Improve IoT-Based Charging Management System for Electric Vehicles Considering Solar Energy Availability

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A B S T R A C T

The decreasing availability of fossil fuels, coupled with escalating environmental concerns, has significantly propelled research and development efforts in renewable energy-based electric transportation systems. The emission of carbon dioxide resulting from the combustion of fossil fuels has prompted the formulation of research policies on electric vehicles (EVs) worldwide, including in Indonesia, where there is a notable increase in EV adoption and a growing demand for enhanced charging infrastructure. Utilizing solar power to charge electric vehicles can substantially decrease carbon emissions when compared to conventional charging methods that draw power from the utility grid. This research endeavors to design, develop, and implement a comprehensive grid-integrated solar-powered EV charging management system that leverages Internet of Things (IoT) technology, with a Raspberry Pi serving as the central control unit. The proposed system will incorporate a pyranometer sensor to accurately measure solar radiation levels and include a sensor to continuously monitor the battery's charging status, specifically the State of Charge (SoC). Through this integrated approach, it is anticipated that the efficiency of EV charging processes can be significantly enhanced, thereby supporting the advancement of sustainable and clean energy infrastructure. Additionally, the implementation of this system aims to contribute to reducing carbon emissions in Indonesia, aligning with national and global environmental objectives.

INTRODUCTION

Since the industrial era, the electricity and transportation sectors have been two major contributors to greenhouse gas (GHG) emissions. These emissions play a significant role in accelerating global warming, given the large scale of energy required and the consumption of fossil fuels that occurs in both sectors [1][2]. This is due to the dependence of both sectors on fossil fuels. In recent years, the transition to more sustainable energy and low-emission transportation systems has become a global focus [3][4]. With dwindling fossil fuel reserves and growing concerns over carbon emissions, renewable energy sources, especially solar power, are being explored as a viable alternative to power EVs [5]. The increasing global demand for EV has accelerated the need for efficient and sustainable charging systems. Indonesia, with its abundant solar energy potential, offers a strategic opportunity to integrate solar energy into EV charging systems [6][7].

The Indonesian government is committed to achieving net zero emissions by 2060 or sooner, as conveyed by President Joko Widodo at the Opening of the 10th Indonesian New, Renewable, and Energy Conservation (EBTKE) Conference at the State Palace, Jakarta in 2021 [8]. The government has initiated a transition to clean and renewable energy, accelerating the use of renewable energy to build a green economy. This effort requires consistent and sustainable measures to control climate change.

One strategy in this transformation is the development of an electric vehicle industry ecosystem [9]. Globally, the use of electric vehicles has increased rapidly, reaching a world market share of 2.6% in 2019 [10][11]. The electrification of vehicles with low carbon intensity is a future trend in efforts to mitigate global warming. However, the increase in the EV fleet also causes an increase in electricity demand and the need for charging infrastructure. Charging using conventional electricity, which is still dominated by fossil fuel generators, can reduce the environmental benefits of EVs [12]. Therefore, integrating electricity sources from renewable energy, such as solar energy, is necessary to ensure sustainability and a more significant positive impact.

In 2020, Indonesia's achievement of the new energy mix target was only about half of the target set for 2025, reaching 11.31% of the 23% target [13]. To accelerate the achievement of this target, it is necessary to increase the use of renewable energy in Indonesia to overcome climate change and anticipate future economic and energy crises. Climate change can cause serious impacts, including a temperature increase of 0.45-0.75°C, changes in rainfall of ±2.5 mm/day, sea level rise of 0.8-1.2 cm/year, and an increase in extreme waves of more than 1.5 m [14]. Solar energy is one of the most widely developed and reliable renewable energy sources. Indonesia, as a tropical country, has significant solar energy potential, with an average of

around 4.8 kWh/m²/day, equivalent to 112,000 GWp, making it a worthy alternative source of electrical energy [15]. Solar energy sources have been prioritized to achieve the New Renewable Energy target of 23% by 2025 and 31% by 2050, as stipulated in Government Regulation No. 79 of 2014 concerning the National Energy Policy. Additionally, integrating distributed generation based on renewable energy at load centers can reduce power losses and increase the voltage of the electricity network [16].

Previous studies have extensively discussed the management of solar-based electric vehicle charging connected to the utility grid. One study developed intelligent charging scheduling and power management strategies on PV-battery-based charging stations [17]. Additionally, optimal management strategies for size and energy on electric vehicle charging stations with flywheel-based energy storage have been reported. Mitigating predictive power fluctuations in grid-connected PV systems with fast response for electric vehicle charging stations is another effort that has been developed. The use of an IoT system based on the NodeMCU ESP32, utilizing the Blynk platform, has been designed to consider the capacity of PV storage batteries, and the results have been published [18-21].

PV is an easy-to-use electrical energy solution, although its performance is greatly affected by weather changes. When the intensity of sunlight is low, the PV cannot work optimally. Therefore, PV can be designed as part of a power generation system combined with electricity sources from the grid utility to ensure energy reserves. With this combination, the supply of electrical energy can occur continuously, ensuring that electricity needs can be met even in the event of changes in weather conditions. The PV system relies on solar radiation to generate electricity, but the intensity of radiation can fluctuate due to weather conditions [22-25]. The Battery Management System (BMS) plays a crucial role in regulating battery charging to prevent overcharging or undercharging of the battery. The BMS will ensure that the charging process takes place efficiently and safely, and maintain battery health. With a weather station to monitor weather conditions, the system can predict when charging can take place optimally, allowing the PV system to continue providing electricity, even in conditions of varying solar radiation.

The novelty of this research lies in providing a real-time, data-driven solution that enhances the consistency and infrastructure of electric vehicle charging, controlled using a Raspberry Pi as a central control unit. Raspberry Pi has the ability to send and receive data wirelessly. With this advantage, users can monitor or control connected devices from anywhere. This feature is particularly useful for IoT project applications and real-time monitoring, as it eliminates the need for direct physical interaction from the device, making it superior for remote automation. This research further combines pyranometer and anemometer sensors to measure solar intensity and wind speed, ensuring an accurate evaluation of the availability of renewable energy for electric vehicle charging. By utilizing the Raspberry Pi as a control center, real-time data processing and decision-making capabilities will be enhanced, resulting in a more efficient energy management system. This system not only advances electric vehicle charging management technology but also

provides added value in terms of energy absorption and carbon emission reduction.

METHOD

This research design employs an experimental method, involving the development of a system prototype. This prototype will be built using a Raspberry Pi as a control center, which is integrated with a pyranometer sensor to measure light intensity and an anemometer to monitor wind speed. The data obtained from these sensors will be used to optimize the EV charging process. There are two approaches to charging electric vehicles using solar power, namely on-grid PV and standalone PV. Ongrid PV allows charging using the electricity grid when sunlight is insufficient and provides the flexibility to export power to the grid when there are no vehicles to charge. Meanwhile, standalone PV is more suitable for remote areas without access to electricity utilities. This study combines both approaches through a hybrid PV system to design and develop an electric vehicle charging management system based on rooftop solar power integrated with the grid. The design diagram of the IoT system is shown in Figure 1. This system encompasses the design of solar panels, fast-charging converters, and IoT-based monitoring, with coordination among solar power plants, batteries, and the grid.

The system integrates automatic power switching between PV and grid PLN, equipped with a battery capacity management system using the coulomb counting (CC) method and a web-based monitoring platform. The MK2P-I relay ensures seamless power source transition, while the battery management system (BMS) prevents overcharge and overdischarge of the VRLA 12V 100Ah battery. Electric vehicle charging utilizes an On-Board Charging concept with a 220VAC/50Hz input and a 12V, 2.25A constant current output. This IoT-based research focuses on developing a smart charging station powered by solar energy, integrating real-time monitoring for radiation, temperature, wind speed, and battery SoC. The Raspberry Pi controls the coordination algorithm, ensuring optimal operation between the solar and grid systems, and this is validated against real-world conditions.

Software design focuses on the design of the device's circuit or wiring. This role consists of designing input and output circuits, as well as the overall circuit. The overall circuit design uses several electronic circuits of the overall input and output schematic circuits that will be connected to the Raspberry PI, consisting of the ADC712 sensor, voltage sensor, DHT11 sensor, ATS, and PZEM sensor.

The design of the electric vehicle charging hardware management system is illustrated in Figure 1, which utilizes solar energy controlled by a Raspberry Pi. The solar panel serves as the primary energy source, which is then distributed to the solar charge controller to regulate the charging of the 12V, 100Ah VRLA battery. This system utilizes the CC method to manage battery capacity, preventing overcharge and overdischarge. Power from the battery can be converted into AC current by the inverter.

ATS is used to automatically switch resources between the PV and the grid PLN. This system is also equipped with a DHT11

temperature and humidity sensor, as well as an anemometer, to detect wind speed. Data from all these sensors is sent to the Raspberry Pi, which acts as the main controller, managing the inputs and outputs of the various components. The Raspberry Pi also runs a web-based monitoring system that allows users to view data remotely. Additionally, the system supports electric vehicle charging using the On-Board Charging concept, where the power source at the station is an AC power source. All components are connected via GPIO or serial communication, such as RS-485, creating automatic integration between energy sources, batteries, and other hardware in this system.
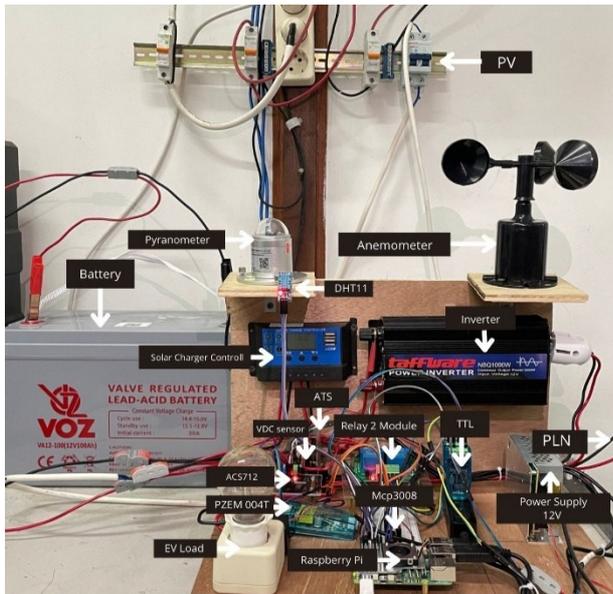

Figure 1. Hardware Design

RESULTS AND DISCUSSION

After engaging in the comprehensive development of the entire system, it is imperative to evaluate and scrutinize the instruments that have been crafted. Assessment is conducted to determine whether the tool's constituents can operate effectively in accordance with the established design. The electric vehicle charging ATS system requires accurate transducers to send correct data to the database. This study utilizes a Fluke standard digital multimeter for sensor calibration and measurement of sensor accuracy. The test results are shown in Table 1.

Table 1. System Component Sensor Accuracy

Component	Sensor	Multimeters	Difference	Average
V DC Battery	12.21	12.22	0.01	
	12.22	12.23	0.01	0.013
	12.21	12.22	0.02	
I DC PV	1.70	1.71	0.01	
	2.96	2.98	0.02	0.16
	4.34	4.36	0.02	
PZEM AC Volt	222.1	221.8	0.3	
	222.3	221.9	0.4	0.33
	222.4	222.1	0.3	
PZEM AC Current	0.18	0.19	0,01	
	0.41	0.414	0.004	0.008
	0.529	0.530	0.001	
PZEM AC Power	38.5	38.1	0.04	
	38.2	37.9	0,03	0.037

| 37.9 | 37.5 | 0.04 |

The system data collection process begins with ATS testing, which enables the switching of resources between the PV and the grid for electric vehicle charging. Two test conditions were conducted: first, switching from PV to the grid, and second, switching from the grid to PV. After that, the battery management system was tested using the coulomb calculation method, which regulates the overdischarge limits (when the PV battery SoC reaches 50%) and overcharge (when the battery SoC reaches 100%). PV battery management testing was carried out under three conditions: (1) charging electric vehicles while the PV battery is charging (charging-discharging), (2) charging electric vehicles while the PV battery is not charging (discharging), and (3) charging electric vehicles using a grid supply while the PV battery is charging (charging).

Data Collection of Electric Vehicle Charging ATS System During the PV Switching Process to Gid
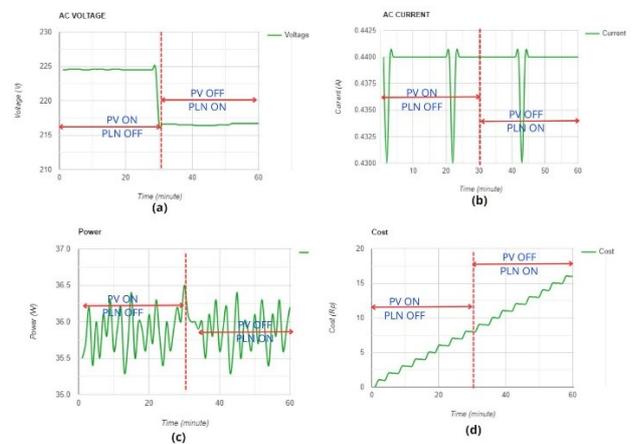

Figure 2. (a) Voltage, (b) Current, (c) Power, (d) Cost of reading electric vehicle charging data, process of switching PV to the Grid

The data collection of voltage, current, power, and electricity costs for the ATS system during electric vehicle charging, particularly during the transition from PV to Grid, is represented in Figure 2. The data was collected while the electric vehicle was charging, with the transition from PV to Grid occurring at the red line mark, which signifies the point of source switching. Initially, the vehicle charges for 30 minutes using the PV source. Afterward, the PV system cuts off, and the power source switches to the Grid, continuing the charging for another 30 minutes.

Based on Figure 2(a), when charging an electric vehicle with the PV electricity source, switching to the Grid electricity source works well with a constant average voltage value from the PV of 224.9 V, switching the source to Grid with a constant average voltage value of 216.3V. In the graph of Figure 2(b) when charging an electric vehicle with a PV power source switching to a Grid power source, it works well with a constant average current value the same as when from PV switching sources to Grid with an average current value of 0.43-044 A. Graph of Figure 2(c) when charging an electric vehicle with a PV power source switching to a PLN power source works well with a constant average power value the same as when from PV switching sources to Grid with an average power value of 36.5 W. In the graph of Figure 2(d), when charging an electric vehicle with a PV

power source, switching to a PLN power source is effective, with a total cost increase that is directly proportional to the increase in energy entering during charging.

Data Collection of Electric Vehicle Charging ATS System During the Switching Process from Grid to PV

Data collection of the ATS system for charging electric vehicles during the switching process from Grid to PV (the red line limit in Figure 3 as the limit for switching electricity sources between PV and Grid) is carried out when charging electric vehicles is taking place, charging the Grid electricity source for 30 minutes, then when the PV has been reactivated, it automatically switches the electricity source from Grid to PV when charging electric vehicles, then charging electric vehicles with PV for 30 minutes.
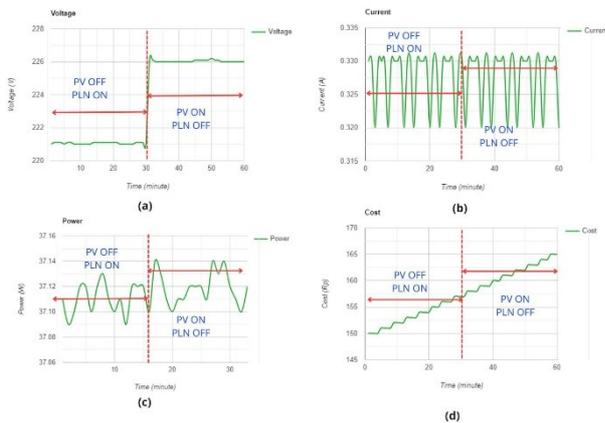

Figure 3. (a) Voltage, (b) Current, (c) Power, (d) Cost of reading electric vehicle charging data for switching process from Grid to PV

The graph in Figure 3(a) was obtained when charging electric vehicles with PLN electricity sources, switching to PV electricity sources. The switching process worked well, maintaining a constant average voltage value from the Grid of 221.11V, switching to PV with a constant average voltage value of 226.23V. In the graph in Figure 3(b), when charging electric vehicles with PLN electricity sources, switching to PV electricity sources yields a constant average current value, similar to the average current value of 0.33A when switching from PLN to PV. Graph Figure 3(c) shows that when charging an electric vehicle with a PLN electricity source, switching to a PV electricity source yields a constant average power value, similar to switching from the Grid to PV, with an average power value of 37.10 W. In graph Figure 3(d), when charging an electric vehicle with a PLN electricity source, switching to a PV electricity source works well in the reading of the total increase in costs, which is directly proportional to the addition of the increasing amount of energy entering when charging an electric vehicle.

Weather Station with SoC

Battery management system data collection is also carried out, namely battery SoC monitoring on the PV system using the coulomb counting method to calculate the battery capacity on the PV system when used. In the battery management system, charging electric vehicles with PV and PV batteries takes place in two charging conditions: first, when the SoC of the PV battery is $\leq 50\%$ and the output current from the PV battery is less than the input current, which allows the battery to be recharged. Second,

when the SoC is between 50% and 100%, the output current and input current are ignored. Charging is stopped when the SoC reaches 100% or higher. If the SoC is below 50% and the output current of the PV battery exceeds the input current, PLN is used as the electricity source to charge the electric vehicle battery. This system ensures optimal and safe charging between PV and the Grid based on the battery SoC status.
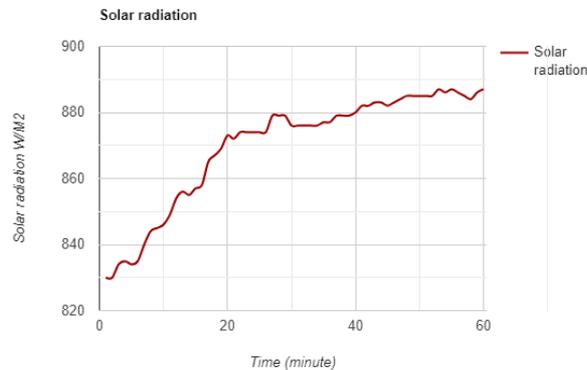

Figure 4. SoC measurement graph for 60 minutes during varying weather

The graph in Figure 4 is generated from the measurement of solar radiation in the morning, when the weather conditions changed from cloudy to sunny. Readings from the pyranometer sensor for 60 minutes indicate an increase in radiation intensity from the 20th to the 60th minute. The effectiveness of solar radiation significantly impacts the performance of the PV system, with irradiation intensity playing a crucial role in optimizing the efficiency of the PV module. PV performance will be optimal if this system receives a consistent and sufficient supply of solar radiation. In addition, the relationship between solar radiation and the State of Charge (SoC) of the battery indicates that even when the SoC is low, charging can still occur as long as the solar radiation intensity is high. SoC is calculated using the Coulomb Counting method, which accurately tracks the incoming and outgoing currents from the battery, ensuring that charging continues safely through the BMS settings that prevent overcharging or undercharging. The results of the overall system data monitoring are displayed in real-time through the application, as shown in Figure 5. Data collection is carried out during the electric vehicle charging process, which involves automatically switching energy sources between the PV and the grid.
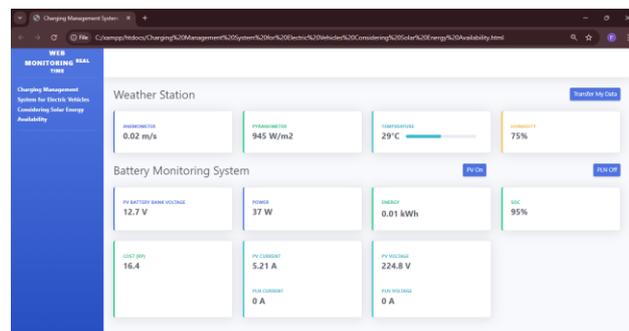

Figure 5. View of the Electric Vehicle Charging Monitoring System on the website.

The data acquisition system for solar radiation, wind speed, and temperature has been successfully designed and is displayed as shown in Figure 5. In addition, the solar power system's battery management operates automatically, based on the remaining SoC of the battery and the availability of solar energy. By utilizing a Raspberry Pi, this system can now be monitored and controlled remotely, enabling more efficient and responsive management of both energy resources and battery conditions. This remote capability enhances the system's overall functionality, allowing for improved decision-making in energy utilization and system optimization.

The web server provides a user-friendly interface that displays real-time data on various aspects of the EV charging process. Key parameters, including charging status, current, voltage, and energy consumption, are readily accessible, enabling users to effectively monitor the system's performance. The ability to access this information in real-time enhances user engagement and facilitates informed decision-making regarding energy usage. Additionally, the system's responsiveness to changes in charging conditions highlights its robustness and reliability. Moreover, the internet-connected Raspberry Pi web server not only simplifies EV charging monitoring but also contributes to the advancement of smart energy solutions, particularly in the context of sustainable urban development. Its ability to optimize the charging process and promote efficient energy management makes it a valuable tool in the realm of electric mobility. The integration of this technology supports the growing need for innovative solutions to manage energy resources effectively, further aligning with the goals of smart city initiatives.

CONCLUSIONS

The comprehensive evaluation of the electric vehicle charging system underscores the importance of precision in sensor calibration and data accuracy for effective performance. The use of a Fluke standard digital multimeter for sensor calibration has proven crucial in ensuring that the system's components deliver reliable data to the database. The validation results presented indicate minimal differences in sensor readings, highlighting the accuracy and reliability of the measurements across various components. Furthermore, the detailed analysis of the data collected during the PV-to-Grid and Grid-to-PV switching processes demonstrates that the system maintains stable voltage, current, and power levels during these transitions, indicating a well-designed and functioning system. Additionally, the successful implementation of a web-based monitoring system powered by Raspberry Pi enhances the operational efficiency and user engagement in managing the energy resources of the ATS. The real-time display of key parameters, along with the ability to remotely monitor and control the system, facilitates informed decision-making and promotes optimal energy utilization. As the system aligns with the objectives of smart city initiatives, it makes a significant contribution to the advancement of sustainable urban development and smart energy solutions. The integration of such technologies not only optimizes the electric vehicle charging process but also addresses the growing demand for innovative approaches to energy management in the context of electric mobility.

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