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TECHNO-ECONOMIC ANALYSIS OF TRIANGULAR ROOFTOP SOLAR PV MODEL/PLN ON-GRID HOUSEHOLD SCALE IN INDONESIA

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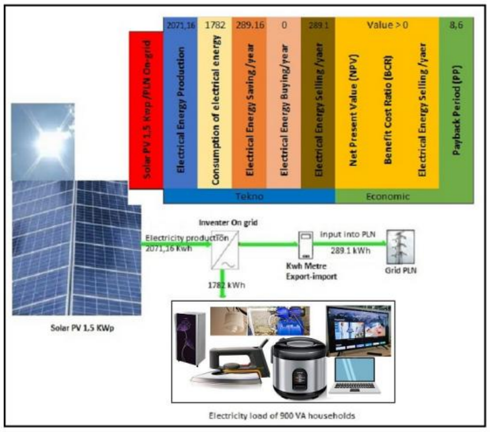
Graphical abstract



Abstract

The use of solar PV as an alternative to fulfill household-scale electricity needs has begun to be widely developed. However, the problem of investment costs and the location of solar PV placement for household scale is still a challenge in its implementation. The construction model of rooftop solar PV can affect the investment cost and performance of solar PV. In this paper, the triangle model of rooftop solar PV on grid with PLN (PT. Perusahaan Listrik Negara) electricity network is studied in terms of technology and economics to determine the feasibility of implementing 900 VA household-scale power plants. Testing the application of solar PV technology under solar radiation conditions in the city of Surabaya, Indonesia as a case study. Calculation of electricity production, energy savings, energy sales, and energy purchases to determine technological feasibility as well Net Present Value (NPV), Benefit Cost Ratio (BCR), and Payback Period (PP) to determine the level of economic feasibility. The results of the research of 1,5 KWP (kilowatt peak) solar PV technology on a household scale are able to meet energy needs and reduce PLN electricity purchases to 0% and can sell electrical energy by 13.96% / year of the total electrical energy produced. In addition, the NPV, BCR with a value greater than zero, and PP of 8.6 is less than 15 years which is the service life of solar PV, so solar PV/ PLN on grid is feasible to be implemented for household scale power generation models.

Keywords: Rooftop solar PV, triangular, on-Grid, household scale, Techno, Economic

1.0 INTRODUCTION

Solar energy is renewable energy which is classified as clean energy and is easy to use to meet the increasing global energy needs [1]. The solar irradiation received by the earth's surface varies depending on the atmosphere and cloud conditions, the effect of scattering by the atmosphere is estimated that the solar energy reaching the earth's surface is 50% of the total solar energy. The variability of solar energy irradiation is also influenced by season, time of day, and latitude location [2,3]. Indonesia Equatorial locations can receive solar energy irradiation throughout the year with an average of 4.8 kWh/m2 and a range of 8-10 hours/day [4, 5].

Solar energy can play an important role in renewable energy systems as an energy source for solar PV power plants that are relevant in rural or urban environments [6–10]. However, the utilization of renewable energy in the draft National Electricity General Plan (RUKN 2015-2034), The renewable energy utilization is targeted at 23% in 2025. [11]. Meanwhile, in 2018 the utilization of solar energy in Indonesia was still 8.8 GW or 0.019% of the total renewable energy of 442 GW [12]. The utilization of solar PV as a renewable energy power plant is regulated in the policy of the Ministry of Energy and Mineral Resources (MEMR) [13, 14, 15]. The application of solar PV can solve the problem of electricity demand in Indonesia, which is increasing by 7% per year due to the growth of the household sector by 13 million [16, 17].

The performance of a solar PV system can be affected by several things, such as; The use of solar PV control systems, controller Pulse Width Modulation (PWM) [18, 19], controller Maximum Power Point Tracking (MPPT) [20, 21, 22], Solar tracker [23], hybrid solar PV with battery power supply [24], solar PV and Storage for household consumer using Agent Based modeling [25], and hybrid solar PV with other energy sources on-grid or off-grid [26, 27, 28]. The system solar PV on-grid or off-grid with PLN (PT. Perusahaan Listrik Negara/PLN) electricity grid has different levels of advantages both in terms of technology and economics [29, 30, 31, 32]. Another, the placement of solar PV can affect the level of solar irradiation that can be converted into electrical energy.

Placement of rooftop solar PV with a higher roof slope reduces the level of shadow loss because it reduces the slope of the panels with respect to the roof surface and the roof surface area increases, resulting in more solar panels installed and an increase in the output power of the array [33]. Meanwhile, building boundary features can have a significant impact on the application of rooftop solar PV technology [34]. The power increase of rooftop solar PV can increase by 2-16% with north-facing installation having strong potential with an optimal annual angle of 177^{o} and a tilt degree of 13^{o} [35]. The installation of solar roofs in the tropics with an annual optimum azimuth angle of 245^{o} and a tilt angle of 32.5^{o} flat roof models at the annual optimum angle is more practical, while gable roof models in the east-west direction are favorable [36].

Therefore, this paper analyses a triangular construction rooftop solar PV model with on grid electricity of PLN (PT. Perusahaan Listrik Negara). The implementation of MEMR policy number 26/2021 which allows household-scale PLN customers to install solar PV on grid [38]. Technological and economic studies were conducted to determine the feasibility of solar PV on grid models to meet household-scale electrical energy needs independently.

Meanwhile, the special emphasis of this research is to investigate the on grid solar PV/PLN model for household scale electricity application with triangular construction solar PV installation. The research objective is to analyze the performance of on grid solar PV/PLN from two aspects, namely; technology and economics. The method used is to design on grid solar PV/PLN with triangular construction roof solar PV. Measurement of solar PV electricity production is carried out to determine the average electricity production per day. Meanwhile, economic analysis was carried out by calculating the value of Net Present Value (NPV), Benefit Cost Ratio (BCR), and Payback Period (PP). The performance of the on grid solar PV/PLN model shows solar PV surplus electricity production of 13.96%/year which can be sold to the PLN power grid. Economically, the on grid solar PV/PLN model is feasible to invest in as a household-scale power plant.

2.0 METHODOLOGY

2.1 Materials

The materials and equipment used solar PV Monocrystalline type 250 Wp with specifications; maximum power (P_{max}) =250 Wp, the voltage at maximum power (V_{mp}) = 30.3 V, current at maximum power I_{mp} = 8,25 A, open circuit voltage V_{OC} = 36.3 V, short circuit current I_{SC} = 8.75 A, *Temperature Range* = 45 ^{o}C – 80 ^{o}C, dimension = 1640 x 992 x 35 mm, max. series fuse rating = 15 A. Inverter prime 2000 W 48 V MPPT, maximum output power =1,1 Kw, grid voltage 180 - 380 V, max. solar array power (P_{max}) 2800 watt, Max. voltage 400 V, max. MPPT Voltage Range = 70 - 380 V, type MPPT 50A.

2.2 Techno Analysis

The angle setting for Solar PV installation is adjusted to the research location in Surabaya City Indonesia as a case study, which is geographically located at 7^{o} 9′- 7° 21′ South Latitude and 112^{o} 36′ – 112^{o} 54′ East Longitude. The azimuth angle of 70^{o} (North-South) adjusted to the position of the sun's apparent trajectory in June, and the solar PV tilt of 30^{o} (East-West) [34]. Measurement of the electricity generated by solar PV/day is calculated using a KWh meter. Schematics of the solar PV system are presented in Figure 1.

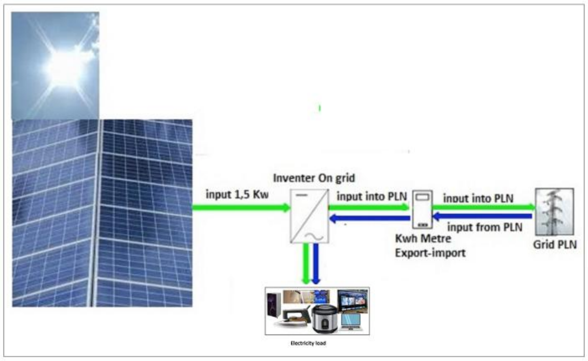


Figure 1 Schematics solar PV/PLN on grid

Another, based on data obtained from NASA Prediction of Worldwide Energy Resources data and Climatology and Geophysics Station Class I Juanda Sidoarjo, such as solar energy potential in the city of Surabaya, temperature, sunshine duration, and PLTS specifications are used for electrical energy calculations using PVSyst 6.43 software.

The rooftop solar PV triangle model uses 250 WP solar PV panels. Solar PV panels amount 6 panels are arranged in a row of three forming a triangle with a tilt angle of 30^{o}. installation of rooftop solar PV with the construction of 3 solar PV panels facing east and 3 solar panels facing west with parallel electrical circuit type. The position of the rooftop solar PV triangle model is designed to overcome the decrease in solar radiation received at the solar PV surface caused by changes in the angle of the sundial and the apparent trajectory of the sun, as presented in Figure 2.

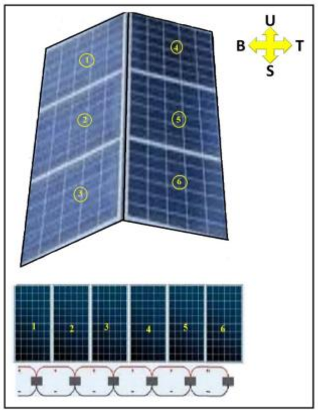


Figure 2 The rooftop solar PV triangular model

Meanwhile, the residential electrical energy consumption such as; LED lamps, iron, water pump, rice cooker, television, laptops, and refrigerators used are presented in Table 1.

Tables 1 Household scale electricity needs

Electricity needs	Electricity consumption (kWh)
4 LED Lamp 12 watt	0,384
6 LED Lamp 20 watt	0,72
Iron 250 watt	0,25
Water pump 125 watt	0,25
Rice cooker 250 watt	0,25
Television 20 inchi 100 watt	0,5
Laptops 15 watt	0,2
Refrigerator 100	2,4
Total electricity needs/day	4,95
Total electricity needs/month	148,62
Total electricity needs/year	1782

2.3 Economic Analysis

The economic analysis is carried out by calculating Net Present Value (NPV) is first-year investment value, Benefit Cost Ratio (BCR) is analyze the feasibility of solar PV investment, and Payback Period (PP) is to calculate the time period needed for the investment funds that go into solar PV investments to be fully recovered [16]. The NPV or first-year investment value is calculated using equation 1.

$$\mathrm{N} = \mathrm{PWB} = \mathrm{PWC} \qquad (1)$$

If the NPV > 0, it means that the investment is feasible, and the NPV < 0, it means that the investment is unfeasible.

Where, Present Worth of Benefit (PWB) is the cash flow taking into account the benefits and can be calculated by equation 2.

$$\mathrm{PWB} = \sum_{t=0}^{n} \mathrm{Cfb}_t \ \mathrm{x}\, (\mathrm{Pif})_t \qquad (2)$$

Meanwhile, Present Worth of Cost (PWC) is a cash flow by taking into account cost and can be calculated by equation 3.

$$PWC = \sum_{t=0}^{n} Cfc_t \ x\, (Pif)_t \qquad (3)$$

Which, n is Age of investment, t is Time Period, Cfb is Cash flow benefit, Cfc is Cash flow cost, Pif is Present Interest Factor. To analyze the feasibility of solar PV investment, the Benefit Cost Ratio (BCR) is calculated using equation 4.

$$BCR = \frac{PWB}{PWC} \qquad (4)$$

If BCR > 1, it means that the investment is feasible, and BCR < 1, it means that the investment is unfeasible. Meanwhile, to calculate the time needed to return investment costs. the payback period (PP) value is calculated using equation 5.

$$\mathrm{PP} = \sum_{t=0}^{n} \mathrm{Cf}_t \geq 0 \qquad (5)$$

Where n is the period, Cf_t is the cash flow period -t. If the PP period is shorter than the solar PV lifetime, the investment is feasible, and if the PP period is longer than the solar PV lifetime, the project investment is not feasible.

3.0 RESULTS AND DISCUSSION

The decrease in irradiation on the surface of solar PV caused by changes in the angle of incidence of sunlight can have an impact on decreasing the production of solar PV electricity, thus having an impact on the instability of the supply of electrical energy for household scale electricity needs. Solar PV installation model triangular roof model with a tilt angle of 30° in the east-west direction is able to increase the capture of sunlight for a full day. Another, the on grid system with PLN which can supply electricity energy non-stop for 24 hours can overcome the shortage of electrical energy supply from solar PV. The solar PV performance on 20 June when the pseudo-trajectory of the sun was north of the equator is presented in Table 2.

Table 2 Electric energy production from 1.5 kWp triangular rooftop solar PV

Time	Electricity energy Production (kwh)
07.00-08.00	0,5365
08.00-09.00	0,86743
09.00-10.00	0,8632
10.00-11.00	0,7231
11.00-12.00	0,8755
12.00-13.00	0,8726
13.00-14.00	0,7812
14.00-15.00	0,5836
15.00-16.00	0,4003
Electrical energy/day	0,7226

Measurement of 1,5 kWp solar PV electricity production is done when the sky conditions are clear (dry season), the electrical energy produced on average of 0.7226 kWh/day (table 2). Solar PV is effectively irradiated for 8 hours/day, the total electrical energy produced by solar PV / day can be calculated from multiplying the output power of solar PV by the length of irradiation during Peak Sun Hour. Meanwhile, the household-scale electrical energy demand per day is 4.95 kWh (table 1). Solar PV technology with rooftop solar PV can be applied to household-scale electrical installations in urban areas and can meet household-scale electricity needs. The results of this study are in line with solar PV research that has been conducted in several countries, such as; Malaysia, Thailand, and Indonesia [2], [4] [16]. Estimates of household-scale electrical energy consumption in Indonesia is presented in Table 3

Table 3 The estimation of household-scale electrical energy consumption

Number	Day	Electricity energy consumption (kWh)		Total
		Daytime (06.00 AM-05.00 PM)	Night time (05.00 PM-06.00 AM)	
1	Monday	2.2	2.89	5.09
2	Tuesday	2.22	2.12	4.34
3	Wednesday	2.48	2.85	5.33
4	Thursday	2.85	2.55	5.4
5	Friday	2.89	2.23	5.12
6	Saturday	2.15	2.12	4.27
7	Sunday	2.8	2.35	5.15
	Consumption of electrical energy/day			4.95

As a case study, calculating solar PV electricity production in Surabaya is influenced by two seasons, namely the dry season (April-November) with an average solar irradiation of 5.54 kWh/m^2 and the rainy season (December-March) with the lowest irradiation of 4.82 kWh/m^2.

Based on the Minister of Energy and Mineral Resources (MEMR) Regulation No. 26/2021 on the Solar PV Electricity Purchase Tariff by PT PLN (Persero), excess solar PV electricity of PLN customers will be purchased by PT PLN (Persero) at 65% of PLN's electricity selling price [37, 38]. Meanwhile, per kWh household-scale electricity rates according to MEMR regulation number 3/2020 concerning the fourth amendment to MEMR Regulation number 28/2016 installed power capacity are; 451 – 900 VA, price 0,089 USD / kWh, and 901 – 1,300 VA, price 0,095 USD/kWh [39,40, 41, 42].

Meanwhile, simulations using PVSyst 6.43 software based on solar potential data in Surabaya city during 2021 (table 4). The performance of on grid solar PV/PLN technology of triangular rooftop solar PV model can be further analysed, such as; solar PV electricity production, electrical energy consumption, Electrical Energy Saving, Electrical Energy Buying, and Electrical Energy Selling. Solar PV electricity production is calculated from the electrical power produced by rooftop solar PV. Electrical Energy Saving is the remaining rooftop solar PV electricity production that is not used to meet daily electricity consumption. Selling energy is Electrical Energy Saving from solar PV production that is sold to PT.PLN with a selling price value of 65% times the kWh of PT.PLN electricity (MEMR Regulation No. 26/2021). The calculation of the performance solar PV roof triangle is presented in Table 5.

Table 4 The electricity energy production from triangular rooftop solar PV

Month	Monthly Average Irradiation (kWh/m2)	Temperature (°C)	Irradiation time (%)	Electrical energy production (Kwh/year)
January	4.54	29.2	55	112.37
February	5.13	28.6	64	147.74
March	4.62	29.1	70	145.53
April	5.06	29.4	71	161.67
May	5.25	29.7	72	170.10
June	5.11	29.2	85	195.46
July	5.36	29.7	88	212.26
August	5.75	29.1	92	238.05
September	6.27	30.3	90	253.94
October	5.82	29.9	75	196.43
November	5.64	29.8	60	152.28
December	5.12	29.9	37	85.25
				2071.16

Table 5 Techno feasibility analysis of a 1.5 kWh triangular model rooftop solar PV/PLN On-grid system

Component	Electric energy price
Solar PV power capacity	1.5 kWp
Installed PLN electric power capacity	900 VA
Electric energy price/kWh	0,095 USD/kWh
Electric energy production (kWh)/year	2071.16
Electric energy Consumption (kWh)/year	1782
Electric Energy Saving /year	
Electric Energy (kWh)	289.16
Rate in	169.29 USD
Electric Energy Buying/year	
Electric Energy (kWh)	0
Rate in	0
Electric Energy Selling /year	
Electricity purchase price by PLN	65% x price 0,095 USD/kWh
Electric Energy (kWh)	289.1
Rate in IDR	17.85 USD

The solar PV/PLN on grid system shows savings in electricity energy consumption costs on a household scale with a capacity of 900 VA with a value of saving electricity energy consumption costs of 169.29 USD/year and benefiting from selling excess electricity to PLN by 17.85 USD/year.

Economic analysis is conducted to assess the benefits of investing in solar PV to meet household-scale electricity needs. The designed solar PV power capacity will determine the investment costs that will be made for the application of solar PV / PLN on grid technology, the value of investment costs is presented in Table 6.

Table 6 Estimated installation of 1.5 kWp solar PV

Number	Component	Price (USD)
1	1,5 kWp Solar PV	1000
2	Inverters On-Grid 2 kW	350
3	Construction cost	75
4	Cable installation	250
	Total	1675

Meanwhile, The simulation results of triangular rooftop solar PV electricity production using PVSyst 6.43 software, as a basis for economic feasibility analysis. The calculation of economic feasibility in terms of investment can be seen from the Net Present Value (NPV), Benefit Cost Ratio (BCR), and payback period (PP). The calculation is carried out by taking into account the total investment costs, maintenance operational costs, and the inflation rate referring to Bank Indonesia data. NPV, BCR, and PP calculations for solar PV investments are presented in Table 7.

Table 7 Economic feasibility analysis

Method	Value
Present Worth of Benefit (PWB)	2917,83 USD
Present Worth of Cost (PWC)	1675 USD
Net Present Value (NPV)	1242,83 USD
Benefit Cost Ratio (BCR)	1,7
Payback Period (PP)	8,6

Table 6 shows the results of the NPV calculation solar PV power capacity all have a value of more than 0 and BCR has a value of more than 1. Therefore, it can be concluded that household-scale solar PV for the power of 1,5 KWp is economically feasible to implement. In addition, the calculation of the payback period with the formula cost of investment solar PV divided by savings in electrical energy costs shows the value of the investment will be less than 15 years. This shows investment is feasible because it is still under the lifetime of solar PV which reaches 15 years. This shows that the use of household-scale solar PV technology in the community can have an economic and social impact on the community, this result is in line with other research in several countries [43] [44].

4.0 CONCLUSION

The placement of rooftop solar PV models can affect the performance and investment costs of solar PV when installed on the PLN electricity grid. Several factors related to rooftop solar PV performance can be improved by installing a triangular rooftop solar PV model to overcome the power drop when placed on the roof of a house. Techno and economic analysis of the on grid solar PV triangular rooftop model with a capacity of 1.5 kWh shows electricity production of 289.16 kWh which is able to meet household scale electricity needs and is able to sell excess electricity to PT PLN by 13.96%, and shows economic feasibility to be invested with investment capital parameters will return in less than 8.6 years. Another, it is necessary to pay attention to the angle of solar PV installation and the shape of the roof of the house so as to overcome the decrease in solar intensity on the surface of solar PV caused by the angle of the sun's irradiation hours and the apparent trajectory of the sun.

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