Energy Yield of a 1.3 kWp Grid-Connected Photovoltaic System Design: Case for a Small House in Bali

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Abstrak: Makalah ini bertujuan untuk mendapatkan performansi produksi energi dari sebuah desain sistem fotovoltaik berkapasitas 1,3 kWp yang terhubung jaringan untuk sebuah bangunan rumah kecil di Bali yang memiliki konsumsi listrik rata-rata 6.36 kWh/hari dengan menggunakan *software* PVSyst. Lokasi rumah berada pada iklim tropis dengan temperatur rata-rata bulanan sebesar 27,2 °C dan rata-rata iradiasi matahari bulanan bervariasi dari 4,41 hingga 7,14 kWh/m². Posisi panel fotovoltaik dioptimalkan pada sudut azimuth 0° dan sudut kemiringan 12,5° menghadap ke utara dengan kemiringan tetap tanpa pelacakan. Desain sistem fotovoltaik terdiri dari empat unit modul jenis multi kristal dengan daya puncak per unit sebesar 325 Wp dan tersambung dalam satu larik untuk membentuk pelacakan titik daya maksimum pada inverter. Satu unit inverter dengan daya luaran nominal 1,6 kW digunakan untuk mengubah daya listrik dari arus DC ke AC. Hasil simulasi menunjukkan bahwa iradiasi global dan produksi energi pada luaran inverter bervariasi antara 4,16 dan 6,65 kWh/m²/hari dan 129,9-199,7 kWh. Rasio performansi bulanan, faktor kapasitas dan efisiensi sistem berfluktuasi masing-masing antara 76,9-78,6%, 17,3-27,7% dan 12,8-13,0%. Kerugian maksimum *array* fotovoltaik dan kerugian sistem adalah 1,35 kWh/kWp/hari dan 0,18 kWh/kWp/hari. Hal ini terjadi pada bulan November dimana efisiensi sistem mencapai nilai terendah yang kemungkinan dipengaruhi oleh temperatur lingkungan yang tinggi.

Kata kunci: Bali, produksi energi, terhubung jaringan, PVsyst, rumah kecil, fotovoltaik.

Abstract: This paper aims to obtain the energy yield performances of a 1.3 kW_p grid-connected solar photovoltaic system design for a small house building in Bali with an average electrical consumption of 6.36 kWh/day by using PVSyst simulation software. The house location is under a tropical climate with 27.2 °C average monthly temperature. The average monthly horizontal solar irradiation varies from 4.41 to 7.14 kWh/m². The photovoltaic panel position is optimized at 0° azimuth and 12.5° tilt angles, which arranged facing north with fixed tilted without any tracking. The proposed photovoltaic system composes of 4 poly-crystalline modules, each 325 W_p capacity connected in one string to establish maximum power point tracking in the inverter. One unit of the inverter of 1.6 kW is used to convert electrical power from DC to AC. The simulation results show that global incident irradiation and energy production at inverter output varies between 4.16 and 6.65 kWh/m²/day and 129.9-199.7 kWh. The monthly performance ratio, capacity factor, system efficiency is found to fluctuate between 76.9-78.6%, 17.3-27.7%, and 12.8-13.0%, respectively. The maximum of array capture and system losses of 1.35 kWh/kW_p/day and 0.18 kWh/kW_p/day occur in November with the lowest system efficiency, which is likely influenced by the high ambient temperature.

Keywords: Bali, energy yield, grid-connected, PVSyst, small house, solar photovoltaic.

I. INTRODUCTION

Electricity constitutes basic needs for the communities in daily life, even in household sector. In Indonesia, such a sector consumes the most extensive electricity of 102,712 GWh or shares of 40.1% over 2018 [1]. The national grid electricity capacity of 1,300 VA is widely installed in the household buildings, which accounts for 90% of the customers. For those, about 87.4% of the electricity supplied from fossil fuelbased power generators [2].

Owing to the environmental and reliable energy supply awareness, shifting the use of fossil fuel to renewable energy sources in energy generation is fundamentally essential. Renewable energy deployment gains more considerable attention that could reduce greenhouse gas emissions as well as reduce environmental and health risks associated with pollutants [3]. Besides technology and economic factors, environmental motivation plays a vital role in energy savings, such as in photovoltaic (PV) households [4].

Indonesia has set a renewable energy target of 23% by 2025, according to the Paris Agreement under UNFCC. Currently, renewable energy contributes 12.6% of the total primary energy supply, in which only 0.19% came from solar PV plants [2]. The country, which lies in the tropics, has enormous solar PV potential of more than 500 GW. However, as per June 2018, the solar PV plants installed capacity in the household is only about 521 kWp [5]. Thus, any efforts have to be made to increase their installed capacity, such as public campaigns supported by the policymakers.

Grid-connected solar PV system becomes an attractive option of electricity source for households in the urban areas since the national grid utility is readily available. Bali, as a tourism province, has a dense

population and private housings, mainly in Denpasar city, which makes it potential to implement the solar PV installation along with the reliability of electricity supply from the grid. Moreover, the Governor of Bali Province has declared a program of Bali Clean and Green and put more attention on renewable energy utilization.

Several researchers reported the simulated performance of grid-connected solar PV systems for households. Dondariya et al. evaluated the performance feasibility of a 6.4 kWp rooftop PV system for a hypothetical household building in Madhya Pradesh, India [6]. They utilized various simulation software, such as PV*SOL, PVGIS, SOLARGIS, and SISIFO, to predict energy generation, performance ratio (PR), and solar fraction. Amongst them, PV*SOL demonstrated robust and easy use for the PV system simulation. Tomar and Tiwari assessed the techno-economic viability of 1.8 kW and 3.8 kW grid-connected PV systems for residential households in New Delhi, India using HOMER software tool [7]. Tarigan et al. analysed techno-economic performances of a 1 kWp PV system for a household in Surabaya using PVSyst and RETScreen simulation tools [8]. The PV system injected electricity into the grid about 3.75 kWh/day with a PR of 72.5% in which technically matched the basic electrical demand of a typical household. Shukla et al. performed simulation analysis of the energy yield and performance ratio of a 110 kWp rooftop PV system with different PV technologies for a residential hostel building in Bhopal India using SOLARGIS-pvPlanner software [9]. They examined that the energy yield and PR ranges are of 2.67-3.36 kWh/kWp and 70-88%, respectively.

The present study is aimed at performing computer simulation by using PVSyst software to obtain energy yield performances of a 1.3 kWp gridconnected solar PV system design applied for a small house building in Bali Province, Indonesia. The system energy balance, performance ratio, capacity factor, system efficiency, and power losses are discussed. Furthermore, the potential of energy savings of such a system compared to the grid-only electricity supply can be predicted.

II. METHODS

A. Research Location and Electricity Usage

The site selected for the study is a household near Denpasar city border, which is at Tegal Jaya Permai I residence, Badung Regency, Bali Province, Indonesia with a latitude of 8.6303 °S and longitude of 115.1794 °E as shown in Figure 1. The house building faces north and has two floors with the land and building areas about 80 m² and 72 m². The grid-connected solar PV panels are designed to be sited on a frame in the flat space of the rooftop with free-mounting.



Figure 1. Satellite image of the research location.



Figure 2. Electricity usage on site.

Figure 2 shows a monthly profile of electricity consumption for the house, which has been derived from monthly electrical bills. The average electrical usage is about 6.36 kWh/day.

B. Solar PV System Design



Figure 3. Schematic diagram of a grid-connected solar PV system.

Figure 3 presents a schematic diagram of a typical grid-connected solar PV system to power household electrical needs. The main components of the system consist of solar PV panels, on-grid inverter, net-meter, house's load appliances, and grid supply transmission. Such a system is configured with no electricity backup by battery banks to avoid additional losses.

This study proposes the solar PV system design capacity of 1.3 kWp. The primary consideration is the Regulation of the Ministry of Energy and Mineral Resources of the Republic of Indonesia Number 49/2018, which states the maximum allowable PV system capacity is as high as 100% of the consumer's grid installed power capacity. Meanwhile, the majority of the household consumers subscribe to the grid power capacity of 1,300 VA.

Table 1. Characteristics of the PV module (Canadian Solar, CS6U 325P-AG, poly-crystalline).

Parameter	Value
Nominal maximum power (P _{max})	325 W
Maximum power voltage (V _{max})	37.0 V
Maximum power current (Imax)	8.78 A
Open circuit voltage (Voc)	45.5 V
Short circuit current (Isc)	9.34 A
Module efficiency	16.56%

The solar PV system components selection is based on market availability, brand reputation, and reliability at affordable costs. The proposed 1.3 kWp PV system composes of 4 poly-crystalline modules of Canadian Solar CS6U 325P-AG, each 325 Wp capacity connected in one string to establish maximum power point tracking (MPPT) in the inverter. The module efficiency is 16.56% under standard test conditions (STC), i.e., cell temperature of 25 °C, solar irradiance of 1000 W/m², and air mass (AM) of 1.5. A singlephase inverter, Growatt 1500TL is used to convert DC to AC power, which then injected directly for selfconsumption and into the grid. The inverter is equipped with ShineNET software for data monitoring via RS232, Bluetooth, and internet connections. The specifications of the PV module and inverter are given in Table 1 and Table 2.

Table 2. Characteristics of the inverter (Growatt 1500 TL).

Parameter	Value
Input:	
Max. DC power	1800 W
Max. DC voltage	450 V
PV voltage range at MPPT	120-450 V
Maximum PV current	10 A
<u>Output:</u>	
Nominal AC output power	1600 W
Grid voltage	230 V
Maximum AC current	8 A
AC voltage range	180-280 V
Maximum efficiency	97%
MPPT efficiency	99.5%

C. Simulation Methodology

In this study, the performance simulation is carried out using PVSyst 8.4 software. The PVSyst is a PC software tool to study, sizing and data analysis of complete PV system configurations, such as grid-connected, stand-alone, pumping and DC grid [10].

The PVSyst simulation involves two basic setups as follows:

- 1. Project's designation, namely site geographical location with corresponding meteorological database (horizontal global and diffuse solar irradiation and ambient temperature) and project settings. The imported meteorological data is derived from Meteonorm 7.2.
- Main input parameters, such as PV orientation, system components, detailed losses, selfconsumption, or user's needs.

The assumptions of PV system losses parameters associated with free mounted modules with air circulation are specified at 29 W/m²K and 0 W/m²K for constant and wind loss factors. The DC circuit wiring loss (ohmic loss) fraction at STC is 1.5%. The module quality loss is 1.5%. The light-induced degradation loss is 0.5%. The module and strings voltage mismatch with power loss at MPP is 1.0% and 0.1%, while the global and mismatch degradation factors due to the individual PV module aging is 3.8% and 0.54%.

The common albedo effects for urban situations range from 0.14 to 0.22 [10]. Subsequently, the value of albedo is set at 0.2 for the simulation. The unshaded solar PV panels are arranged facing north with fixed tilted without any tracking due to limited area on the rooftop and avoiding additional capital and maintenance costs.

D. Performance Indices

The performance indices given by the International Energy Agency (IEA) to analyse the energy-related performance of a grid-tied solar PV system include array yield (Y_a), final yield (Y_f), reference yield (Y_r), PR, capacity factor (CF), system efficiency (η_{svs}) and specific energy losses [11-14].

Array yield (Y_a) is the ratio of DC energy output from the PV array (E_{array}) on daily, monthly or yearly basis to its nominal power ($P_{PV,nom}$) at STC and is denoted by [13-14]:

$$Y_a = \frac{E_{array} (kWh)}{P_{PV,nom} (kWp)}$$
(1)

Final yield (Y_f) is the ratio of actual AC energy output (E_{avail}) by the PV system on daily, monthly or yearly basis to its nominal power $(P_{PV,nom})$ at STC and is denoted by [13-14]:

$$Y_f = \frac{E_{avail}(kWh)}{P_{PV,nom}(kWp)}$$
(2)

Reference yield (Yr) is the ratio of total daily incident global irradiation in the collector plane to the

solar irradiance at STC (G_{STC}) and is denoted by [13-14]:

$$Y_r = \frac{GlobInc (kWh/m^2)}{G_{STC} (kW/m^2)}$$
(3)

where G_{STC} is 1000 W/m².

Performance ratio (PR) is the ratio of the final yield to the reference yield and is denoted by [14]:

$$PR = \frac{Y_f}{Y_r} \tag{4}$$

Capacity factor (CF) is the ratio of actual annual AC energy output of the PV system (E_{avail}) to its full nominal energy generated as it operates 8760 hours yearly and is denoted by [12]:

$$CF = \frac{E_{avail} (kWh)}{P_{PV,nom}(kWp) x 8760 h}$$
(5)

The monthly PV system efficiency [13-14] is denoted as

$$\eta_{sys} = \frac{E_{avail}}{GlobInc \ xA_{array}} \tag{6}$$

where A_{array} is the PV panels area.

Specific energy losses in the grid-tied solar PV system includes array capture or collection loss (L_c) and system loss (L_s). Array capture loss refers to the thermal loss in the solar cell due to the cell operating temperature is higher than that of STC temperature at 25°C. DC wiring (ohmic) loss, shading effect, dust/soil deposition effect, degradation/mismatch loss contribute to the array capture loss. While the system loss occurs due to the conversion loss of DC into AC by inverter. Array capture and system losses are calculated as [14]:

$$L_c = Y_r - Y_a \tag{7}$$

$$L_s = Y_a - Y_f \tag{8}$$

III. RESULTS AND DISCUSSION

The PVSyst provides optimization of tilt and azimuth angles as an orientation step. For Bali province, the optimum values are 12.5° and 0° for the tilt and azimuth angles concerning the yearly irradiation yield as shown in Figure 4.

Table 3. shows daily averages of monthly global solar irradiation (horizontal, incident in collector plane, and effective with correction for incident angle modifier/IAM and shadings) and ambient temperature data of the study site.

The global incident irradiation varies from 4.16 kWh/m² in January to 6.65 kWh/m² in November, while the ambient temperature fluctuates from 26.11 °C in July to 27.84 °C in December. From November to February, the global horizontal irradiation shows

higher than that of the incident and effective global irradiation, which correspond with the highest ambient temperature variation over the year from 27.67 °C to 27.84 °C. The daily average of monthly global horizontal and incident irradiation is 5.35 kWh/m²/day (or 1.953 MWh/m²/year) and 5.46 kWh/m²/day (or 1.993 MWh/m²/year), respectively.



Figure 4. Orientation optimization by the PVSyst.

 Table 3. Daily average of monthly global irradiation and ambient temperature

Month	Horizontal	Incident	Effective	Ambient temp.
	(kWh/m²)	(kWh/m²)	(kWh/m²)	(°C)
Jan	4.41	4.16	4.00	27.67
Feb	4.94	4.77	4.61	27.76
Mar	5.00	5.01	4.84	27.79
Apr	5.39	5.67	5.48	27.63
May	5.42	6.00	5.82	27.60
Jun	5.26	5.95	5.77	26.55
Jul	5.13	5.73	5.55	26.29
Aug	5.26	5.64	5.47	26.11
Sep	5.56	5.71	5.53	26.24
Oct	5.91	5.77	5.58	27.51
Nov	7.14	6.65	6.42	27.71
Dec	4.79	4.47	4.30	27.84
Mean	5.35	5.46	5.28	27.22

Figure 5 shows the monthly energy production as a DC output from the PV panel, an AC output at inverter output, and panel temperature variation. The PV system generates maximum DC and AC energy of about 206.7 kWh and 199.7 kWh in November due to the maximum capture of the solar irradiation, which causes the highest panel temperature at 48.03 °C. Interestingly, both the DC and AC energy production are considerably high of about 187.8 kWh and 181.4 kWh in July, with the corresponding panel temperature as low as 44.9 °C. It indicates that solar irradiation is intensive at that month and with the benefit of the lowest ambient temperature, as shown in Table 4, resulting in more efficient PV energy conversion. It can be observed that the energy production mainly depends on the combined effects of solar irradiation and ambient temperature. The annual DC and AC energy generation are 2.087 MWh and 2.014 MWh, respectively.



Figure 5. Energy production and panel temperature over the year.

Figure 6 presents the monthly variation of the PV system energy yield, namely reference, array, and final yields over the operation period of one year. The nominal capacity of the proposed design PV system is 1.3 kW_p . As can be seen, the reference yield varies from 4.16 kWh/kW_p /day in January to a maximum of 6.65 kWh/kW_p /day in November. It is coincident with the array and final yields that fluctuate between 3.36 and 5.3 kWh/kW_p /day and 3.23 and 5.12 kWh/kW_p /day, respectively.



Figure 6. Variation of energy yield over the year.

The capacity factor and energy balance between the user's demand and energy supply from the PV system and grid are shown in Figure 7. The CF is observed stable at 23.5-25.01% between April and October. The maximum CF is 27.7% in November, while the minimum is 17.3-18.6% % for January and December. The CF represents actual energy (AC) at inverter output

divided by nominal PV energy generation over the monthly period. The user's energy demand is maximum of 216 kWh (November) and 218 kWh (April). The lowest energy demand is for September (155 kWh). The user's energy demand is fulfilled by the sum of energy supply from the PV system (E_solar) and imported electricity from the grid (E_frGrid). The monthly energy supply from the PV plant and the imported electricity from the grid vary between 63.7-91.83 kWh and 91.3-131.2 kWh in September and April. The higher the user's energy demand, the higher both the energy supply from the PV plant and the imported electricity from the grid and vice versa.



Figure 7. Balance of energy system and capacity factor over the year.

Figure 8 illustrates the variation of monthly energy injected to the grid and performance ratio over the whole year.



Figure 8. Energy injected into the grid and performance ratio over the year.

The maximum energy injected into the grid is shown for August (109.2 kWh), September (109.7 kWh), May (107.4 kWh), and November (107.9 kWh) and the minimum for January (57.7 kWh), February (58.6 kWh) and December (59.7 kWh). The maximum PR is 78.6% in July, and the minimum PR is 76.9% in November. As can be observed, the decrease in PR is due to the increase in solar irradiation and panel temperature, and vice versa. The annual average PR is 77.8%, which means about 22.2% of solar energy is not effectively utilized as a usable electricity output.



Figure 9. Normalized losses and system efficiency over the year.



Figure 10. Diagram of PV system losses.

Figure 9 shows the variation of the monthly normalized energy losses and system efficiency for the whole year. As can be seen, the loss is majorly by the array capture loss, which is about 7 times the system loss. The high solar irradiation causes high surface panel temperature, which then degrades the solar panel efficiency. The maximum of array capture and system losses are 1.35 kWh/k W_p /day and 0.18 kWh/k W_p /day in November. It also indicates the month of the lowest system efficiency of 12.75% over the year.

The loss diagram of the PV system design during generation on an annual basis is depicted in Figure 10. The loss due to the solar irradiation level is 1.3%, while the losses on the PV panel and inverter are 17.7% and 3.5%, respectively. As can be seen, the annual energy production at inverter output, energy supplied to the user from the PV system, energy injected into the grid, and energy imported from the grid are 2.014 MWh, 928 kWh, 1.086 MWh, and 1.392 MWh, respectively.

IV. CONCLUSIONS

The performance simulation of a 1.3 kW_p gridconnected solar PV system design for a small house building of 1.3 kVA installed capacity in Bali has been carried out using PVSyst software. The simulation results reveal as follows:

- The global incident irradiation varies between 4.16 kWh/m²/day and 6.65 kWh/m²/day. The month with the highest global irradiation is November.
- The PV system generates DC and AC energy generation of 2.087 MWh/year and 2.014 MWh/year, respectively. The maximum energy output of DC (206.7 kWh) and AC (199.7 kWh) occurs in November in which maximum capture of the global incident irradiation causes panel temperature increases as high as 48.03 °C.
- 3. The reference yield varies from 4.16 kWh/kW_p/day in January to a maximum of 6.65 kWh/kW_p/day in November. It is coincident with the array and final yields that fluctuate between 3.36 and 5.3 kWh/kW_p/day and 3.23 and 5.12 kWh/kW_p/day, respectively.
- 4. The maximum CF is 27.7% in November, and the minimum CF is 17.3% and 18.6% % for January and December, respectively.
- 5. The maximum PR is 78.6% in July, and the minimum PR is 76.9% in November. The annual average PR is 77.8%, which means about 22.2% of solar energy is not captured as a usable electricity output.
- 6. The maximum of array capture and system losses are 1.35 kWh/kWp/day and 0.18 kWh/kWp/day in November with the lowest system efficiency of 12.8%. The loss due to the solar irradiation level is 1.3%, while the losses on the PV panel and inverter are 17.7% and 3.5%, respectively.

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