for the Grid system (PLN) is zero because it only uses supplies from PLN, so there will be no cost-saving. This system is a base case system as a comparison of on grid solar systems.

Table 3. BEP of On-grid and Full Grid System

BEP Types	**BEP**			
	Full Grid	**On-Grid 100 Wp**	**On-Grid 200 Wp**	**On-Grid 300 Wp**
Simple Payback	0	8.02 yrs	8.06 yrs	7.40 yrs
Discounted Payback	0	9.59 yrs	9.34 yrs	8.48 yrs

E. Levelized Cost of Energy (COE)

Levelized Cost of Energy (COE) is defined as the average cost per kWh of electricity production that is consumed by the system.

Table 4. Levelized Cost of Energy in Different Types of Solar Panel

COE (IDR)				
Grid	**On-Grid 100 Wp**	**On-Grid 200 Wp**	**On-Grid 300 Wp**	**Saving**
1,467.28	483.7	490.67	498.54	66.02-67.04%

To calculate the COE, the annual cost of producing electricity is divided by the total used electrical energy produced by the system according to (10).

$$COE = \frac{Total\_annualized\_cost}{Consumption\_energy \frac{kWh}{year}} \quad (10)$$

F. Initial Capital

The calculation of components or devices contained in the solar power system consists of solar panels (12) and inverters (13) to be the basis for calculating the initial capital cost in accordance with (11). The prices of each component are listed in Table 5.

$$Intial\ Capital = PVCost + InverterCost + KWH\ MeterCost \quad (11)$$

$$PV_{Cost} = \frac{Amount\ of\ PV\ used\ \times Price}{unit} \quad (12)$$

$$Inverter_{Cost} = \frac{Amount\ of\ Inverter\ used\ \times\ Price}{unit} \quad (13)$$

Table 5 shows the specifications of the PV system used in this research. The components used are inverter, PV, and KWH EXIM.

G. Operating and Maintaining Cost (O&M)

Operational costs are the annual costs of operating and maintaining a component. Operating costs can be calculated by adding up O&M costs (IDR/yr) and component replacement or replacement costs (IDR/yr). O&M costs refer to the Electric Power Research Institute (ELRI) which has been provided in Table 5.

Table 5. Assumptions and Parameters Used

Parameter	**Grid**	**PV**	**PV/PLN Hybrid**
System types	2200VA	100Wp-300Wp	100Wp-300Wp with PLN
System total capital cost	IDR 1,467.46 /kWh	IDR 1,250,000-3,350,000	Dependant on Grid energy purchase
System lifetime	-	25 yrs	25 yrs
Discount rate	5%	5%	5%
NPC evaluation period	25 yrs	25 yrs	25 yrs
Inverter cost	-	IDR 3,300,000	IDR 3,300,000
Inverter lifetime	-	10 yrs	10 yrs
Annual O&M cost	-	$ 6	$ 6
KWH meter Cost	-	-	IDR 1,600,000

H. Solar Panel Electricity Production

The production of electrical energy from solar panels is calculated using the following formula.

$$P_{PV} = Y_{PV}.f_{PV}\left(\frac{G}{G_{ref}}\right)\left[1+\alpha_p\left(T_C-T_{ref}\right)\right] \tag{14}$$

PPV, YPV, fPV, and α_p represent power production of solar panels, solar panel ratings, derating factor, and temperature coefficient of power respectively.

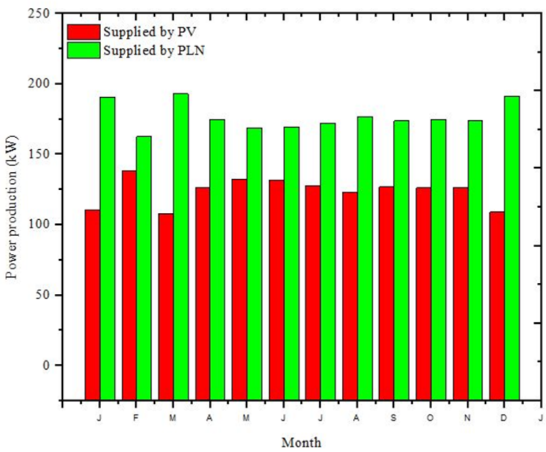

Fig. 7. Power production of on-grid PV power system.

Based on Fig. 7 more than 50% of electricity production in the solar grid system is supplied by the PV system.

IV. Discussion

On-grid solar power system for the category of 2200 VA power was simulated with three PV case capacity studies (100 Wp, 200 Wp, and 300 Wp). Analysis in relation to energy economic factors for small-scale PV power systems (100 Wp to 300 Wp) have been examined and evaluated using Hybrid Optimization of Multiple Electric Renewables software. Based on the optimization results and the addition of modeling sensitivity, the three on-grid solar power systems have an NPC of 45 percent lower than the full Grid system (Table 2). Furthermore, a power reduction of 21.89 percent, which is 2.15 kWh can reduce NPCs by 13.12% - 15.31% which is in the range of costs of IDR 23,060,260 - IDR 25,195,970 (see Fig. 6) for each on grid solar power system.

BEP values for each variation of PV capacity show values below 10 years, namely 7.99 years, 8.18 years, 7.60 years respectively for 22 PV 100 Wp capacity, 11 PV 200Wp capacity, and 7 PV 300Wp capacity (Table 3). While the investment costs required in installing solar power with a power capacity of 7.67 kWh for the needs per day reached IDR 32,100,000, IDR 32,100,000, and IDR 29,000,000 respectively for 22 PVs with a capacity of 100 Wp, 11 PVs with a capacity 200 Wp and 7 PV with 300 Wp capacity. Furthermore, more than 50% of the power production on the solar grid system is supplied by the PV system (see Fig. 7).

Based on the consideration of the NPC and BEP value of the most economical and quick return on-grid solar design (Table 3) is the design of an on-grid solar power system that uses 7 PVs with a capacity of 300Wp (Table 2). Furthermore, the on-grid solar system with 7 PVs with a capacity of 300 Wp is able to save electricity costs by IDR 23,060,260 compared to the use of 100% electricity from the PLN grid. In addition, technically a PV power system with a configuration of seven 300 WP solar panels requires less roof area than the configuration of 22 100 WP solar panels and 11 200 WP solar panels. Therefore, both the initial capital, installation, and maintenance costs for solar panels with the highest peak power with a narrow active area are much cheaper than solar panels with a peak power difference of 100 WP but require a large active area.

V. Conclusion

This paper presents, models and optimizes on-grid solar power systems that are used to electrify household loads with 2200 VA power. Various factors are considered for developing a system operational strategy, namely energy demand estimation; source allocation; system energy production ratio, and economic aspect ratio. These four parameters are evaluated through the Hybrid Optimization of Multiple Electric Renewables software. Three scenarios of solar grid systems are proposed to determine the optimal design of the system by considering economic criteria.

Three scenarios of solar grid systems namely, 22 pieces of PV capacity of 100 Wp, 11 pieces of PV capacity of 200 Wp, and 7 pieces of PV capacity of 300 Wp connected to the PLN network. The most economical and quick return on-grid solar power design is the design of an on-grid solar power system that uses 7 PVs with a capacity of 300Wp. This system is able to save electricity costs by IDR 23,060,260 compared to the use of 100% electricity from the PLN grid.

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