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# Design and Implementation of a Smart EV Charging Station with Solar Monitoring and Grid Integration using ESP32

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## Abstract:

The rapid growth of electric vehicles (EVs) has significantly increased the demand for efficient, reliable, and sustainable charging infrastructure, while most existing systems remain heavily dependent on conventional grid power, leading to higher load demand and limited utilization of renewable energy sources. This paper presents the design and development of a smart EV charging station that integrates solar energy as the primary source with grid supply as a backup to ensure continuous operation. The proposed system is built around an ESP32 microcontroller, which performs real-time monitoring of solar voltage, grid availability, and charging current, and implements an intelligent decision-making mechanism for automatic source selection. A relay-based switching system is used to seamlessly transition between solar and grid power based on predefined threshold conditions, ensuring uninterrupted charging and optimal energy usage. Additionally, a current sensing module and display unit are incorporated to provide real-time system feedback and improve user interaction. The overall design emphasizes simplicity, low cost, and reliability, making it suitable for small-scale and prototype-level applications. Experimental observations confirm that the system effectively prioritizes renewable energy while maintaining stable performance under varying environmental conditions, thereby contributing to reduced dependency on non-renewable sources and supporting the advancement of sustainable electric mobility.

*Keywords* — **Electric Vehicle, Solar Energy, ESP32, Grid Integration, Smart Charging, Renewable Energy, Automatic Switching.**

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## I. INTRODUCTION

The global shift toward sustainable transportation has accelerated the adoption of electric vehicles (EVs) as an effective solution to reduce greenhouse gas emissions and dependence on fossil fuels. However, the widespread deployment of EVs is highly dependent on the availability of efficient, reliable, and scalable charging infrastructure. Most existing EV charging systems rely heavily on conventional grid power, which not only increases the load on electrical networks but also raises concerns regarding energy sustainability and operational cost. In regions with unstable power supply or limited grid capacity, this dependency further affects the reliability of EV charging services.

To overcome these challenges, the integration of renewable energy sources, particularly solar energy, into EV charging systems has gained significant attention in recent research. Solar-based charging solutions offer an eco-friendly and cost-effective alternative by utilizing abundant and clean energy. However, solar energy is inherently intermittent and depends on environmental conditions such as sunlight availability, making it insufficient as a standalone solution. Therefore, a hybrid approach that combines solar energy with grid support is essential to ensure uninterrupted and stable charging operations.

Recent studies have explored various hybrid EV charging architectures incorporating solar photovoltaic (PV) systems, energy storage units, and intelligent control mechanisms. For instance, solar-powered charging stations with IoT-based monitoring systems have demonstrated improved energy management and scalability, although they often introduce higher complexity and cost [1]. Similarly, optimization-based models focusing on power-aware charging coordination have shown significant improvements in efficiency but are generally suited for large-scale applications due to their computational complexity [2]. Advanced systems utilizing maximum power point tracking (MPPT) and grid-interactive converters have achieved higher energy efficiency; however, their implementation requires sophisticated power electronics and increases overall system cost [3].

In contrast, there is a growing need for a simplified, low-cost, and intelligent charging solution that can be implemented at a prototype or small-scale level without compromising reliability. This paper addresses this gap by proposing a smart EV charging station that integrates solar energy with grid backup using an ESP32 microcontroller. The system employs real-time monitoring and an automatic source switching mechanism based on predefined threshold conditions, ensuring optimal utilization of available energy sources. By prioritizing solar energy and seamlessly switching to grid supply when necessary, the proposed system provides a balanced solution between performance, cost, and implementation simplicity.

The main contribution of this work lies in the development of a cost-effective hybrid charging system with intelligent control, real-time monitoring, and reliable operation under varying conditions. This approach not only enhances energy efficiency but also supports the broader goal of sustainable and eco-friendly transportation infrastructure.

## II. Literature Review

The integration of renewable energy with electric vehicle (EV) charging infrastructure has been widely explored to improve sustainability, efficiency, and reliability. Several research works have focused on combining solar energy with grid systems to overcome the limitations of conventional charging methods. A solar-powered smart EV charging station with IoT-based monitoring was presented in [1], where real-time data acquisition and remote accessibility improved system efficiency and scalability. However, the reliance on IoT platforms increased system complexity and implementation cost, making it less suitable for low-cost applications.

An optimized EV charging infrastructure model incorporating power-aware operations and energy market strategies was proposed in [2]. The study demonstrated significant cost reduction and improved energy utilization through intelligent scheduling. Despite its advantages, the model involved complex optimization algorithms and was primarily designed for large-scale commercial deployment, limiting its applicability in small-scale systems.

In another study, a solar–grid interactive EV charging system using high-frequency DC–DC converters and Maximum Power Point Tracking (MPPT) techniques was developed in [3]. The system achieved high efficiency and enabled effective power exchange between solar, battery, and grid sources. However, the requirement of advanced power electronic converters and precise control mechanisms increased the overall system cost and design complexity.

A solar-based EV charging station with a tilt-adjustable photovoltaic panel was proposed in [4], which improved energy harvesting efficiency through mechanical adjustment. While the approach enhanced solar utilization, it lacked intelligent control, automatic source switching, and real-time monitoring features, reducing system reliability under varying conditions.

Similarly, a hybrid solar-grid charging system incorporating MPPT and bidirectional power flow was presented in [5], demonstrating improved renewable energy utilization and reduced grid dependency. However, the system required sophisticated control strategies and grid synchronization techniques, making it less practical for low-cost prototype applications.

From the above studies, it is evident that while advanced systems provide high efficiency and intelligent energy management, they often involve increased complexity and cost. On the other hand, simpler systems lack automation and real-time monitoring capabilities. Therefore, there is a clear need for a balanced solution that combines intelligent control, cost-effectiveness, and reliable performance. The proposed system addresses this gap by implementing an ESP32-based hybrid EV charging station with automatic source switching and real-time monitoring, offering a practical and scalable solution for small-scale applications.

TABLE I

COMPARATIVE ANALYSIS OF EXISTING SMART EV CHARGING SYSTEMS

| Author & Year | System Type / Approach | Core Features | Strengths | Limitations |
|---|---|---|---|---|
| Ulagammai et al. (2024) [1] | Solar-based EV charging with IoT monitoring | Cloud connectivity, real-time data tracking, smart control | Scalable architecture, remote accessibility | High implementation cost, increased system complexity |
| Sayarshad (2024) [2] | Optimization-driven EV charging infrastructure | Power-aware scheduling, energy market integration | Reduced operational cost, efficient energy utilization | Complex algorithms, not suitable for small-scale systems |
| Monny et al. (2023) [3] | Solar–grid hybrid system with MPPT | High-frequency converters, efficient power exchange | High efficiency, reduced grid dependency | Expensive components, complex design |
| Gayathri et al. (2021) [4] | Solar charging with tilt-adjustable PV panel | Mechanical solar optimization | Improved energy harvesting, simple design | Lack of automation and intelligent control |
| Ashok Kumar et al. (2020) [5] | Hybrid solar-grid system with MPPT and bidirectional flow | Grid interaction, enhanced solar utilization | Better renewable integration, high performance | Requires advanced control techniques and synchronization |
| Proposed System | ESP32-based hybrid EV charging station | Automatic source switching, real-time monitoring, simple architecture | Low cost, reliable, easy implementation, suitable for prototypes | Limited scalability for large-scale deployment |

## III. METHODOLOGY

The proposed smart EV charging station is designed as a hybrid energy system that integrates solar power with grid supply to ensure reliable and uninterrupted operation. The methodology focuses on the systematic development of hardware architecture and control logic to achieve intelligent energy management with minimal complexity and cost.

### *A. System Design Overview*

The system consists of three major subsystems: input subsystem, control subsystem, and output subsystem. The input subsystem includes a solar photovoltaic (PV) panel as the primary energy source and a regulated grid-based DC supply as a backup source. A battery is incorporated to store excess solar energy and maintain system stability. The control subsystem is built around the ESP32 microcontroller, which acts as the central processing unit and performs real-time monitoring and decision-making. The output subsystem consists of a relay-based switching mechanism, current sensing unit, and display module for user interaction.

### *B. Hardware Implementation*

The hardware design is developed using low-cost and easily available components to ensure practical implementation. The solar panel generates DC power, which is regulated before being supplied to the system. The grid supply is converted from AC to DC using an adapter and serves as a secondary source. Voltage divider circuits are used to scale down both solar and grid voltages to safe levels suitable for the ESP32 analog input pins.

A current sensor (ACS712) is used to measure the charging current, enabling performance monitoring and fault detection. The relay module, driven by a transistor (BC547), is used to switch between solar and grid sources based on control signals from the ESP32. A voltage regulator (7805 IC) ensures a stable 5V supply to sensitive components. Additionally, a 16×2 LCD display is integrated to provide real-time information such as voltage levels, selected power source, and charging status.

### *C. Control Strategy and Algorithm*

The system operates on a priority-based energy management algorithm, where solar energy is given the highest priority due to its renewable nature. The ESP32 continuously monitors the voltage levels of both solar and grid sources and executes decision-making logic based on predefined threshold values.

- If solar voltage is above the required threshold, the system selects solar energy as the primary charging source.
- If solar power is insufficient, the system automatically switches to grid supply.
- If both sources are unavailable, the system enters a safe shutdown mode to prevent improper operation.

To avoid frequent switching due to minor voltage fluctuations, a hysteresis mechanism is implemented in the control logic. This ensures stable operation and reduces relay wear.

### *D. System Operation Flow*

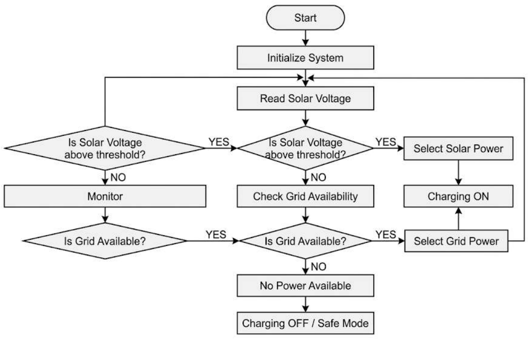


*Fig. 1: System Operation Flow of Proposed EV Charging System*

The operation of the system follows a continuous monitoring and control loop. Initially, the system is powered ON and all components are initialized. The ESP32 reads voltage values from the sensing circuits and evaluates the availability of energy sources. Based on this evaluation, the appropriate power source is selected through relay switching. The charging current is continuously monitored, and real-time data is displayed on the LCD. This process repeats continuously to ensure efficient and reliable operation under varying conditions.

### *E. Key Features of the Proposed Methodology*

- Automatic source switching between solar and grid
- Real-time monitoring of voltage and current
- Priority-based renewable energy utilization
- Low-cost and simple hardware design
- Reliable and stable operation with minimal complexity.

## IV. SYSTEM ARCHITECTURE

The architecture of the proposed EV charging station is designed to integrate multiple energy sources through a centralized control system, ensuring efficient power management and reliable operation. The system follows a modular structure consisting of energy input units, sensing circuits, control unit, switching mechanism, and output load. This modular approach improves system flexibility, scalability, and ease of implementation.

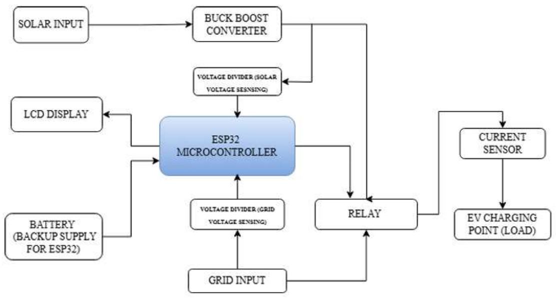


*Fig. 2: Block Diagram of EV Charging System with Solar and Grid Integration*

### *F. Overall Architecture*

The overall system architecture is centered around the ESP32 microcontroller, which acts as the main control and decision-making unit. The system integrates two primary energy sources: a solar photovoltaic (PV) panel and a grid-based DC supply. The solar panel serves as the primary renewable source, while the grid acts as a backup to ensure uninterrupted charging. Both sources are connected to voltage sensing circuits that provide real-time input to the controller.

### *G. Functional Modules*

The system is divided into the following functional modules:

#### *1. Input Module*

The input module consists of:

- Solar Panel: Generates DC power using photovoltaic conversion.
- Grid Supply: Provides backup power through an AC-to-DC adapter.
- Battery (Optional): Stores excess solar energy and stabilizes output.

This module ensures continuous energy availability under varying environmental conditions.

#### *2. Sensing Module*

Voltage divider circuits are used to step down the solar and grid voltages to a safe range suitable for the ESP32 analog-to-digital converter (ADC). Additionally, a current sensor (ACS712) is used to measure the charging current. These sensing elements enable real-time monitoring and provide essential data for decision-making.

#### *3. Control Module*

The ESP32 microcontroller serves as the core processing unit. It continuously reads input signals from sensing circuits and processes them using predefined logic. Based on the comparison of voltage levels, the controller determines the most appropriate energy source for charging.

#### *4. Switching Module*

The switching mechanism is implemented using a relay controlled by a transistor driver circuit. The relay ensures that only one power source is connected to the load at a time, preventing electrical conflicts. This module enables automatic and seamless switching between solar and grid supply.

#### *5. Output Module*

The output module includes:

- EV Charging Load: Represents the electric vehicle battery being charged.
- LCD Display: Provides real-time information such as voltage levels, selected source, and charging status.

This module ensures effective power delivery and user interaction.

### *C. Data Flow and Operation*

The system operates through continuous data acquisition and processing. Voltage signals from the solar panel and grid supply are sensed and converted into digital values by the ESP32. The controller evaluates these values against predefined thresholds and generates control signals for the relay module. Based on this decision, the appropriate power source is connected to the EV load. Simultaneously, system parameters are displayed on the LCD for monitoring purposes. This real-time data flow ensures efficient energy utilization and stable system performance.

*D. Advantages of the Proposed Architecture*

- Modular and scalable design
- Efficient integration of renewable and conventional energy
- Real-time monitoring and intelligent control
- Automatic and safe source switching
- Suitable for low-cost and prototype applications

## V. CONCLUSION AND FUTURE SCOPE

The performance of the proposed smart EV charging station was evaluated through both hardware implementation and functional testing under different operating conditions. The system was tested to verify its ability to monitor voltage levels, perform automatic source switching, and maintain stable charging operation. The results demonstrate that the system effectively prioritizes solar energy and ensures uninterrupted charging by switching to grid supply when required.

*A. Hardware Implementation*

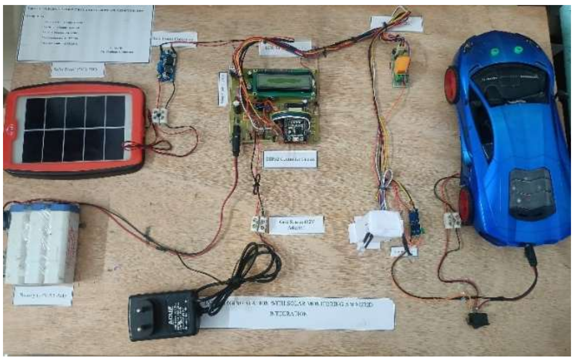

*Fig. 3: Hardware Implementation of Proposed EV Charging System*

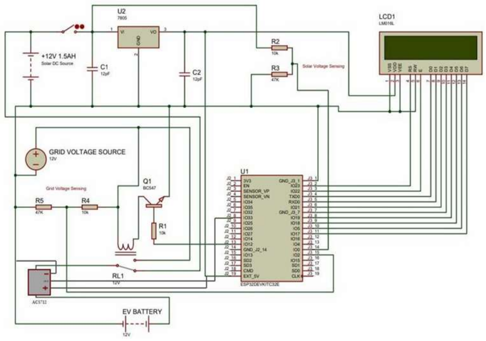

*Fig.4: Circuit Diagram of Proposed EV Charging System*

*B. Source Switching Operation*


*System Initialization (Calibration Mode)*


*Voltage Monitoring of Solar and Grid*


*Solar Mode Operation.*


*Grid Mode Operation.*


*Current and Power Monitoring*

*Fig. 5: Real-Time Display Showing Source Selection and System Status*

  

*C. System Performance Analysis*

The system was tested under different environmental conditions to evaluate its performance. During daytime operation, when solar voltage exceeded the predefined threshold, the system successfully selected solar energy as the primary charging source. The relay switching mechanism operated efficiently without delay, ensuring smooth transition and stable power delivery.

In low sunlight conditions or during nighttime, the system automatically switched to grid supply, maintaining uninterrupted charging. The transition between sources was seamless due to the implemented control logic, and no instability or fluctuation was observed in the output.

The current sensing module provided consistent readings, allowing accurate monitoring of the charging process. The LCD display continuously updated system parameters, improving transparency and user interaction. The overall system demonstrated reliable performance, efficient energy utilization, and stable operation under varying input conditions.

*D. Observed Results*

TABLE II
PERFORMANCE ANALYSIS OF SYSTEM UNDER DIFFERENT CONDITIONS

| Sr. No. | Operating Condition | Solar Voltage (V) | Grid Availability | Selected Source | Charging Status | System Response |
|---|---|---|---|---|---|---|
| 1 | High sunlight (Daytime) | 11V – 12V | Available | Solar | Charging ON | Solar prioritized, stable operation |
| 2 | Moderate sunlight | 8V – 10V | Available | Solar | Charging ON | Solar used if above threshold |
| 3 | Low sunlight (Cloudy) | 4V – 7V | Available | Grid | Charging ON | Automatic switching to grid |
| 4 | No sunlight (Night) | 0V | Available | Grid | Charging ON | Continuous operation via grid |
| 5 | No solar + Grid OFF | 0V | Not Available | None | Charging OFF | System enters safe mode |
| 6 | Fluctuating solar input | Variable | Available | Solar/ Grid | Charging ON | Stable switching with hysteresis |

*C. System Performance Analysis*

The results clearly indicate that the proposed system achieves a balance between simplicity, cost-effectiveness, and functionality. Unlike complex systems that require advanced converters and control strategies, the developed model provides reliable performance using a straightforward architecture. The automatic source switching mechanism ensures optimal utilization of renewable energy while maintaining system continuity.

Compared to existing approaches, the proposed system reduces dependency on grid power, minimizes operational complexity, and offers an affordable solution for small-scale and educational applications. Although the system is limited in terms of large-scale deployment, it provides a strong foundation for further enhancements such as IoT integration, battery management systems, and smart grid connectivity.

## VI. CONCLUSION AND FUTURE SCOPE

**A. Conclusion**

The proposed smart EV charging station successfully demonstrates an efficient and reliable hybrid energy system that integrates solar power with grid supply for continuous operation. The system effectively prioritizes solar energy as the primary source and automatically switches to grid power when solar availability is insufficient, ensuring uninterrupted charging. The implementation of the ESP32 microcontroller enables real-time monitoring, intelligent decision-making, and smooth control of the switching mechanism. The hardware results confirm stable performance under varying environmental conditions, with accurate sensing and consistent operation of the relay-based switching system.

The design emphasizes simplicity, low cost, and practical implementation, making it suitable for small-scale applications and educational purposes.

  

Compared to existing complex systems, the proposed model provides a balanced approach by combining essential features such as automatic source selection, real-time monitoring, and reliable operation without increasing system complexity. Overall, the system contributes toward the development of sustainable EV charging infrastructure by reducing dependency on conventional energy sources and promoting the use of renewable energy.

**B. Future Scope**

Although the proposed system performs effectively at the prototype level, several enhancements can be implemented to improve its functionality and scalability. The integration of Internet of Things (IoT) technology can enable remote monitoring and control through mobile or web applications. Advanced battery management systems can be incorporated to improve energy storage efficiency and extend battery life. The system can also be upgraded with Maximum Power Point Tracking (MPPT) techniques to maximize solar energy utilization under varying conditions.

For large-scale deployment, the design can be extended to support multiple charging points and fast-charging capabilities. Integration with smart grid infrastructure and energy management systems can further enhance efficiency and load balancing. Additionally, incorporating data logging and predictive analytics can help optimize system performance and maintenance. These improvements will transform the proposed prototype into a more advanced, scalable, and commercially viable EV charging solution.

## REFERENCES

[1] Ulagammai R., Karthik S., and Pradeep Kumar R., "Smart Solar-Based Electric Vehicle Charging Station with IoT Monitoring," International Journal of Renewable Energy Research, vol. 14, no. 2, pp. 1023–1030, 2024.

[2] Sayarshad H. R., "Optimization of Electric Vehicle Charging Infrastructure with Power-Aware Operations," IEEE Transactions on Smart Grid, vol. 15, no. 1, pp. 455–466, 2024.

[3] Monny J. K., Das R. K., Noman M. A. A., and Razzak M. A., "Solar–Grid Interactive Electric Vehicle Charging Station with Maximum Power Exchange," IEEE Access, vol. 11, pp. 56789–56800, 2023.

[4] Gayathri A., Prasanna C., Priyanka M., Rahul M., and Abdullah K. M., "Solar Based Charging Station for Electric Vehicles Using Tilt Adjustable PV Panel," International Journal of Engineering Research & Technology (IJERT), vol. 10, no. 5, pp. 345–349, 2021.

[5] Ashok Kumar M., Vijayakumar K., Navaneetha Krishnan M., and Jayanthy T., "Hybrid Solar-Grid Electric Vehicle Charging System with MPPT Control," International Journal of Power Electronics and Drive Systems, vol. 11, no. 3, pp. 1201–1208, 2020.

[6] "ESP32 Datasheet," Espressif Systems, 2023. [Online]. Available: https://www.espressif.com/

[7] "ACS712 Current Sensor Datasheet," Allegro Microsystems, 2022. [Online]. Available: https://www.allegromicro.com/

[8] "7805 Voltage Regulator Datasheet," Texas Instruments, 2021. [Online]. Available: https://www.ti.com/

[9] B. A. Forouzan, Data Communications and Networking, 4th ed., New York, NY, USA: McGraw-Hill, 2007.

[10] A. S. Tanenbaum, Computer Networks, 4th ed., Upper Saddle River, NJ, USA: Pearson Education, 2003.

  