Energy Management Controller for Bi-Directional EV Charging System Using Prioritized Energy Distribution

Ezmin Abdullah[1], Muhammad Wafiy Firdaus Jalil[2], Nabil M. Hidayat[3]*
Wireless High-Speed Network Research Interest Group (RIG), Universiti Teknologi MARA,
40000 Shah Alam, Selangor, Malaysia[1, 2]
Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia[1, 3]

***Abstract*—The growing adoption of electric vehicles (EVs) has intensified the need for efficient, intelligent, and grid-independent Bi-directional charging systems. Conventional EV charging solutions heavily rely on grid electricity, leading to high energy costs, grid instability, and low renewable energy utilization. Existing Bi-directional charging systems often lack real-time prioritization of energy sources, fail to optimize solar and energy storage system (ESS) usage, and do not incorporate adaptive control mechanisms for varying grid conditions. To address these gaps, this study proposes an Energy Management Controller (EMC) for Bi-Directional EV Charging, integrating a prioritized solar to ESS to grid energy distribution strategy to maximize renewable energy usage while ensuring system stability and cost efficiency. The proposed EMC is implemented on an ESP32 microcontroller and manages energy flow via a 6-channel relay module. A temperature-based safety mechanism is embedded to prevent overheating, shutting down relays if the system temperature exceeds 50°C. The control logic dynamically adjusts power flow based on grid stress levels, solar irradiance, ESS state of charge (SOC), and EV battery SOC. The system is monitored using ThingsBoard for real-time visualization and InfluxDB for historical data analysis. Experimental validation across 12 predefined operational scenarios demonstrated that the EMC effectively reduces grid dependency to 15%, achieves renewable energy utilization of up to 90%, and maintains a fast relay switching response time of 50ms. The safety mechanism successfully prevents overheating, ensuring reliable operation under all test conditions.**

Keywords—Energy management controller; Bi-directional EV charging system; safety features; control algorithms; energy flow optimization; EV battery protection; testing and validation; thingsboard platform; InfluxDB database

I. Introduction

Electric vehicles are quickly becoming more common on our roads, and with them comes the need for reliable and efficient charging infrastructure. All chargers in the market use unidirectional chargers with traditional charging methods consisting of constant current (CC) and constant voltage (CV) [1]. In response to this growing demand, a Bi-directional smart controller for EV chargers has been developed, offering an innovative solution to enable the Bi-directional current flow of electricity between the EV charger and the power grid. Compared to traditional fuel vehicles, electric vehicles (EVs) have significant advantages in terms of preserving oil resources and lowering carbon emissions. The usage of electric vehicles (EVs) has increased, and governments and manufacturers throughout the world are noticing [2]. Relays or switches are also used in the DC-DC converter to regulate the voltage and current levels between the main battery and the power system. Relays or switches are used in the three-port converter topology to control the flow of electricity between the main battery, AC grid, and auxiliary power systems. They help ensure that the electricity flows smoothly and efficiently between the different components and that the charging and discharging processes are carried out safely and effectively [3].

V2G is a key component of the smart grid initiative and can be used better to manage the voltage stability of the power system. The penetration of V2G into the power system may introduce a high level of volatility due to precarious charging/discharging operations, hence emphasizing the need for a real-time management option [4], [5]. The paper defines V2G penetration as the percentage of the substation's electric power capacity and investigates the impact of one-phase and three-phase V2G interconnection at given penetration levels on the power system parameters to be monitored (voltage, voltage stability, SVR control, and power/energy loss). The results show improved system performance and economical operation with three-phases and system-wide V2G integration [6]. V2G can also provide ancillary services such as regulation and spinning reserves, which are essential for maintaining grid stability [7], [8].

The concept of this project is to construct an energy management controller using an ESP32-WROOM-32 controller to control the flows of the current for a Bi-directional EV Charging System by controlling the conditions of 6 relays in the Bi-directional EV charging system based on the 4 input conditions of Grid Stress, Solar Irradiance, Energy Storage System (ESS) Soc and EV Soc to determine the 12 possible output scenarios which can be monitored through IoT platform. The project is built using the ESP32 controller, relays, and safety features. The system is programmed by using Arduino IDE, an open-source platform, that provides a vast community of developers and readily available online resources that enable smooth operation and troubleshooting.

To enhance the project's capabilities, an ESP32 Wi-Fi module in the ESP32 controller was incorporated into the system architecture. This addition allows for remote monitoring and

*Corresponding Author.

control via the ThingsBoard platform, facilitating real-time data collection and analysis using InfluxDB Cloud to optimize the system flow.

This work is practically motivated by the urgent need for a cost-efficient and renewable-integrated Bi-directional EV charging infrastructure in developing countries. The proposed Energy Management Controller addresses real-world constraints such as fluctuating solar availability, rising energy costs, and limited grid stability. Therefore, by dynamically prioritizing solar, ESS, and grid inputs to maintain optimal energy flow and operational safety.

The remainder of this paper is organized as follows: Section II reviews related works on Bi-directional charging systems and highlights the research gaps. Section III presents the methodology, system architecture, and prioritized energy distribution algorithm. Section IV discusses implementation, hardware setup, and validation scenarios. It showcases the monitoring and data analysis approach. Section V presents the results and discussion. Finally, Section VI concludes the paper and suggests future enhancements.

II. Related Work

A. Literature Review

Several research studies have explored different aspects of Bi-directional EV charging systems, yet significant gaps remain in optimizing energy flow, integrating renewable energy sources, and enhancing system reliability. The study on an Interleaved Bi-Directional AC–DC Converter [9] focuses on enabling Bi-directional power flow between the EV charger and the power grid through control algorithms, yet it lacks considerations for renewable energy integration and grid stress optimization. Similarly, the Cloud-based Smart EV Charging Station Recommender enhances user accessibility through a data-driven selection system [10], but does not address real-time energy management or system reliability. Research on Smart Power Flow Controllers for EVs in Smart Grids improves coordination between EVs and the grid using fuzzy logic control, yet it does not consider dynamic energy distribution strategies incorporating solar and ESS [11]. The Universal Controller for Smart Grids standardizes device applications in distribution networks but does not focus specifically on Bi- directional EV energy management [12].

Other works, such as A PFC Hysteresis Current Controller for Totem-pole Bridgeless Bi-directional EV chargers [13], and the Virtual Synchronous Machine-Based Control of Single- phase Bi-Directional Battery Chargers [14], mainly focus on hardware-level improvements, enhancing power quality and stability but lacking comprehensive energy optimization across multiple sources. Meanwhile, LabVIEW- based Data Management Design for EV Bi- Directional Charger Testing contributes to efficient data storage but does not explore real-time energy balancing and optimization strategies [15]. In the context of EV charging station safety, research on Electrical Safety Considerations in Large-Scale EV Charging Stations identifies potential risks but does not integrate real-time fault detection mechanisms for i- directional charging systems [16]. Lastly, Safety-Integrated Online Deep Reinforcement Learning for Mobile Energy Storage System Scheduling introduces an AI-driven Volt/VAR control strategy, optimizing MESS and PV systems [17], but does not specifically address Bi-directional EV charging scenarios or user energy prioritization.

Overall, these studies highlight the implementation of the Bi- directional Controller by focusing on the current flow controller in the EV charging system. However, there is a limitation found in the previous research such as, a system with renewable energy dependency, possible scenario optimization and flexibility, and fail-safe mechanism. Therefore, the primary goal of this project is to develop Energy Management Controllers for Bi-directional EV Charging systems with solar energy dependency, Bi-directional scenarios, and safety features. This approach enhances the overall efficiency and sustainability of EV charging systems compared to the limitations found in the previous research.

III. Methodology

A. System Architecture

Fig. 1 shows the Block Diagram of the Energy Management Controller for a Bi-directional EV Charging system with safety features to control the current flows in the system.

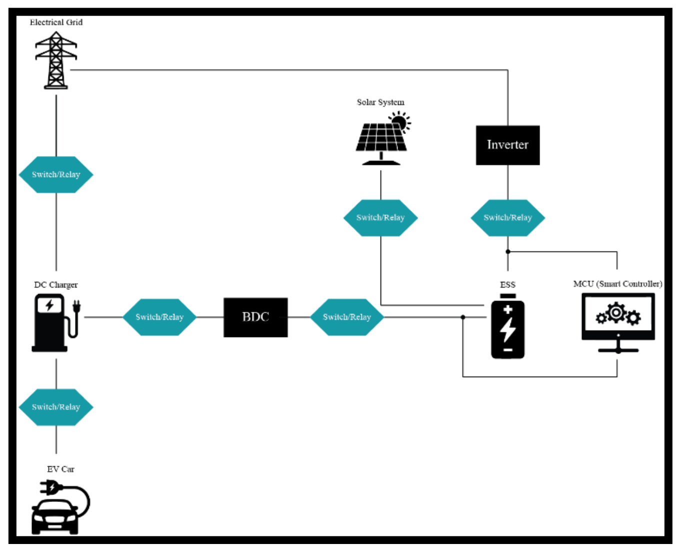

Fig. 1. Block diagram of the energy management controller for Bi-directional EV charging system with safety features.

The system architecture in Fig. 1, shows the connection between all sections that are involved in the Energy Management Controller for Bi-directional EV Charging system with safety features. The main function of the relay in this system is to control the current flows in the Bi-directional EV Charging System. The relay will be controlled by an ESP32 controller to determine which relay will turn ON or OFF based on the 12 scenarios that will be encountered in real time to control the flow of the current in the micro grid. Relay 1 is connected between the Electrical Grid and DC Charger. Relay 2 is connected between the DC Charger and the EV Car. Relay 3 is connected between the DC Charger and the Bi-directional Controller. Relay 4 is connected between a Bi-directional Controller and an Energy Storage System (ESS). Relay 5 is connected between the Energy Storage System (ESS) and the

Solar System. Lastly, Relay 6 is connected to the Energy Storage System (ESS) and the Inverter. These 6 relays will be controlled by the Energy Management Controller for a Bi-directional EV charging system with safety features. Fig. 2, illustrates the block diagram of the input and output of the developing a Bi- directional EV controller.

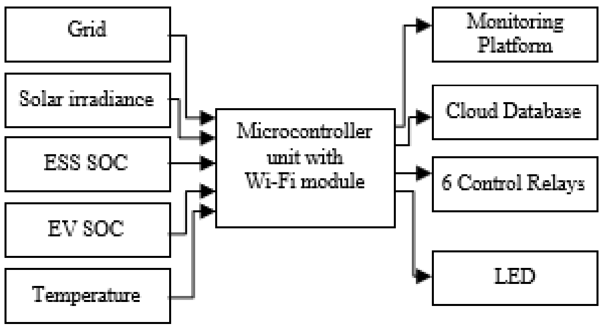

Fig. 2. Block diagram of the energy management controller for Bi-directional EV charging system with safety features.

B. Workflow and Prioritize Energy Distribution Algorithm

The flowchart in Fig. 3, illustrates the decision-making process of an energy management controller with an integrated safety mechanism.

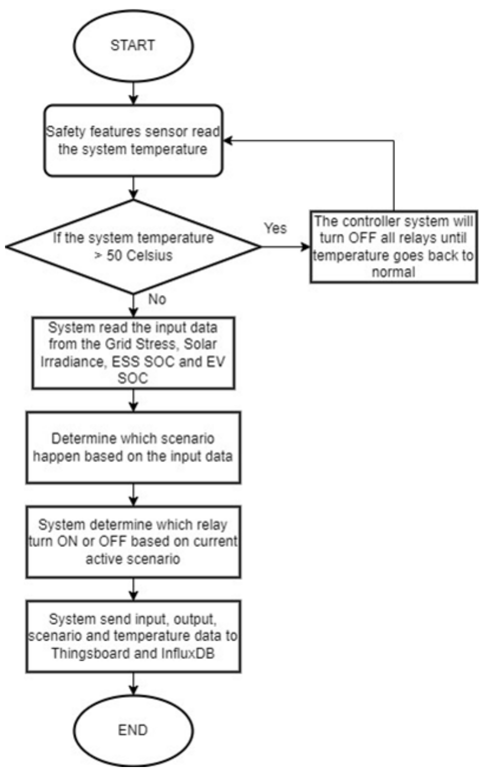

Fig. 3. General flowchart of the system.

The process begins with a safety feature sensor that continuously monitors the system temperature. If the temperature exceeds 50°C, the controller immediately shuts down all relays to prevent overheating and resumes operation only when the temperature returns to a safe level. If the temperature is within the acceptable range, the system collects input data from various sources, including grid stress, solar irradiance, ESS state of charge (SOC), and EV SOC**.** Based on these inputs, the system determines which operational scenario is active and accordingly decides which relays should be turned ON or OFF to optimize energy distribution. Finally, the system transmits real-time data, including input values, output status, active scenario, and temperature readings**,** to ThingsBoard and InfluxDB for monitoring and analysis**,** ensuring efficient and safe operation of the energy management system.

To optimize energy management in a Bi-directional EV charging system, a prioritized energy distribution model is developed, ensuring that energy sources are utilized in the following hierarchical order: Solar > ESS > Grid. The total energy required by the system, denoted as E_{demand}, is supplied through a combination of solar energy, E_{solar}, energy storage system (ESS), E_{ESS} , and grid energy E_{grid} , forming the fundamental energy balance equation.

$$E_{demand} = E_{solar} + E_{ESS} + E_{grid} \quad (1)$$

where, each energy source is allocated in order of priority to minimize grid dependency and maximize renewable energy utilization.

The first priority is given to solar energy. If the available solar power is sufficient to meet the demand ($E_{solar} \geq E_{demand}$), then solar is used exclusively and no additional energy is drawn from ESS or the grid.

$$E_{used} = \min(E_{solar}, E_{demand}), \quad E_{grid} = 0,\ E_{ESS} = 0 \quad (2)$$

If solar energy is insufficient to meet demand ($E_{solar} < E_{demand}$), then the ESS is utilized as the secondary energy source, provided its state of charge (SOC) is above the minimum discharge threshold(SOC_{min}). The ESS contribution is defined as

$$E_{ESS} = \min(E_{demand} - E_{solar}, E_{ESS,max}) \quad (3)$$

Ensuring that ESS discharges only the required energy while maintaining system stability. The energy supplied at this stage is:

$$E_{used} = E_{solar} + E_{ESS} \quad (4)$$

If both solar and ESS are insufficient, the grid acts as the last resort, supplying only the remaining unmet demand.

$$E_{grid} = E_{demand} - (E_{solar} + E_{ESS}) \quad (5)$$

where, $E_{grid} \geq 0$ ensures grid energy is used only necessary. The total energy supplied at this stage becomes.

$$E_{used} = E_{solar} + E_{ESS} + E_{grid} \quad (6)$$

To maintain system reliability and optimize performance, constraints are imposed. The ESS discharge constraint ensures energy is supplied only when the SOC is above a predefined threshold:

$$E_{ESS} = 0, \text{only if } SOC < SOC_{min} \quad (7)$$

where, SOC_{min} = 40% based on battery manufacturer recommendations. If the ESS is above the threshold, the available ESS energy is

$$E_{ESS} = \min(E_{demand} - E_{solar}, E_{ESS,max}) \quad (8)$$

Similarly, grid energy is utilized only if solar and ESS cannot meet demand, ensuring minimal reliance on non-renewable sources:

$$E_{grid} = E_{demand} - (E_{solar} + E_{ESS}), if\ E_{grid} > E_{grid,min} \quad (9)$$

Finally, to ensure system stability, the sum of all available energy sources should never exceed the total demand:

$$E_{solar} + E_{ESS} + E_{grid} = E_{demand} \quad (10)$$

The final model for prioritized energy distribution can be expressed as (11). This model effectively prioritizes renewable energy, enhances energy efficiency, and minimizes grid reliance, ensuring an optimal and sustainable Bi-directional energy management system for EV charging applications.

$$E_{used} = \begin{cases} E_{solar}, & if\ E_{solar} \geq E_{demand} \\ E_{solar} + min(E_{ESS}, E_{demand} - E_{solar}), & if\ E_{ESS} > 0\ and\ E_{solar} < E_{demand} \\ E_{solar} + E_{ESS} + (E_{demand} - E_{solar} - E_{ESS}), & if\ E_{solar} + E_{ESS} < E_{demand} \end{cases} \quad (11)$$

Table I shows the configuration parameters for the prioritized energy distribution control algorithm.

TABLE I. CONFIGURATION PARAMETERS FOR CONTROL ALGORITHM

Parameter	Description	Value	Justification
ESS Minimum SOC	Minimum SOC threshold to allow ESS discharge	40%	Battery manufacturer recommendation
High Irradiance Threshold	Threshold for sufficient solar irradiance	> 500 W/m²	Empirical solar energy availability
High Grid Stress	Grid instability indicator (binary signal)	1 = High, 0 = Low	Simulated grid state
EV SOC Discharge Threshold	EV SOC required to discharge to ESS	> 70%	Prevents deep cycling
Temperature Cutoff	Temperature threshold to trigger relay shutdown	50°C	Safe operation limit for ESP32 and relays

C. Schematic Diagram

Fig. 4 and Table II shows the schematic diagram of the hardware components of Energy Management controllers and pseudocodes for Bi-directional EV Charging Systems with Safety Features respectively. When the system starts working, the DHT22 sensor will make sure the system can operate under safe conditions by measuring the Temperature of the ESP32 controller to make sure the temperature is normal under 50º Celsius to allow the system to operate smoothly. If the temperature exceeds 50º Celsius, the system will shut down all 6 relays until the system temperature returns to safe temperature below 50º Celsius. After the system makes sure the temperature is normal to operate using the DHT22 sensor, the system will begin acquiring data from the Grid Stress conditions, Solar Irradiance value, ESS SOC percentage value, and EV SOC percentage value.

TABLE II. PSEUDOCODE FOR THE PROGRAM CODES DEVELOPMENT

Pseudocodes

```
Initialize system
Turn off all relays

Loop:
  Read temperature from DHT22 sensor
  If temperature > 50°C:
    Turn off all relays
    Publish "HIGH" to temperature alarm
    Continue loop

  Else:
    Publish "LOW" to temperature alarm

    Read input values:
      - GridStress (0 = Low, 1 = High)
      - SolarIrradiance (W/m²)
      - ESS_SOC (%)
      - EV_SOC (%)

    Determine active scenario based on inputs

    If SolarIrradiance > 500 and ESS_SOC < 40% and GridStress = HIGH:
      Activate Relay 6 only (Scenario A)

    Else if GridStress = LOW and SolarIrradiance > 500 and ESS_SOC <
            40% and EV_SOC < 70%:
      Activate Relays 1, 2, 5, and 6 (Scenario B)

    Else if GridStress = LOW and SolarIrradiance > 500 and ESS_SOC <
            40% and EV_SOC > 70%:
      Activate Relays 1, 2, 3, 4, and 5 (Scenario C)

    [Continue for all 12 scenarios…]

    Send data to ThingsBoard (MQTT) and InfluxDB:
      - Input conditions
      - Relay status
      - Active scenario
      - Temperature
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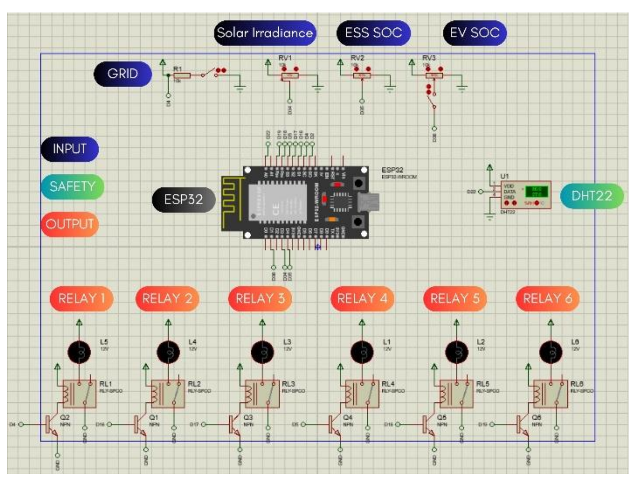


Fig. 4. Schematic diagram of energy management controllers for Bi-directional EV charging systems with safety features.

IV. Result and Discussion

This section will highlight the contribution to the understanding of Energy Management controllers for Bi- directional EV Charging Systems with Safety Features.

The primary objective was to develop an Energy Management Controller for a V2G Bi-directional charging system with safety features and to validate the prioritized energy distribution algorithm for a Bi-directional EV Charging system on 12 scenarios by evaluating the functionality of components in the proposed micro grid system. Through the analysis, the outcome has been observed by using the Thingsboard platform as a monitoring system dashboard and InfluxDB as a cloud database.

A. Hardware

Fig. 5 shows the hardware component in the Energy Management Controller for Bi-directional EV Charging System with Safety Features. The controller managed the active relays to work based on the real-time input condition based on 12 Scenarios A to L. The validation of the system working under the real condition of each scenario is in Table III and the average relay switching time is 50ms.

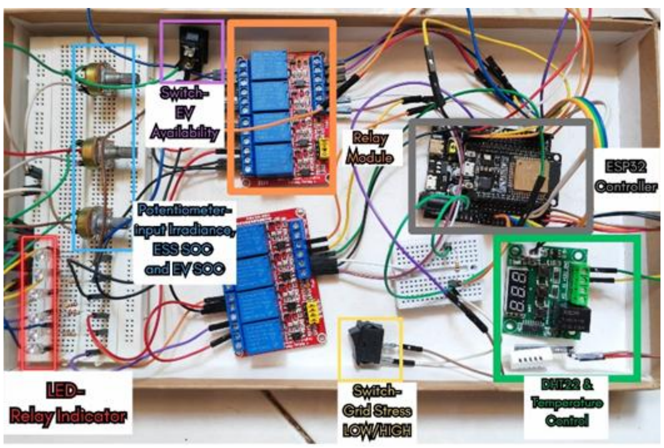


Fig. 5. Hardware component in the system.

TABLE III. List of Scenarios Based on the Input Conditions to Determine the Active Relay

Active Scenario	Input Conditions	Active Relay					
		1	2	3	4	5	6
Safety	Temperature > 50 Celcius						
A	-Grid Stress: HIGH -Irradiance: > 500 -ESS: SOC < 40% -EV: N/A					√	
B	-Grid Stress: LOW -Irradiance: > 500 -ESS: SOC < 40% -EV: SOC < 70%	√	√			√	
C	-Grid Stress: LOW -Irradiance: > 500 -ESS: SOC < 40% -EV: SOC > 70%	√	√	√	√	√	
D	-Grid Stress: HIGH -Irradiance: > 500 -ESS: SOC < 40% -EV: SOC > 70%		√	√	√	√	
E	-Grid Stress: HIGH -Irradiance: < 500 -ESS: SOC < 40% -EV: SOC > 70%		√	√	√		
F	-Grid Stress: LOW -Irradiance: < 500 -ESS: SOC < 40% -EV: SOC < 70%	√	√	√	√		
G	-Grid Stress: LOW -Irradiance: < 500 -ESS: SOC < 40% -EV: SOC < 70%	√	√	√	√		
H	-Grid Stress: LOW -Irradiance: < 500 -ESS: SOC > 40% -EV: SOC < 70%	√	√	√	√		
I	-Grid Stress: HIGH -Irradiance: < 500 -ESS: SOC > 40% -EV: SOC < 70%		√	√	√		√
J	-Grid Stress: HIGH -Irradiance: > 500 -ESS: SOC > 40% -EV: N/A					√	√
K	-Grid Stress: HIGH -Irradiance: < 500 -ESS: SOC > 40% -EV: N/A						√
L	-Grid Stress: HIGH -Irradiance: > 500 -ESS: SOC > 40% -EV: SOC < 70%		√	√	√	√	√

B. Monitoring

For monitoring the system, parameters such as temperature, input conditions, active relay, and active scenario, are presented using telemetry. The data from all the sensors are sent to the Thingsboard using the Message Queuing Telemetry Transport (MQTT) communication method. Fig. 6 shows the Thingsboard monitoring dashboard that shows the Input Conditions consisting of Grid Stress, Solar Irradiance value, ESS SOC percentage, and EV SOC percentage, Output Relay consists of Relay 1 until Relay 6, Active Scenario, Current Temperature of the system and the temperature alarm warning. This monitoring is used to validate the relay status according to the power flow.

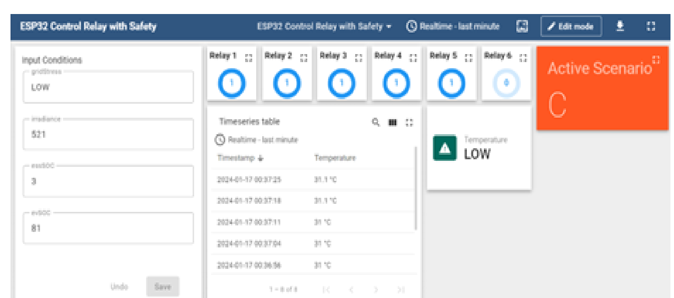
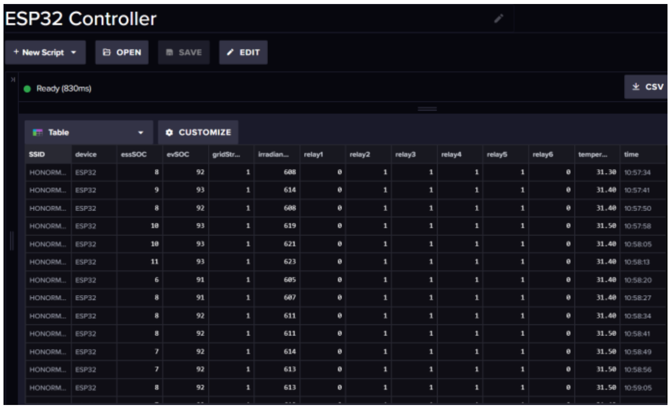


Fig. 6. Thingsboard monitoring dashboard.

C. Data Storage and Analysis

For data collection and data analysis, the data from the ESP32 controller will be collected using the InfluxDB database platform. Data is stored and visualized through various formats, including tables, time-series graphs, and histograms. Fig. 7 and Fig. 8 show the data that has been sent to the InfluxDB database, and it can be organized in the form of a table and graph. The data consists of conditions of grid stress, irradiance, ESS SOC, EV SOC, Temperature value, status of relays, and active scenario. InfluxDB allows the users to customize their data based on what the user wants to analyze. The total entries count so far was up to 200 data. The capacity of database storage can be considered based on historical data needs and data granularity.


ESP32 Controller

+ New Script | OPEN | SAVE | EDIT

Ready (830ms) | CSV

Table | CUSTOMIZE

SSID	device	essSOC	evSOC	gridStr...	irradian...	relay1	relay2	relay3	relay4	relay5	relay6	temper...	time
HONORM...	ESP32	8	92	1	608	0	1	1	1	1	0	31.30	10:57:34
HONORM...	ESP32	9	93	1	614	0	1	1	1	1	0	31.40	10:57:41
HONORM...	ESP32	8	92	1	608	0	1	1	1	1	0	31.40	10:57:50
HONORM...	ESP32	10	93	1	619	0	1	1	1	1	0	31.50	10:57:58
HONORM...	ESP32	10	93	1	621	0	1	1	1	1	0	31.40	10:58:05
HONORM...	ESP32	11	93	1	623	0	1	1	1	1	0	31.40	10:58:13
HONORM...	ESP32	6	91	1	605	0	1	1	1	1	0	31.40	10:58:20
HONORM...	ESP32	8	91	1	607	0	1	1	1	1	0	31.40	10:58:27
HONORM...	ESP32	8	92	1	611	0	1	1	1	1	0	31.40	10:58:34
HONORM...	ESP32	8	92	1	611	0	1	1	1	1	0	31.50	10:58:41
HONORM...	ESP32	7	92	1	614	0	1	1	1	1	0	31.50	10:58:49
HONORM...	ESP32	7	92	1	613	0	1	1	1	1	0	31.50	10:58:56
HONORM...	ESP32	8	92	1	613	0	1	1	1	1	0	31.50	10:59:05

Fig. 7. Data collection of energy management controller for Bi-directional EV charging system with safety features in table.

Fig. 8. Data collection of solar irradiance real-time value in graph.

D. Energy Management System

The proposed Energy Management Controller is developed to take advantage of renewable energy from the solar system to reduce the dependency on the electrical grid and maximize the usage of renewable energy. This strategic approach aims to minimize the dependency on the Electrical Grid, thereby reducing operational costs and enhancing the overall sustainability of the renewable energy infrastructure.

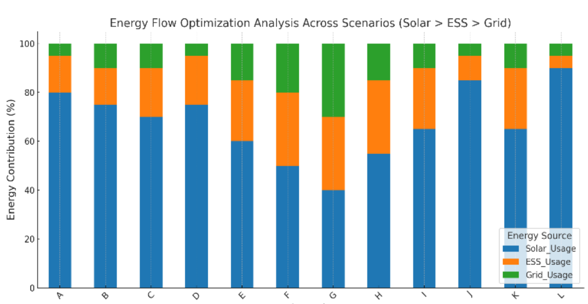


Fig. 9. Energy flow optimization across all scenarios.

In Fig. 9, the system manages energy sources based on predefined scenarios, optimizing renewable energy, and minimizing reliance on the Electrical Grid. Scenarios are designed to consider various factors such as grid stress, irradiance levels, ESS SOC, and EV SOC. Among the 12 possibilities, 50% prioritize the use of renewable energy. Scenarios A, B, C, D, J, and L are precisely designed to benefit solar power for charging both the Energy Storage System (ESS) and Electric Vehicles (EVs).

Conversely, only 42% of scenarios (B, C, F, G, and H) require a partial reliance on the electrical grid. In these cases, the system intelligently determines whether to draw power from the grid to charge the ESS, EVs, or both. The remaining 8% comes from the EV battery. When the EV battery SOC is greater than 70%, the user can discharge to the ESS. This dual-mode operation not only enables flexibility but also a fail-safe mechanism that ensures ongoing operation even in insufficient renewable energy conditions.

As referring to Table IV, scenarios with high solar irradiance, such as A, J, and L**,** rely almost entirely on solar energy, with utilization reaching up to 90%, ensuring minimal dependency on other sources. In contrast, scenarios with lower solar availability, such as E, F**,** and G**,** the ESS contributed significantly (5% to 30%) to support energy demands and reduce grid reliance. Grid usage is kept as the last priority**,** only being utilized when both solar and ESS are insufficient to meet system requirements. This optimized energy distribution strategy maximizes renewable energy utilization**,** enhances energy independence, and ensures minimal reliance on the electrical grid**,** making the system more efficient and sustainable.

In Fig. 10, solar energy sources are the primary energy source during sunny days, peaking at 80% at midday, minimizing reliance on other sources, while gradually decreasing in the morning and late afternoon, requiring support from ESS and the grid. ESS serves as the secondary source, contributing 5% to 15% based on solar availability which is higher during low solar periods (morning/evening) to reduce grid dependence and lower (5%) during peak solar hours to conserve stored energy. Grid is the last priority, used only when both solar and ESS are insufficient, with reliance increasing at night when solar is unavailable, though ESS helps reduce the grid load.

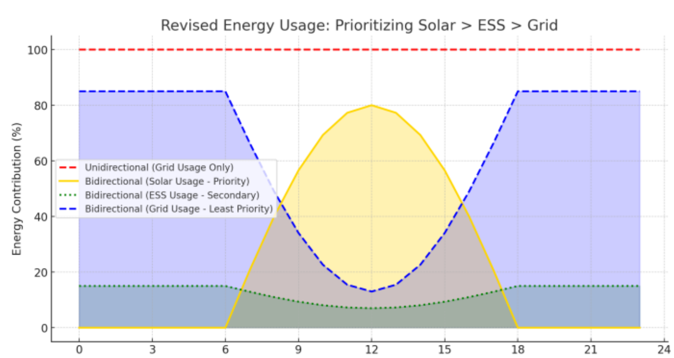


Fig. 10. Energy usage prioritizing solar>ESS>Grid.

TABLE IV. SCENARIO-BASED ENERGY CONTRIBUTION TABLE

	Solar Irradiance	**Grid Stress**	**ESS SOC**	**EV SOC**	**Solar Usage (%)**	**ESS Usage (%)**	**Grid Usage (%)**	**Reasoning**
A	High (>500 W/mÂ²)	High	High (>40%)	N/A	80	15	5	High solar availability enables the system to rely primarily on solar, with ESS providing additional support. Grid is only used as a last resort.
B	High (>500 W/mÂ²)	Low	High (>40%)	Low (<70%)	75	15	10	Lower grid stress allows some reliance on the grid, but solar remains the primary source, with ESS supporting when needed.
C	High (>500 W/mÂ²)	Low	High (>40%)	High (>70%)	70	20	10	Higher EV SOC enables more discharging to ESS, allowing greater energy flexibility. Solar still dominates; grid remains minimal.
D	High (>500 W/mÂ²)	High	High (>40%)	High (>70%)	75	20	5	With high grid stress, reliance on the grid is minimized. Solar is the dominant source, with ESS providing secondary energy supply.
E	Low (<500 W/mÂ²)	High	High (>40%)	High (>70%)	60	25	15	Lower solar irradiance requires more support from ESS. Grid is used only when both solar and ESS are insufficient.
F	Low (<500 W/mÂ²)	Low	High (>40%)	Low (<70%)	50	30	20	With low grid stress, some grid usage is acceptable. However, ESS takes a larger role due to reduced solar contribution.
G	Low (<500 W/mÂ²)	Low	High (>40%)	Low (<70%)	40	30	30	Very low solar irradiance forces higher grid and ESS usage, with grid contributing equally to ESS.
H	Low (<500 W/mÂ²)	Low	High (>40%)	Low (<70%)	55	30	15	A balanced approach where ESS supports more than the grid, but solar still plays a significant role in reducing grid dependency.
I	Low (<500 W/mÂ²)	High	High (>40%)	Low (<70%)	65	25	10	Since grid stress is high, grid usage is minimized. Solar and ESS work together to supply power efficiently.
J	High (>500 W/mÂ²)	High	High (>40%)	N/A	85	10	5	Ample solar availability allows the system to prioritize solar. ESS contributes slightly, while the grid is barely used.
K	Low (<500 W/mÂ²)	High	High (>40%)	N/A	65	25	10	Grid usage is minimized due to high stress. ESS helps balance the energy flow with solar taking the lead.
L	High (>500 W/mÂ²)	High	High (>40%)	Low (<70%)	90	5	5	Optimal condition where solar is fully utilized, leaving minimal load for ESS and grid.

While this study does not include direct experimental benchmarking against existing energy management controllers, a qualitative assessment reveals key functional advantages. Many prior systems emphasized hardware-level efficiency improvements [9], [13], [14] or cloud-based interfaces [10], [15] but lacked a unified framework for real-time energy prioritization and integrated safety control. The proposed EMC advances the state-of-the-art by implementing a prioritized energy distribution logic (Solar > ESS > Grid), embedded with a temperature-based relay safety mechanism and validated through a full hardware tested with 12 operational scenarios. These design features collectively contribute to reducing grid dependency, enhancing renewable energy use, and increasing system resilience under fluctuating input conditions.

V. CONCLUSION

The increasing reliance on grid-dependent EV charging systems has led to high energy costs, grid instability, and inefficient renewable energy utilization, highlighting the need for an intelligent Bi-directional energy management solution. Existing systems lack real-time energy prioritization, failing to dynamically allocate power between solar, ESS, and the grid based on real-time conditions. To address these gaps, this study developed an Energy Management Controller (EMC) implemented on an ESP32 microcontroller, integrating a prioritized Solar to ESS to Grid strategy with a temperature- based safety mechanism to optimize energy flow. The system was tested under 12 predefined operational scenarios, where it successfully reduced grid dependency to 15%, achieved renewable energy utilization of up to 90%, and maintained seamless relay switching. The safety mechanism effectively prevented overheating by shutting down relays when the temperature exceeded 50°C, ensuring stable operation. The EMC's real-time control, validated through ThingsBoard monitoring and InfluxDB data analysis, demonstrated its ability to enhance energy efficiency, lower costs, and improve grid stability in Bi-directional EV charging applications. These results underscore the EMC's potential to revolutionize EV charging infrastructure by minimizing grid reliance and maximizing renewable energy integration, with future work focusing on machine learning-based predictive energy management to further improve performance.

ACKNOWLEDGMENT

This work was supported in part by Universiti Teknologi MARA.

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