Solar photovoltaic system with self-consumption in villa

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Abstract. Grid-tied photovoltaic (PV) installations equipped with net metering devices become significant interests among villa owners in urban areas. Such devices can help to make sure of exporting excess power to the grid as well as to favor the self-consumption ratio. The self-consumption means that the owners directly utilize PV power production. This paper is aimed at simulating the energy and economic performances of a 3.24 kW_p grid-tied PV system applied in the villa. The case study is a private villa located at Tibubeneng, Bali Province, Indonesia. The Sunny Design Web simulation tool is used for the PV system assessment. The simulation results reveal that the energy yield of the PV system is 4,653 kWh/year, out of which 300 kWh/year is feeding to the grid. The self-consumption and self-sufficiency ratios are 93.5 percent and 35.6 percent, respectively. The PV system also delivers a performance ratio of 81.4 percent, the specific energy yield of 1,436 kWh/kW_p, and the payback period of 9.3 years.

1. Introduction

Indonesia has great potential for solar energy, which favorable as a renewable energy source for electricity generation through photovoltaic (PV) energy conversion. The level of solar irradiation is mostly stable throughout the year of about 4.8 kWh/m^2 on a daily average [1]. The deployment of solar energy can minimize the dependence on fossil-based energy, which has limited reserves as well as potential risks to global warming.

Solar PV plants generate electricity in three ways, namely, on-grid, stand-alone, and hybrid systems. The stand-alone systems work independently, employing battery energy storage without connection to the utility grid, while the on-grid systems require a grid-tied connection. The hybrid PV systems are a combination of both systems. The grid-tied PV systems have the advantage of less expensive and more effective power supply compared to the off-grid and hybrid systems for the same power capacity. A reliable or uninterrupted grid electrical supply is mandatory for the grid-tied PV systems to secure energy supply to the loads [2-4].

The household sector in Bali is the second largest electricity customer of about 42.4% or 260,018 GWh of electricity consumption over 2018. Private villas are of typical household built for the visitors to stay in Bali as alternative tourism accommodation to the star and non-star hotels, which grow significantly about 19.2% each year [5]. Recently, the interest of the villa owner to install PV systems increases due to their concern to cut energy costs and live more environmentally friendly.

Limited studies are found on PV system applications for private villas with grid-tied connections, particularly in urban areas in Bali. A feasibility study before the real PV system installation is fundamentally essential to provide quantitative information for the PV owners, both technical and economic. So far, fortunately, the national utility grid, namely Perusahaan Umum Listrik Negara (PLN), provides a secure and reliable electricity supply to the customers. It supports the broad application of the PV system in the villas.

A common technique to quantify the feasibility of the PV system is a computer simulation, which includes analysis in the view of the technical, economic, and environmental [6]. The PV system and its components are sizing to deliver useful energy production in order to match the energy demand requirements by self-consumption as the priority. This research presents an assessment study of a grid-tied PV system with self-consumption for a typical private villa application in Bali, which demonstrates the technical and economic performance.

2. Literature review

Numerous studies have been reported on the grid-connected PV system with simulation and measurement. Performance analysis of a 190 kW_p grid-tied solar PV plant installed in Khatkar-Kallan, India, was presented by [7]. Their study showed that energy yield is maximum during March, September, and October, and the minimum is in January. The average annual measured energy and predicted by using PVSYST software is 812.76 kWh/kW_p and 823 kWh/kW_p, respectively. The rooftop solar PV evaluation of the city of Lethbridge was conducted by [8] with the annual PV electricity generation about 301 GWh, and 96% of the recognized PV system shows economically feasible. A techno-economic assessment of a 1 kW_p grid-connected PV system using PVSYST software was reported in [6] for a residential house in Surabaya. An annual of 1.3 MWh electricity is fed into the grid, with the PV performance ratio of 72.5 %. Their simulated PV system provides payback 8 years under the feed-in tariff scheme of 0.25 USD/kWh based on RETScreen simulation.

Design analysis of a 148.5 kW_p roof-mounted grid-connected PV system was presented by [9] in a local government office in Nigeria. The PV*SOL software was used for the energy yield simulation. Results showed that the highest PV production is about 20.3 GWh in November, and 75% of the energy is exported to the grid. The design and evaluation of a grid-connected rooftop solar PV system is conducted by [10] using PVSYST for the academic campus. The results showed that the PV system could generate electricity of about 11% of the total annual energy consumption. Simulation of the techno-economic performance of a grid-connected residential PV-battery system in Kyushu, Japan, was carried out by [11]. They found that the self-consumption can be increased by adding battery size, and the payback period of the PV system achieved 18 years without incentives. The PV self-consumption was reviewed by [12]. The increase of self-consumption by 13-24% can be increased with a battery storage capacity of 0.5-1 kWh/kW_p and by 2-15% with the demand-side management method.

3. Site information

The focused study is a private villa name Joglo Kumis in Tibubeneng area, Canggu district, Badung regency, Bali province, Indonesia, as shown in Figure 1. The villa is located at 8.6323 ^{0}S latitude, and 115.1592 ^{0}E longitude with land and building areas of 400 m^2 and 192 m^2, respectively. The on-site PLN installed electrical capacity is 4,400 VA. The daily electrical load is depicted in Figure 2. The peak load of 4.74 kW occurs at 1 pm.

Figure 1. Villa location.

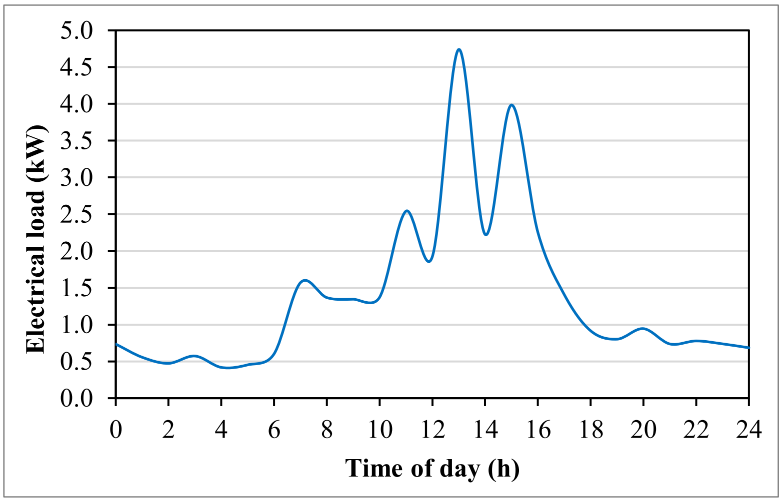

Figure 2. Electrical load on the site.

4. Methodology

Figure 3 shows a typical grid-tied PV system that can be applied for the villa adapted from SMA company [13]. Such a system comprises of the solar PV array, grid-tied inverter, net meter, utility grid supply, and AC loads. The net meter records the amount of electricity supplied by the grid to the load during deficit PV generation while feeding electricity into the grid during surplus.

In this work, Sunny Design Web software version 4.21.1 is used to simulate the technical and economic performance of the PV system design of the studied villa. The configuration of the PV system with and without self-consumption, off-grid system, and PV hybrid system can be simulated using this software. The software recommends the combination of PV array and inverter so that closely matched to the requirement of the energy yield of the planned PV system. The software program can determine and optimize the self-consumption potential of the PV energy system generation, sizing wire, and efficiency evaluation [13].

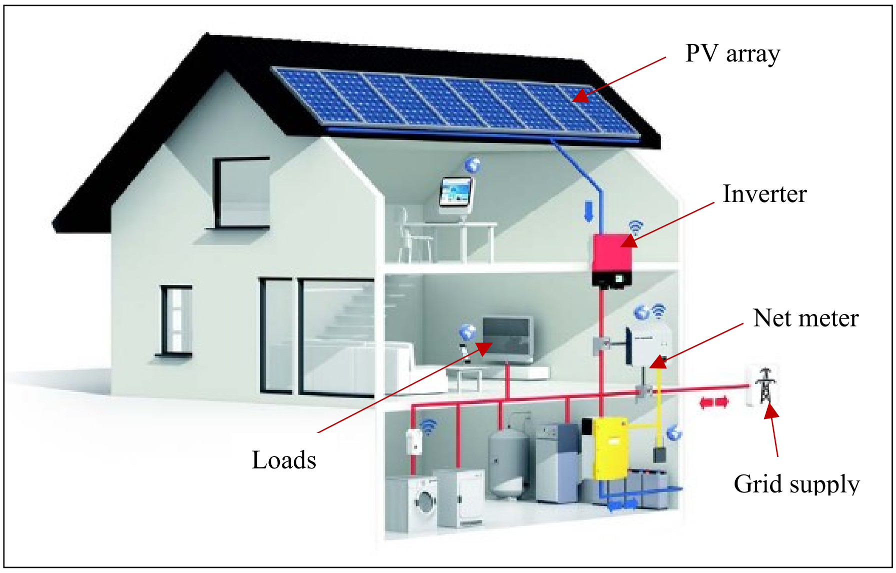

Figure 3. A typical grid-tied PV system for household [13].

The grid-tied PV system in villa is simulated as the following steps: (1) determine project data includes project name and location, meteorological data, voltage level, inverter grid connection, ambient temperature settings, and DC and AC line losses consideration, (2) specify load profile details on an annual, daily or hourly basis, (3) configure the PV system components, namely PV array (PV module capacity, number of modules, manufacturer, mounting type and orientation) and inverter selection based on manual design or design consideration or automatic design), (4) sizing wire and calculate line losses, (5) determine possible self-consumption with and without increased self-consumption, (6) specify the energy management plan by adding communication products for PV system monitoring, control, energy management, and visualization of key system data, (7) analyze profitability based on PV system costs, financing parameters, electricity purchase costs, and feed-in tariff, (8) present technical and economic results.

A 3.24 kWp PV system is designed for low voltage with a grid voltage of 220V (110V/220V) 50 Hz, single-phase feed-in, and voltage tolerance of ±10%. The average ambient temperature is set at 30 ^{0}C, while the annual extreme high temperature is 35 ^{0}C. A maximum unbalances load of 4.4 kVA is taken into account. The daily average electrical load is approximately 33 kWh according to the data reading from the remote monitoring system via the website server.

Table 1 shows the technical specification of the PV module and inverter. The compatibility check between PV array and inverter is carried out by considering the constraint values as follows: (a) maximum DC power of the PV array and inverter should be closely matched, (b) maximum power point (MPP) voltage of the PV array string during the design process at cell temperature of 54 ^{0}C is less than the maximum MPP voltage inverter, (c) open-circuit voltage of the PV array string at minimum cell temperature of 20 ^{0}C is less than maximum DC input voltage (inverter), (d) maximum operating input current per MPP tracking, and (e) maximum short-circuit current of the inverter per MPP tracking.

The DC and AC lines configuration is shown in Figure 4. The cable uses copper material of 32 m length and 4 mm^2 of diameter and 6 m length and 6 mm^2, respectively. The PV system is set to prioritize self-consumption without an increased self-consumption option during operation. It means that the grid feed-in energy is allowed with no advanced control by an intermediate storage system of excess PV energy.

Table 1. PV module and inverter specification.

Components/Parameters	Specification
PV module:	
Type	Mono-crystalline
Model	SolarWorld AG 270 mono (02/2014)
Nominal power	270 W_p
Number of modules required	12
Total installed capacity	3.24 kW_p
MPP voltage	30.9V
Number of cells in the module	60
MPP current	8.74A
Open-circuit voltage	39.2V
Short-circuit current	9.44A
Module efficiency	16.1%
Temperature coefficient for open-circuit voltage	-117.6 mV/^{o}C
Temperature coefficient for short-circuit current	4.15 mA/^{o}C
Dimension	1.001 x 1.675 m
Weight	21.2 kg
Inverter:	
Type	Grid-connected inverter
Model	SMA SB 3000TL-21
Rated input voltage	400VDC
Number of inverter required	1
Maximum input voltage	750VDC
Minimum input voltage	125VDC
Maximum MPP voltage	500VDC
Max. operating input current per MPPT	15A/15A
Max. input short-circuit current per MPPT	20A/20A
Rated power	3 kW
Nominal AC voltage range	180-280V
Maximum efficiency	97%
Weight	26 kg

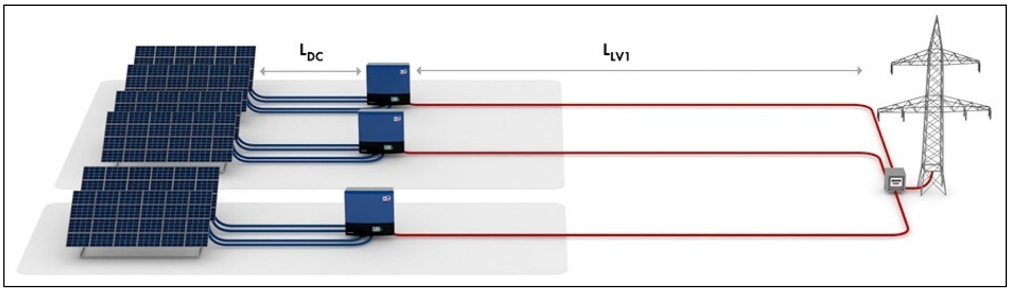

Figure 4. Layout of DC and LV (low voltage) lines.

5. Results and discussion

The results of the PV array and inverter compatibility checks are shown in Table 2. It can be seen that the input power, voltage, and current from the PV array is within the inverter specification, except the maximum DC power is slightly different.

Table 2. PV/Inverter compatible.

Parameters	Inverter	PV array
Maximum DC power	3.2 kW	3.24 kW_p
Minimum DC voltage	125V	317V
Typical PV voltage		330V
Maximum DC voltage (inverter)	750V	478V
Maximum operating input current per MPPT	15A/15A	8.7A
Maximum input short-circuit current per MPPT	20A/20A	9.4A

Table 3 shows the energy balance of the PV system on a monthly basis. The global horizontal irradiation on the study location achieves 1,877 kWh/m^2/year or approximately 5.14 kWh/m^2 per day. The highest irradiation is in October about 181 kWh/m^2, and the lowest one is 136 kWh/m^2 in January. The annual energy demand is 12,219 kWh, while the total energy yield is 4,653 kWh. It can be seen from the table that the peak energy yield occurs in October, which is coincident with the highest solar irradiation. The lowest energy yield of 334 kWh is observed in June with a low ambient temperature of 26.8 ^oC and solar irradiation of 152 kWh/m^2. The annual self-consumption is amounting for 4,352 kWh or 93.5% of the total energy yield, while the annual grid feed-in electricity is about 300 kWh. The purchased electricity is approximately 64.4% of the electricity demand or in other words, 35.6% of savings gained by operating the PV system.

Table 3. Monthly energy balance of the PV system.

Months	Global horizontal irradiance (kWh/m^2)	Ambient temperature (^{o}C)	Energy demand (kWh)	Energy yield (kWh)	Self-consumption (kWh)	Grid feed-in (kWh)	Purchased electricity (kWh)
January	136	27.6	1,038	367	341	26	697
February	138	27.6	937	366	344	22	593
March	156	27.7	1,038	391	364	27	674
April	161	27.9	1,004	385	361	23	643
May	167	27.5	1,038	376	364	12	674
June	152	26.8	1,004	334	328	6	676
July	160	26.2	1,038	358	349	8	688
August	159	26	1,038	370	353	16	684
September	166	26.6	1,004	412	378	34	627
October	181	27.5	1,038	474	425	49	613
November	152	28	1,004	410	372	38	633
December	150	27.8	1,038	411	373	39	665
Year	1877	27.3	12,219	4,653	4,352	300	7,867

Figure 5 shows the variation of energy yield and performance ratio of the PV system over the year. The low energy yield is observed in January, February, June, and July of 334-367 kWh. In September, November, and December, the energy yield is almost stable around 410-412 kWh. Amongst them, it is apparent that higher solar irradiation and lower ambient temperature in September increase the energy yield compared to November and December. The maximum performance ratio is 82% in April, July, August, September and October, while the minimum one is 81% in January, February, March, November and December. The annual performance ratio is approximately 81.4%. It means that 18.6% of the maximum electricity generation by the PV system at STC (standard test condition) is lost throughout the year.

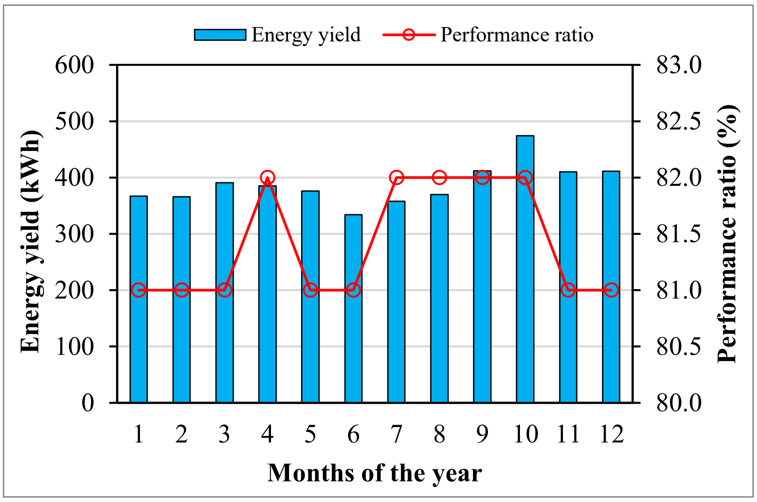

Figure 5. Variation of energy yield and performance ratio over the year.

Figure 6 shows the fluctuation of grid feed-in electricity, self-consumption, and self-sufficiency ratio over the year. Grid feed-in refers to the electricity injected into the grid as the excess of the PV energy production. Self-consumption is the difference between the energy yield and the grid feed-in electricity.

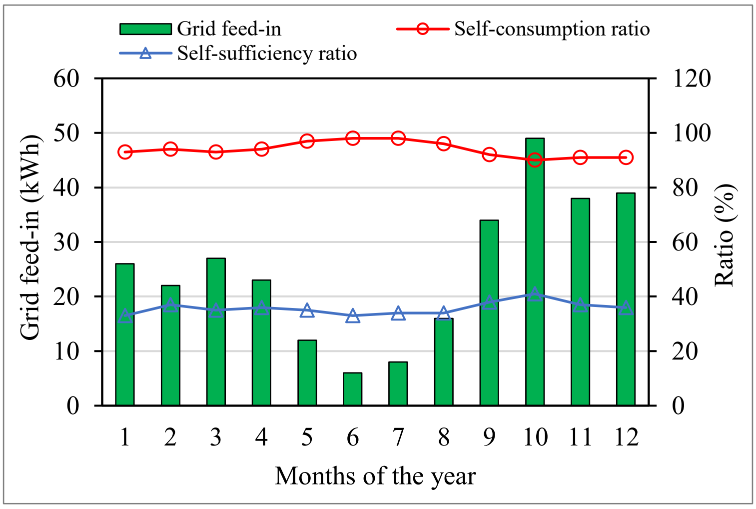

Figure 6. Profile of grid feed-in, self-consumption and self-sufficiency ratios over the year.

The ratio of the self-consumption to the energy yield, which called the self-consumption ratio, reaches a high value of 96-98% in May, June, July, and August. In June, the self-consumption is at the lowest level as well as the energy yield, which results in a higher self-consumption ratio. On the contrary, the self-consumption achieves the lowest of 90% in October, along with the highest energy yield and grid-feed in electricity. Meanwhile, the self-sufficiency ratio, which is the ratio of the self-consumption to the site energy consumption, shows the opposite characteristics. The highest self-sufficiency ratio is 41% in October due to the highest self-consumption in the month with an energy consumption of 1,038 kWh. The annual self-consumption ratio and self-sufficiency ratio is 93.5% and 35.6%, respectively. The way of increasing self-consumption can be done by using intelligent control with the intermediate storage system through shifting the excess electricity that is stored in battery banks to match the load [SMA].

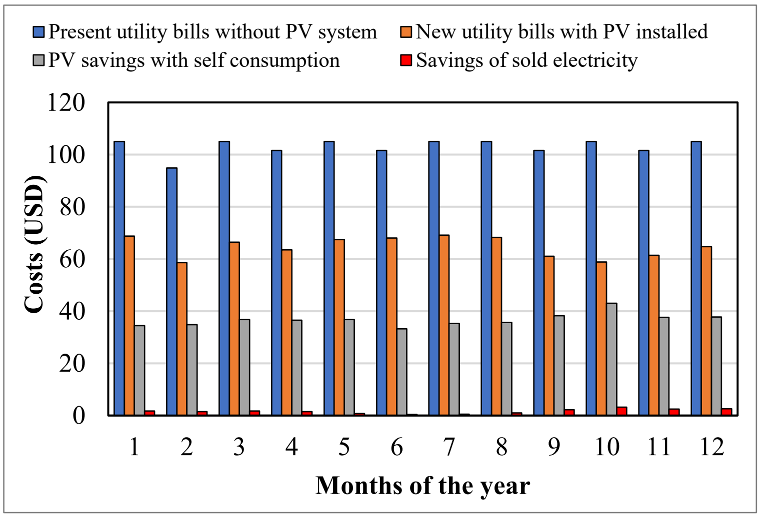

Figure 7. The energy costs and savings over the year.

The variation of electricity purchased and savings with self-consumption and exported electricity into the grid is presented in Figure 7. Without the PV system, the electricity purchased is 105.4 USD in January, March, May, July, August, October, and December. The PV savings with the self-consumption achieve the highest of 43.01 USD as well as the savings of sold electricity of 3.22 USD in October. The annual utility bills without a PV system is 1,236.5 USD, while the annual utility bills with the installed PV system is 776.3 USD. The net savings is 460.1 USD. The specific investment costs of the PV system are 1,325.34 USD/kWh, which delivers a payback period of 9.3 years.

6. Conclusions

The simulation of a 3.24 kW_p grid-tied PV system in villa reveals as follows: the global irradiation available in the Tibubeneng area is 1,876.25 kWh/m^2/year or approximately 5.14 kWh/m^2/day. The energy consumption in the villa is 12,219 kWh/year; the PV system generates electricity of 4,653 kWh/year. The specific energy yield is 1,436 kWh/kW_p; the PV energy generation used as a self-consumption is 4,352 kWh/year, while the grid feed-in is 300 kWh/year; the PV system provides an annual self-consumption ratio of 93.5%, a self-sufficiency ratio of 35.6%, and a performance ratio of 81.4%; the payback period for the installed PV system is 9.3 years.

7. References

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