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Web-based low–cost rooftop solar power plant for household application

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Abstract

The global warming issue has been resolved through Sustainable Development Goals (SDGs) agreed upon by the world. One of the SDGs is affordable and clean energy. Green energy, such as solar energy, is a solution to realize it. Solar energy has massive potential as renewable energy in tropical countries. On the one side, solar energy is an excellent renewable energy. On the other side, solar energy has a low maturity level of technology. It is proven by the extravagant investment cost of building a solar power plant. Indonesia has an investment cost of up to 1200 USD per kWh, which is unsuitable for household applications. This investment cost will continue to be higher when it uses an IoT system for monitoring or managing the solar power plant. The low-cost solar power plant was designed using a hybrid system to reduce the investment cost. The industrial standard components include ACS712 as a current sensor, ZMPT101B as an AC voltage sensor, and ESP32 as a data processor and IoT module. The Blynk platform, connected to ESP32, is a web-based monitoring system. The success parameter consists of the DC voltage and current from battery and solar panel, AC voltage and current from single phase inverter. The low-cost solar power plant is designed in a 1.92 kWh battery pack with 1 kWh of AC continuous output power with total investment cost 1080 USD. The proposed solar power plant design decreases an investment cost by 14.29% up to 50.00 % per kWh.

Keywords:
Green Energy, photovoltaic, web-based system, renewable energy, blynk platform.

1 Introduction

Indonesia has total renewable energy potency equivalent to 442 GW for power plants. The most significant renewable energy potency comes from solar energy, covering 207.8 GWp or more than 47% of total renewable energy potency [1]. Geographical factors cause this enormous potency in the solar energy sector.

Energy consumption for the household sector in 2020 reached 19.8 million Tones of Oil Equivalent (TOE), with the electricity demand of more than 50%. Unfortunately, more than 62.0% of electricity is produced using fossil fuels, and only 18.2% is based on renewable energy [2]. Using fossil fuels will cause serious environmental problems, such as increasing pollution and greenhouse gas emissions that cause global warming [3], [4], [5]. The solution to this issue is to increase household-scale renewable energy-based electricity production, such as rooftop solar power systems [6]. The solutions offered have been supported by regulations and policies from the Indonesian government, such as Nationally Determined Contribution (NDC), Long Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR), RUPTL (*Rencana Usaha Penyediaan Tenaga Listrik PT. PLN* or PLN's Electricity Supply Business Plan) 2021 – 2030, and regulation No. 26/2021 on rooftop solar photovoltaic [7], [8], [9]. In other countries such as India, Korea, and Kuwait, the regulations and policies about renewable energy have been legalized since 2013 [10], [11], [12].

The capital cost of renewable energy in large-scale wind farms installed in Indonesia in 2019, according to the Leveled Cost of Energy (LCOE) standard, is around 1400 – 2000 USD/kW [13], [14], [15]. This capital cost is not much different from Europe. These investments in North and South America and Africa are cheaper than in Indonesia (1300 USD/kW). Moreover, India and China have investment costs of around 1100 USD/kW. The solar power system's capital cost is similar to the wind system. Indonesia has 700 to 1200 USD/kW of capital cost, which is higher than Europe, China, and India, under 1000 USD/kW [16].

Solar hybrid systems are generally combined with other energy sources, such as wind turbines, improved storage systems, and diesel generators [17], [18], [19]. That makes the capital cost of solar power plants costly due to controller costs. IoT systems for monitoring solar systems have been developed and applied to solar power plants, pumping systems, and other massive-scale applications [20], [21]. This application sector creates high capital costs in IoT systems. This research discusses IoT systems in low-cost rooftop solar power systems designed in 1.92 kW for household applications with an average capital cost below 600 USD/kW. This system uses the commercials application as a web-based monitoring of success parameters. The success parameters consist of: voltage, current, and power from PV, voltage, current, and power of battery pack, and voltage, current, and power of output inverter.

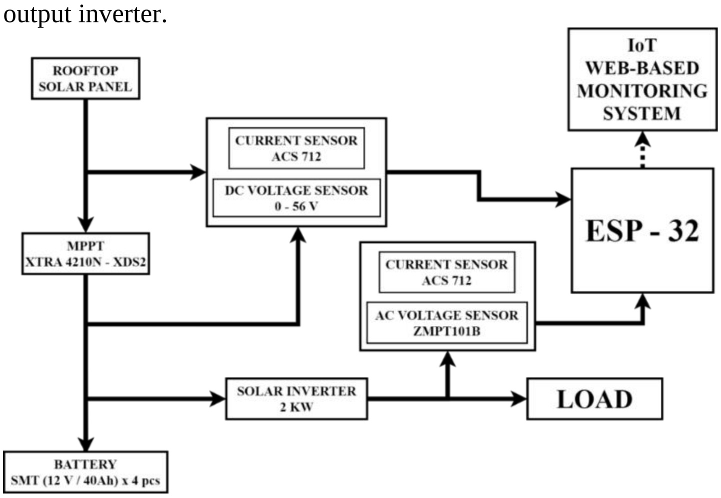

Fig 1. Diagram of web-based rooftop solar system

2 Materials and Methods

The hybrid system allows using more than one source of electrical energy. Generally, the primary power source comes from the state electricity company, and the backup power uses a diesel generator or renewable energy power plant [22], [23]. Fig. 2 shows the hybrid system using Low Voltage Disconnected (LVD) module XH-M609 as an Automatic Transfer Switch when the battery pack of the solar power plant runs out.

The diagram and hardware architecture design of the solar power plant which is shown in Fig. 1 and Fig. 3. It consists of 400 Watt-pat (Wp) polycrystalline solar photovoltaic (PV), 1040 W of Maximum Power Point Tracking (MPPT), 1.92 kW of the battery pack, 2 kW of solar power inverter, sensors (current and voltage sensors), and IoT devices.

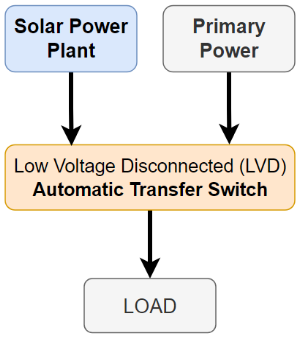

Fig 2. Hybrid system design using LVD

The PV module uses SUN-ASIA SP100-18P, which has 17.8 V of maximum power voltage, 21.8 V of open circuit voltage, 5.62 A of maximum power current, and 6.05 A of open circuit current, as shown in Table 1. The PVs are connected using the series-parallel connection. Therefore, the maximum power voltage is 35.6 V, the open circuit voltage is 43.6 V, the maximum power current is 11.24 A, and the open circuit current is 12.1 A, as shown in Fig. 4(a). Fig. 4(b) shows solar power plants panel using hybrid systems. This panel consists of sensor components, distribution power systems, solar power inverter, MPPT, LVD module, and IoT devices such as a microcontroller ESP32 and a Wi-Fi module. The IoT system is connected to the blynk IoT platform for web-based monitoring systems that can be accessed using a log-in account [24], [25], [26].

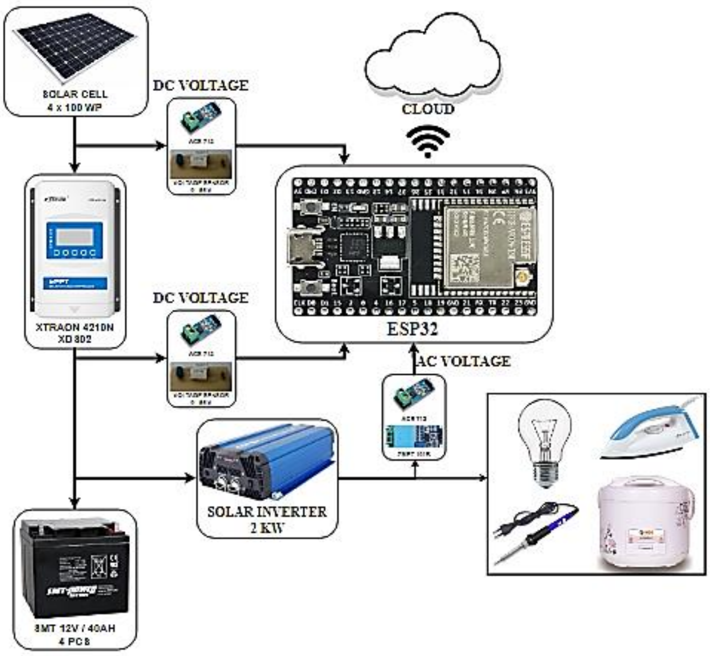

Fig. 3. Hardware architecture of web-based rooftop solar system.

Table 1. PV module specification

Parameter	Variable
Model	SP100-18P
Peak Power (Pmax)	100 W
Cell Efficiency	16.93 %
Max. Power Voltage	17.8 V
Max. Power Current	5.62 A
Open Circuit Voltage	21.8 V
Short Circuit Current	6.05 A
Power Tolerance	±3 %
Max. System Voltage	1000 V
Series fuse rating	12
Number of Bypass Diode	3
Operating Temperature	-4ºC to +85ºC
Maximum System Voltage	1000 V DC

(a)

(b)

Fig. 3. Implementation of web-based rooftop solar system. (a) The open circuit current is 12.1 A, and (b) Solar power plants panel using hybrid systems

MPPT is used to improve efficiency and generate maximum PV power. MPPT was independent of temperature and solar radiation. It maintains the PV operating point at the maximum power point. The development of MPPT proliferates due to its benefit for green energy technology [27], [28]. Further development of MPPT appears in artificial intelligence such as fuzzy logic controller, artificial neural network, sliding mode control, and Fibonacci series-based MPPT to find global maximum power point [29], [30]. This research uses XTRA4210N, invented by EPSOLAR TECHNOLOGY, which technical specification shows in Table 2. It covers 24V battery pack systems with a 1.92 kWh capacity. It handles four PVs with 100 watt-peak capacity installed in series-parallel connection that is worthy of household application.

Table 2. MPPT technical specifications

Parameter	Variable
System nominal voltage	12 / 24 VDC (Auto)
Rated charge current	40 A
Rated discharge current	40 A
Battery voltage range	8 ~ 32 V
Max. PV open circuit voltage	100 V / 92 V
MPP voltage range	
Rated charge power	Battery Voltage +2V ~ 72 V
Max. conversion efficiency	520 W (12 V) / 1040 W (24V)
Full load efficiency	98.6%
Self-consumption	96.5%
Discharge circuit voltage drop	≤ 30 mA (12V) / ≤ 16mA
Temperature compensate	(24V)
coefficient	≤ 0.23 V
Grounding	-3 mV / ºC / 2V(Default)
	Common Negative

A solar power inverter changes the output of the PV or battery pack to 220 V of AC voltage. The input of solar power inverter uses 12V, 24V, or 48V adapted with battery pack voltage configuration or PV's output. The DC stabilizer is applied in solar power configuration when connected to PV.

The development of solar power inverters is focused on the controller side [31], [32]. Artificial intelligence is used to increase efficiency and guarantee the robustness of the output voltage [33], [34]. This research uses the pure sine wave inverter with a maximum power of 2000 watts as a solar power inverter. It has 1000 watts of continuous output power.

This solar power inverter is suitable for middle-class households where the installed electric power is below 1000 watts. The datasheet of the pure wave inverter shows in Table 3.

Table 3. Solar power inverter datasheet

Parameter	Variable
Surge Power	2000 W
Continues Output Power	1000 W
Input Voltage	24 V DC
Output Voltage	220 V AC
Frequency Output	50 Hz
Waveform	Pure sine wave

3 Results and Discussion.

Low-cost rooftop solar power plants are evaluated based on household applications' power consumption and a web-based monitoring system. Evaluation of household power consumption is based on daily electricity consumption. The IoT systems are designed web-based using the blynk platform. The IoT monitoring ensures that low-cost rooftop solar power plants work properly.

Low-Cost Evaluation

Solar power plant systems are designed based on daily electricity energy demand per capita. The strategic plan of the ministry of energy and mineral resources 2020–2024, the electrical energy demand in 2022 be 1268 kWh per capita yearly. That means the daily electrical energy consumption is 3.47 kWh per capita. The systems are designed to reduce more than 55% of electrical energy consumption, with an investment cost below 600 USD shown in Table 4.

The investment cost is suitable for developing countries such as Indonesia, whose yearly average income per capita is less than 4500 USD. The recent government policies and regulations support the development of renewable energy systems, especially in rooftop solar power plants.

Table 4. The cost of 1.92 kW rooftop solar power system

Component	Price (USD)
PV	230
Hybrid system panel	320
Battery	275
IoT monitoring	105
Sensor and data acquisition	55
Consumables material	95

3.1 Electrical Consumption Evaluation

Electrical energy demand per capita has averagely increases 5.33% from 2009 to 2022 (Table 5). This enhancement was power full before covid-19 pandemic in 2019. In pandemic situation, the electrical energy demand per capita decrease about 2% in 2019 and 0.96% in 2020. After the pandemic has passed, it increased 0.81% in 2021 and sharply in 2022 with 12.6%. This solar power plant is designed to cover up to 54% of the annual electrical consumption per capita.

Table 5. Electrical energy demand per capita

Year	Electrical Consumption (kWh/Capita)
2009	650
2010	700
2011	740
2012	790
2013	840
2014	880
2015	910
2016	950
2017	1020
2018	1060
2019	1080
2020	1090
2021	1109
2022	1268

3.2 Web-based IoT System

The IoT system used in this research is a web-based monitoring system. The success parameters shown on the website takes from current and voltage sensors. The DC parameters from PV and accumulator are measured using ACS-712 as a current and voltage divider-based sensor which converts from 0-40V of series-parallel PVs output voltage into 0-3V due to the ESP32 Analog to Digital Converter voltage level.

Fig. 5 shows the current, voltage, and power data of the PV and accumulator in the website dashboard using the blynk platform. The blynk platform was shoosen due to its ease of use and security [35], [36]. The accumulator's DC voltage and current will be recorded every second to calculate its power. The calculation of accumulator power shows in Eq. 1. The solar power panel voltage, current, and power conversion monitoring show the real-time condition, where $P_{accumulator}$ is accumulator power, $V_{accumulator}$ is accumulator voltage, and $I_{accumulator}$ is accumulator current.

$$P_{accumulator} = V_{accumulator} \ x \ I_{accumulator} \tag{1}$$

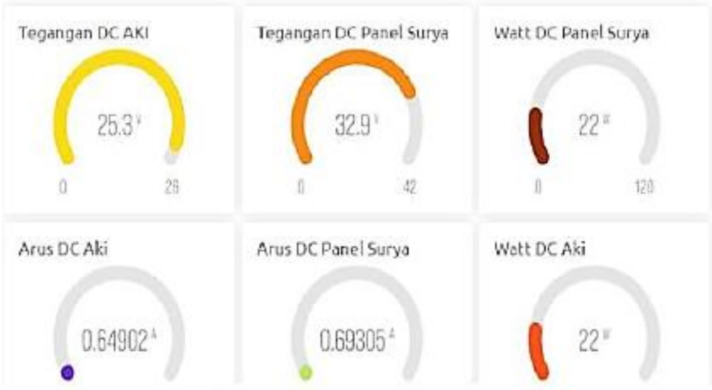

Fig. 4. Web-based DC response of battery and PV

The solar power converter uses pure sine waveform, which uses Sinusoidal Pulse Width Modulation (SPWM) as a modulation technique. The solar power inverter consists of two parts. The first is a buck-boost converter as a DC-to-DC converter to convert 24V DC battery pack voltage into 311V DC voltage. The last part is DC to-AC converter (inverter) which converts 311V DC voltage to 220V AC voltage with 50 Hz. The capacity of the solar power inverter is adjusted to the electric power for household needs (continuous output power = 900 watts). The success parameter for the output of the solar power inverter is current, voltage, and power in an alternating waveform, as shown in Fig. 6. The success parameters are shown in numeric, gauge dashboard, and graphic chart with historical data up to 3 months by using the blynk platform.

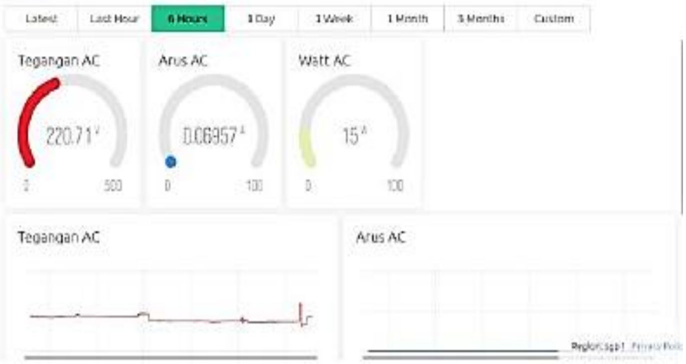

Fig. 5. Web-based AC response from solar inverter

4 Conclusions.

A low-cost solar power plant applied in the household is suitable to minimize monthly electricity bills. The proposed solar power plant can cover up to 54% of the electricity bills. This solar power plant was designed in a hybrid system with a blynk platform as an IoT monitoring system. The success parameters for monitoring the condition of solar power plant covers battery pack condition, PV panel performance, and solar inverter output condition. ACS712 is a current sensor, ZMPT101B is an AC voltage sensor, and the DC voltage sensor uses a resistor circuit based on the voltage-divider theory. The AC and DC power is measured by multiplying the current and voltage data from the sensor. Microcontroller ESP32 is an IoT module that processes sensor data and connects to the blynk platform. The investment cost of a low-cost solar power plant is less than 600 USD per kWh. This cost is less than the average investment for a solar power plant in Indonesia, which achieves 700 to 1200 USD per kWh. The investment cost has decreased by 14.29% to 50% per kWh.

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